The Pennsylvania State University
The Graduate School

ATMOSPHERIC EFFECTS ON VOICE COMMAND INTELLIGIBILITY FROM ACOUSTIC HAIL AND WARNING DEVICES

A Thesis in
Acoustics
by
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Abstract

Measurements of voice command sound pressure levels (SPLs) from acoustic hail and warning devices (AHWDs) were performed at listener locations up to 1500 m in order to determine how changes in meteorological condition affect variations in received voice command SPL. Variations in measured voice command SPL were compared to variations in meteorological condition, the results of other experiments, and the international standard for the attenuation of outdoor sound, ISO 9613-2. Similar to other experiments, our measurements indicate that variations of more than 30 dB should be expected to occur throughout the course of each day at listener locations at and beyond 200 m. However, unlike other experiments variations in measured voice command SPL of as much as 17 dB in a 6 minute time period were shown.

The American standard for the calculation of the speech intelligibility index, ANSI S3.5, was used to calculate the intelligibility of measured voice commands in order to determine how intelligibility at a listener location varies as a function of meteorological condition. When a moderate background noise level was present, a change in measured voice command SPL of only 3–4 dB was necessary to cause a partially intelligible voice command to become either fully intelligible or unintelligible. This result is significant because measured voice command SPLs were shown to vary by 30 dB at a listener location of 200 m due to changes in meteorological condition. The intelligiblity rating at a listener location can be estimated using a constant signal-to-noise ratio (S/N) for signal SPLs below 60 dB. However, for speech signals above 60 dB, the S/N must be increased to ensure the same intelligibility rating. This result is significant because AHWDs are commonly broadcast into high background noise level environments and/or into high insertion loss enclosures where signal SPLs above 60 dB must be used.

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Letter symbols

b Strength constant of the logarithmic sound speed profile, (m/s), p. 26

c Adiabatic sound speed, (m/s), p. 26

c_{eff} Effective sound speed, the sum of the adiabatic sound speed and the wind velocity, (m/s), p. 26

EA Excess attenuation due to a meteorological condition, (dB *re* 20 μPa), p. 35

IL Insertion loss, (dB *re* 20 μPa), p. 69

$\text{L}_{\text{p,output}}$ Output sound pressure level measured at a reference distance r_0 from the source, (dB *re* 20 μPa), p. 5

$\text{L}_{\text{p,received}}$ Received sound pressure level measured at a listener location, (dB *re* 20 μPa), p. 5

L_{pEQ} Equivalent sound pressure level, (dB *re* 20 μPa), p. 17

L_{pEQL} Equivalent sound pressure level from 400-4000 Hz, the limited frequency range of adequate signal-to-noise ratio, (dB *re* 20 μPa), p. 30

r Sound propagation distance, (m), p. 5

r_0 Reference distance from source for measurement of output sound pressure level, (m), p. 5

S/N Signal-to-noise ratio at a listener location, (dB *re* 20 μPa), p. 69

u Wind speed, (m/s), p. 26

W Moisture content of soil, (%), p. 11

W_s Saturation value of the moisture content of soil, (%), p. 11

z Height above ground, (m), p. 26

z_0 Aerodynamic roughness length of ground surface, (m), p. 26

Greek symbols

α Atmospheric absorption coefficient, (dB/m), p. 35

σ Flow resistivity, (Pa s/m^2), p. 11

ISO 9613-2 calculation symbols

α Atmospheric absorption coefficient, (dB/km), p. 50

A Total absorption from sound propagation, (dB *re* 20 μPa), p. 49

A_{atm} Attenuation due to atmospheric absorption, (dB *re* 20 μPa), p. 50

A_{bar} Attenuation due to barriers, (dB *re* 20 μPa), p. 50

A_{div} Attenuation due to geometrical divergence, (dB *re* 20 μPa), p. 49

A_{gr} Attenuation due to the ground effect, (dB *re* 20 μPa), p. 50

A_m Middle ground area, (dB *re* 20 μPa), p. 50

A_{misc} Attenuation due to miscellaneous effects, (dB *re* 20 μPa), p. 50

A_r Receiver ground area, (dB *re* 20 μPa), p. 50

A_s Source ground area, (dB *re* 20 μPa), p. 50

D_c Directivity correction, (dB *re* 20 μPa), p. 49

G Ground type, porous to non-porous, (unitless), p. 50

h_r Receiver height, (m), p. 50

h_s Source height, (m), p. 50

$L(DW)$ Sound pressure level at downwind receiver location, (dB *re* 20 μPa), p. 49

L_W Source sound power level, (dB *re* 1 pW), p. 49

q Temporary variable in the calculation of A_m, (unitless), p. 50

ANSI S3.5-1997 calculation symbols

A Band audibility function, (unitless), p. 57

B Larger of the spectrum levels for equivalent noise and self-speech masking, (dB *re* 20 μPa), p. 56

B_A Bandwidth adjustment, (dB *re* 20 μPa), p. 57

C Slope per octave of the upward spread of masking, (dB/octave), p. 56

D Equivalent disturbance spectrum level, (dB *re* 20 μPa), p. 54

E Speech spectrum level, (dB *re* 20 μPa), p. 54

E' Equivalent speech spectrum level, (dB *re* 20 μPa), p. 54

F Center frequency of one-third octave band, (Hz), p. 56

I Band importance function, (unitless), p. 57

i Individual band number used in calculation of the speech intelligibility index, (unitless), p. 56

L Speech level distortion factor, (dB *re* 20 μPa), p. 57

N Noise spectrum level, (dB *re* 20 μPa), p. 54

N' Equivalent noise spectrum level, (dB *re* 20 μPa), p. 54

n Number of bands in the speech intelligibility index procedure, (unitless), p. 56

S Speech intelligibility index (SII), (unitless), p. 57

U Standard speech level for normal vocal effort, (dB *re* 20 μPa), p. 57

V Self-speech masking spectrum level, (dB *re* 20 μPa), p. 56

X' Equivalent internal noise spectrum level, (dB *re* 20 μPa), p. 54

Z Equivalent masking spectrum level, (dB *re* 20 μPa), p. 56

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Chapter 1

Introduction

1.1 Introduction to AHWDs

Acoustic hail and warning devices (AHWDs) are widely used to broadcast voice commands at distances of up to 1.5 km and beyond. These voice commands alert listeners to the presence of danger, restricted space, emergency situations, or other conditions. AHWDs are often arrays of sound sources which emphasize speech-relevant frequencies (160 to 8000 Hz). For an array of coherent sound sources, there is a 6 dB increase in far-field sound pressure level (SPL) for each doubling of the number of sources. Noting this fact, there is a cost-benefit ratio between the number and size of the individual sound sources to their output SPL. AHWDs are constructed from as many as 100 planar magnetic transducers, or from as few as two folded horn loudspeakers. Source SPLs for AHWDs are typically 120–150 dB (*re* 20 μPa) at 1 m in front of the source.

AHWDs may range in size from a 0.5 m cube to a 2x2x1 m array, or larger. AHWD electrical power ranges from a few hundred watts RMS to as much as 10,000 watts RMS. Amplifiers may be enclosed inside the AHWD case or be separate. AHWD components must be installed in a rugged, waterproof case to increase durability. AHWDs may be mounted on buildings, boats, or ground vehicles (e.g., Humvee). Often, voice commands must be broadcast to listeners in high background noise level environments and/or into automobile cabs or ship cabins. Several examples of AHWD scenarios include: a checkpoint for border or harbor patrol, an entrance to a restricted facility, and enforcement of a restricted boundary around navy ships while in port. This last scenario plays a significant role in AHWD history.

1.2 Motivation

In the last 10 years, AHWDs have become more important, particularly for their use to help control the access to restricted areas. One scenario which made world news was the bombing of the USS Cole in the port of Aden, Yemen on October 12, 2000. In this attack, an unidentified vessel approached the USS Cole and detonated explosives along the ship hull, which killed 17 sailors and injured 47 [1]. Military personnel did not use force against this unidentified vessel because a threat had not been established. One way to determine the intent of an unidentified vessel is to broadcast a voice command and observe the reaction.

If a voice command is used which demands a change in course of the unknown vessel under threat firing upon it, and we can guarantee that it is intelligible to listeners on the unknown vessel, harmful intent can be established if the unknown vessel does not alter its course. Similarly, innocent listeners will hear the command and change their course immediately. However, the voice command must be intelligible, or else harmful intent cannot be guaranteed. Once the intent is assured, the safety of both listener and source parties is increased. The source party gains knowledge about whether the unidentified vessel is hostile, while innocent listeners are warned against possible military action. The farther the distance that the voice command message may be broadcast intelligibly, the greater the time for reaction and planning.

It is recognized that high background noise environments, such as those found on ships or in other scenarios, can adversely affect the intelligibility of a voice command. However, a factor which has received little, if any, attention from the research community is quantifying the direct influence of the atmosphere on voice command intelligibility. The effects of the atmosphere on sound propagation are well understood [2–8]; however, predicting specific SPLs at a listener location in a non-homogeneous, non-quiescent atmosphere still pose a serious challenge. The combination of many factors creates variations of 30 dB or more in received SPL [9–18], which creates large variations in intelligibility.

1.3 Background, objective, and approach

An AHWD's voice command is attenuated in a variety of ways during propagation through the atmosphere. Geometrical divergence causes an attenuation which is logarithmic (in decibels) with increasing distance. Atmospheric absorption causes an attenuation which is linear (in decibels) with increasing distance, and higher frequencies are attenuated greater than lower frequencies. Additionally, atmospheric absorption is dependent on factors such as temperature, humidity, and pressure, which change in time. Acoustic signals reflect from the ground surface, creating an alternate sound path. This alternate sound path may constructively or destructively interfere with the direct sound path, depending on the frequency, path difference and type of ground surface (e.g., grass or concrete). Refraction is caused by changes in the sound speed with height due to temperature and wind speed differences which change dramatically in time. These changes in sound speed cause sound rays to bend upward or downward. When sound rays bend upward, a shadow zone is created near the ground where no direct sound penetrates, resulting in decreased received SPLs. When sound rays bend downward, the received SPLs are increased due to the addition of multiple ray paths. Additionally, scattering from atmospheric turbulence causes random fluctuations in received SPL. Refraction and atmospheric turbulence cause changes in received SPL which vary dramatically over the course of each day.

Documentation of the atmospheric effects on sound propagation to correlations in the intelligibility of a speech signal at a listener location has not been found. It is known that there are significant variations in received SPL due to propagation through the atmosphere, but how is the intelligibility affected at a listener location in a noisy environment? The objective of this thesis is to provide insight into the answer to this question.

To accomplish this task, measurements of voice command SPLs are performed in a variety of meteorological conditions and at propagation distances from 200–1500 m. Wind speed and temperature are monitored with weather stations in order to estimate the refractive condition along the sound propagation path. Next, variations in measured voice command SPLs at listener locations are compared to changes in meteorological condition, variations in SPL found in other experiments, and the SPL predicted by the international standard for outdoor sound propagation, ISO 9613-2 [19]. The intelligibility of voice commands is calculated using ANSI S3.5 [20, 21] and the effect of changes in signal and noise SPLs on the intelligibility is determined. Finally, the variability in an intelligibility rating is related to meteorological condition.

1.4 Thesis outline

In Chapter 2, a basic introduction to outdoor sound propagation is given. Next, the experimental procedure is explained. The results of the outdoor sound propagation experiment are discussed and compared with variations in meteorological conditions and the variation in measured SPL found in other experiments. Additionally, measured voice command SPLs are compared with predictions by ISO 9613-2 [19].

In Chapter 3, the intelligibility calculation using ANSI S3.5 [20, 21] is outlined. Next, the signal and noise levels used in the calculation are discussed and the results of calculations are presented. The intelligibility is calculated for the received voice command SPLs and generalizations are made about the variations in intelligibility for different meteorological conditions. Finally, the importance of the need to understand meteorological conditions in order to properly assess intelligibility of voice commands from AHWDs is emphasized.

In Chapter 4, the work accomplished in this thesis is summarized. First, variations in measured voice command SPL in relation to meteorological condition are discussed. Next, variations in voice command intelligibility are examined and intelligibility ratings are related to a signal-to-noise ratio. Finally, future work is recommended.

Appendix A lists the received voice command SPLs and the meteorological condition data provided by the weather stations. Appendix B displays the Matlab code that was used to calculate attenuation due to atmospheric absorption and reflection from the ground, and the intelligibility using ANSI S3.5.

Chapter 2

Atmospheric effects on voice command propagation

2.1 Background information on sound propagation in the atmosphere

Many tutorials and reviews have been written on the subject of outdoor sound propagation [2–8]. This section is an overview of some of the material related to sound propagation from AHWDs. The overview includes information on geometrical divergence, atmospheric absorption, reflections from the ground, refraction, and turbulence. Particular emphasis is given to frequencies important to speech intelligibility (160–8000 Hz) [20], as well as 400–4000 Hz, the range of adequate signal-to-noise ratio in the experiment.

2.1.1 Geometric divergence

AHWDs are commonly constructed as an array of many small sources, and each of these sources may be considered acoustically small compared to acoustic wavelengths for speech. Therefore, sound from each source spreads spherically, independent of the speech frequency. The received sound pressure level from an AHWD with a particular output sound pressure level, $\mathrm{L}_{\mathrm{p,output}}$, is

$$\mathrm{L}_{\mathrm{p,received}} = \mathrm{L}_{\mathrm{p,output}} - 20\log_{10}(r/r_0), \tag{2.1}$$

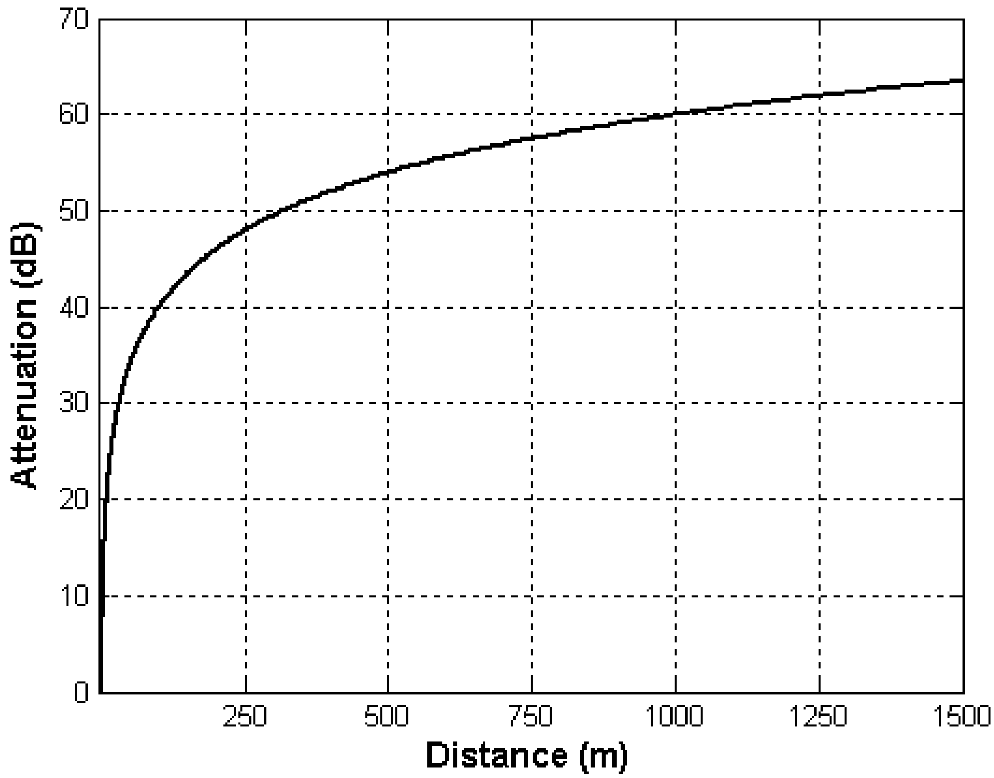

Figure 2.1. Attenuation of a sound source from a reference distance of 1 m due to spherical spreading. The SPL is highly attenuated near the source due to the logarithmic dependence (in decibels) of the attenuation.

where r is the propagation distance and r_0 is the reference distance where $L_{p,output}$ was measured. For each doubling of propagation distance, the SPL drops by 6 dB. This attenuation is shown in Figure 2.1 for a reference distance of 1 m. The SPL is highly attenuated near the source, compared to the additional attenuation at longer propagation distances, due to the logarithmic dependence. In the first 100 m the SPL is attenuated by 40 dB, but for the next 100 m it is only attenuated by an additional 6 dB. Source SPL must be about 50 dB higher than the desired SPL at 300 m to account for the attenuation due to spherical spreading.

2.1.2 Atmospheric absorption

Atmospheric absorption is caused by molecular relaxation and thermal and viscous losses between interacting molecules. This effect is dependent on temperature, humidity, and pressure. Unlike spherical spreading, this attenuation has a linear effect (in decibels) with distance. Additionally, atmospheric absorption is proportional to frequency squared. The attenuation can be calculated using equations published by Bass [22, 23] or using a standard [24, 25]. Appendix B.1 displays the Matlab code used to calculate this effect.

During the experiment, air temperatures ranged from 10–25°C and relative humidity (RH) ranged from 50–90%. Figure 2.2 shows several examples of the attenuation due to atmospheric absorption, calculated for an afternoon, morning, and late afternoon test session during the experiment. These three examples express the range of absorption values found during the experiment. A fourth case with dry air is shown for contrast; this case did not occur during testing. Figure 2.2 shows that there was little change in attenuation values due to atmospheric absorption during the experiment. Specifically, when frequencies between 400 and 4000 Hz are considered, there was less than 0.5 dB difference in attenuation between different measurement times. However, for dry air (e.g., 5% RH) absorption values may be significantly different. During the experiment, attenuation due to atmospheric absorption becomes a more significant effect above 1 kHz, where an attenuation of 0.5 dB per 100 m is surpassed.

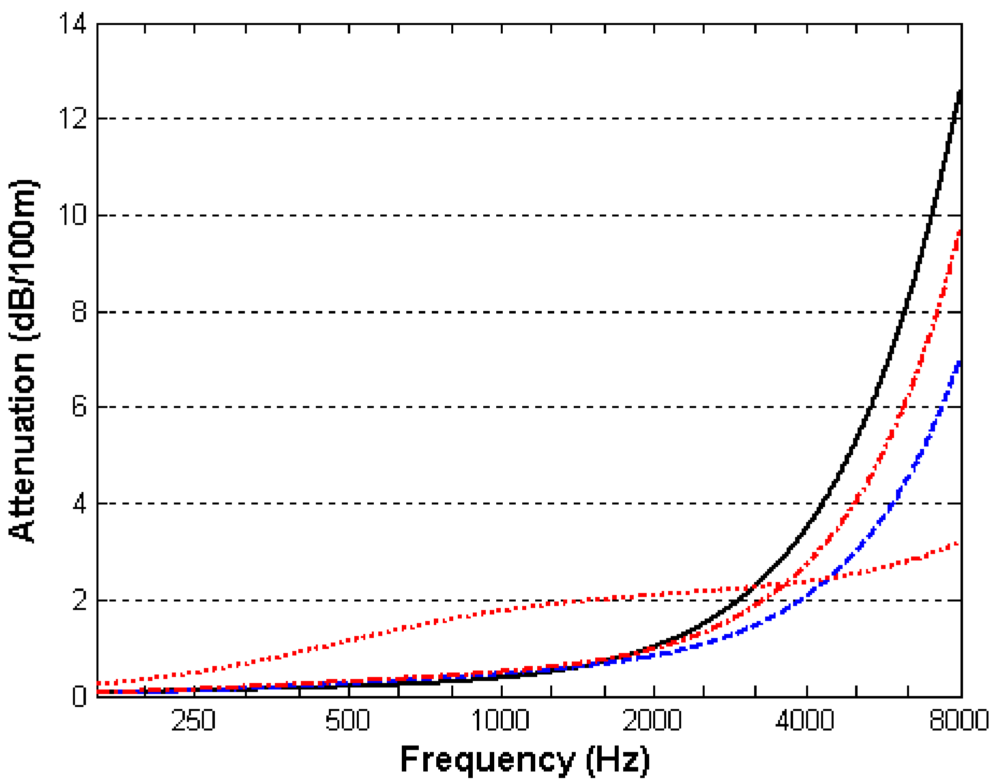

Figure 2.2. Four examples of the attenuation due to atmospheric absorption: in the afternoon, 10°C and 65% RH (solid black line); in the morning, 17°C and 90% RH (blue dashed line); in the late afternoon, 22°C and 50% RH (red dot-dashed line); and in dry air 10°C and 5% RH (red dotted line). Below 4 kHz, there was less than a 2 dB (per 100 m) change in the attenuation due to atmospheric absorption during the experiment.

2.1.3 Reflection from the ground

The ground reflects sound, allowing sound propagation from source to listener by both direct and ground-reflected ray paths. The reflected ray travels a larger distance than the direct ray, and often endures a change of phase at the boundary. Therefore, the reflected ray will constructively or destructively interfere with the direct ray at the listener location, depending on the frequency, properties of the ground surface, and path length difference.

2.1.3.1 Calculating the ground effect

One model used to calculate the ground effect is the Delany-Bazely model [26], which accounts for the phase change at the boundary using a single parameter called flow resistivity. The equations for calculating this effect are outlined in detail by Salomons [27]. Appendix B.2 displays the Matlab code used to calculate this effect. Figure 2.3 shows the attenuation due to the ground effect for a 10 m propagation distance with source and listener heights of 2.0 and 1.5 m, respectively. The calculation is performed for the typical values of flow resistivity of grass (200 kPa s/m^2) and old asphalt (32,000 kPa s/m^2) [28], to show the difference between a porous and a hard surface. Figure 2.3 shows a pattern of alternating constructive and destructive interference, which occurs at about every 550 Hz. 550 Hz corresponds to a wavelength of about 0.5 m, which is the approximate path length difference between the direct and reflected rays. Regions of constructive and destructive interference occur at different frequencies for the asphalt and grass case due to the difference in phase change at the boundary. In practice, the peaks will not be as sharp due to relative changes in phase between the two paths created by atmospheric turbulence, which will be discussed in following sections.

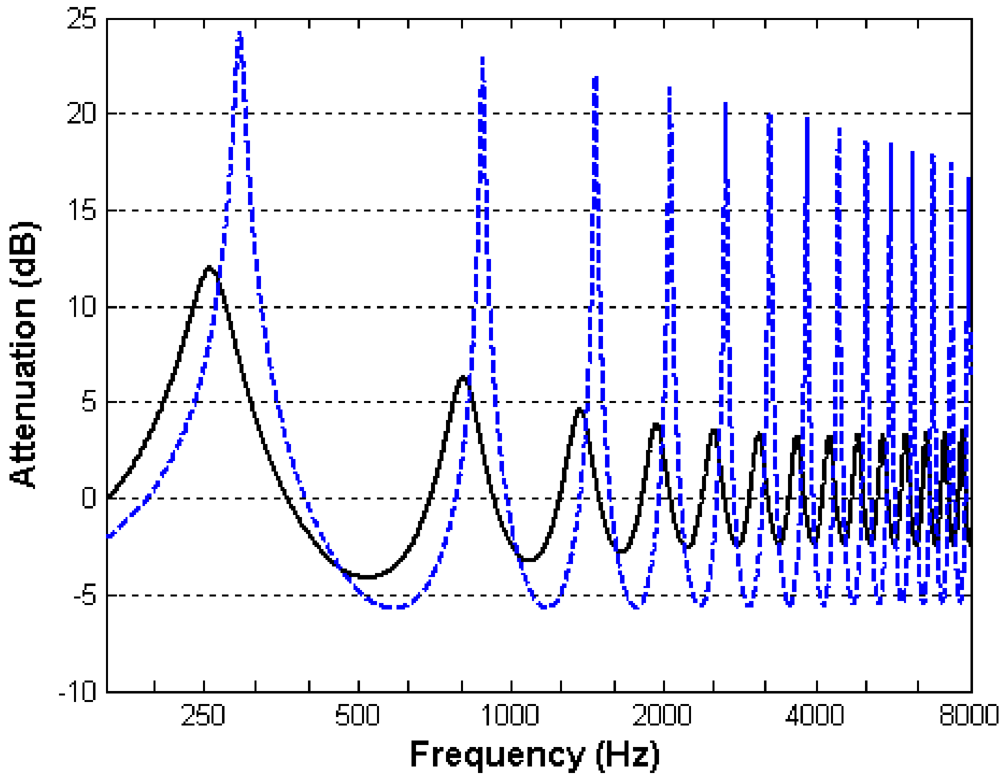

Figure 2.3. Attenuation due to the ground effect at a propagation distance of 10 m for sound above grass (solid black line) and old asphalt (blue dashed line). Reflection from the ground causes a phase change, so that regions of constructive and destructive interference occur at different frequencies for the two cases.

2.1.3.2 Changes in moisture content of grass soil

The change in moisture content of grass soil causes a change in the effective flow resistivity [29]. An empirical formula was developed for the flow resistivity, σ, as the moisture content of grass soil, W, changes, given as

$$\sigma = 360 \log_{10} \left(\frac{1}{(1 - W/W_s)} \right) + 150, \tag{2.2}$$

where W_s is the saturation value of the soil (assumed to be 40%) [29]. Figure 2.4 shows the change in attenuation due to the ground effect at 10 m propagation distance for moisture contents of 5, 15, and 25%. As moisture content (and flow resistivity) increases, the location of the interference minima shift upward in frequency. To calculate the change in each one-third octave frequency band, the curves are averaged (in pressure-squared) over each band. Table 2.1 shows this average change in received SPL for a propagation distance of 10 m, for an equal weighting of logarithmically distributed frequencies in each band. This calculation was performed for an average flow resistivity of grass, 200 kPa s/m^2 [28], or about 15% moisture content. These values are used to correct the output of the AHWD for the ground effect in the ISO 9613-2 calculation in subsection 2.3.3, on page 48. The difference in SPL is 1 dB or less between the 5 and 20% moisture contents (flow resistivity of 200 and 400 kPa s/m^2, respectively) in any one-third octave band from 400–4000 Hz. This suggests that the effect of changes in moisture content on the measurement of the output SPL of the AHWD can be neglected.

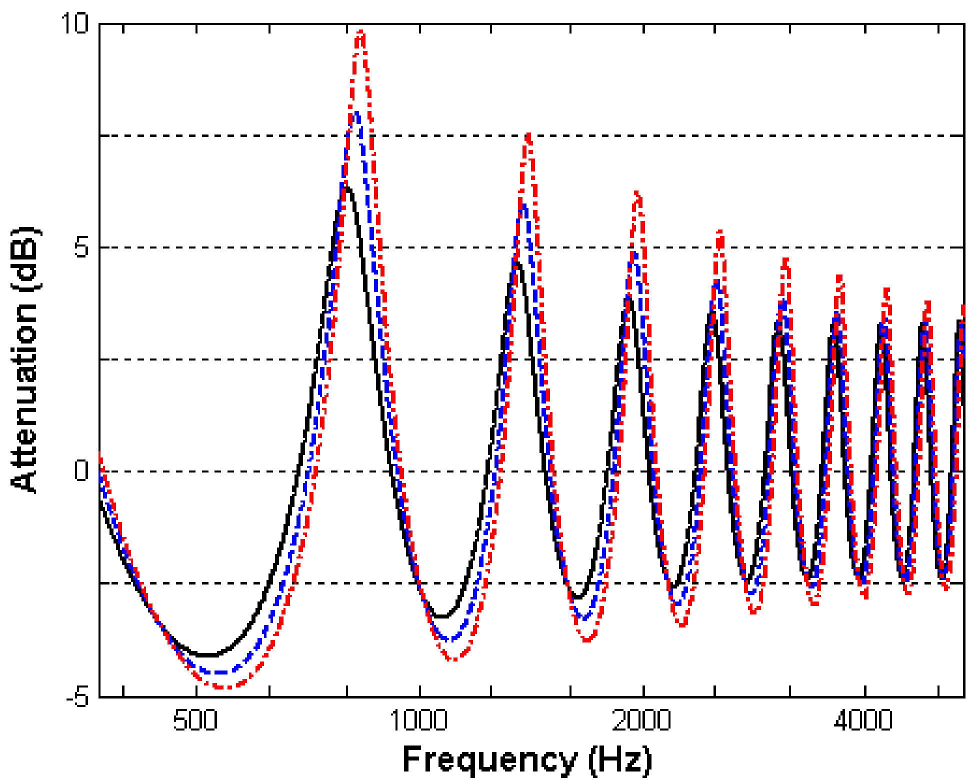

Figure 2.4. Attenuation from the ground effect at 10 m propagation distance for moisture contents of 5 (solid black line), 15 (blue dashed line), and 25 (red dotted line) percent. This change in attenuation due to varying moisture content of grass soil is neglected in the experiment because is was not measured.

Table 2.1. Attenuation from the ground effect at 10 m propagation distance averaged over each one-third octave frequency band. The average flow resistivity of grass, 200 kPa s/m^2, is used. A positive attenuation indicates destructive interference between the direct and ground-reflected ray paths, while a negative attenuation indicates constructive interference.

Frequency (Hz)	Attenuation (dB)
400	−2.0
500	−3.9
630	−2.3
800	3.7
1000	−2.1
1250	0.1
1600	−1.5
2000	−0.2
2500	−0.6
3150	−0.5
4000	−0.3
5000	−0.6

2.1.4 Refraction and turbulence

The atmosphere is a complex, moving medium, which almost always has differences in air temperature and wind speed with height. Due to these inhomogeneities, the sound speed is not constant and sound rays do not follow straight paths. Often, these effects are estimated using linear, logarithmic, or linear-logarithmic profiles for the effective sound speed in the atmospheric surface layer. The effective sound speed accounts for the combination of the temperature and wind effects.

2.1.4.1 Temperature

Solar radiation causes differences in temperature with height in the boundary layer. These differences are due to the absorption and radiation of solar energy by the ground surface. On a sunny day, the ground absorbs and reradiates heat, causing air closer to the ground to become warmer than the air above it, and a decrease in temperature with increasing height is found. This change in temperature is called a temperature lapse. During a very cloudy day, there is little heating of the ground because the majority of solar radiation is reflected by the cloud cover, and the increase in temperature with height is less dramatic. In the evening after sunset, the ground becomes cooler than the air above it, causing an increase in temperature with height. This change in temperature is called a temperature inversion. A large variety in temperature variations with height are found during each day.

2.1.4.2 Wind

The wind speed is assumed to be zero at the ground surface due to friction (i.e., the no-slip boundary condition), and increases with increasing height above the surface. For wind speeds much smaller than the sound speed in air, the wind speed can be added to the sound speed, and a new, *effective* sound speed is defined as the sum of the two [30]. Since the wind speed is not constant with height, a different sound speed is given for different heights—the same result as for temperature differences. Sound propagating in the direction of the wind is bent downward because the sound speed is faster at greater heights. Likewise, sound propagating against the wind direction is bent upward, away from a listener location near the ground.

2.1.4.3 Combination of temperature and wind, and the addition of turbulence

The combination of the two effects of temperature and wind on sound speed produces an overall sound speed gradient, or change in the effective sound speed with height. This gradient characterizes the refractive effect of the atmosphere. When sound is refracted downward, (e.g., at night with minimal wind), there are many ray paths from the source to the listener. Most of these ray paths have multiple interactions with the ground surface. Several ray paths are shown in Figure 2.5. When multiple sound rays reach the listener, the sound level is increased.

When sound is propagated in an upward refracting condition, (e.g., upwind of a source or during a sunny day with little wind), there may be no direct ray path for the sound to reach the receiver because the sound rays are bent upward. Figure 2.6 illustrates this condition, where the listener location is said to be in the shadow zone. Near the edge of the shadow zone, diffraction is the dominant mechanism responsible for sound energy. Farther into the shadow zone, scattering by atmospheric turbulence is responsible for the received sound energy. Once scattering becomes the dominant mechanism, received SPLs in the shadow zone are expected to be at a constant level between 20 and 30 dB lower than expected from the combined attenuation from the effects of geometrical divergence and atmospheric absorption [31].

Turbulence is caused by buoyancy from thermals (e.g., rising volumes of warm air) or wind shear. Turbulence results in spatial and temporal fluctuations in the effective sound speed, which create random fluctuations in received SPL at a listener location. These fluctuations in SPL result from phase and direction changes of sound rays as they travel through the turbulence. Turbulence increases with increasing wind speed. Changes in measured SPLs from the effect of turbulence have been shown to have up to 6 dB standard deviation [32].

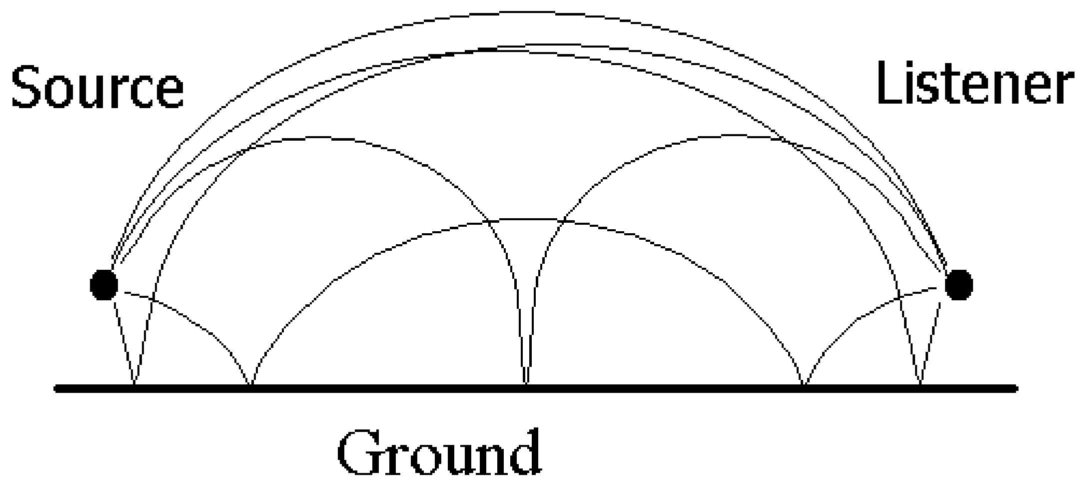

Figure 2.5. Several sound ray paths from source to listener in a downward refracting atmosphere. Most ray paths have multiple interactions with the ground surface. However, multiple interactions with a porous ground surface highly attenuate the sound signal along an individual ray path.

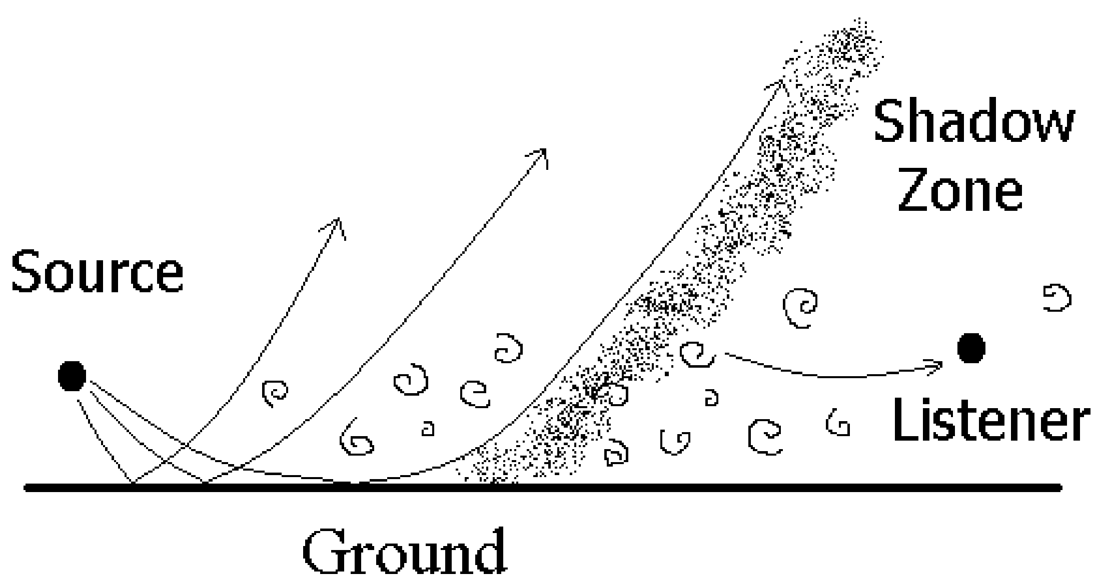

Figure 2.6. Several sound ray paths in an upward refracting atmosphere. In the shadow zone, the listener does not receive direct sound, but only diffracted and/or scattered sound.

2.2 Experimental set-up and approach

In this section the experimental site and equipment are introduced. The procedure is discussed. The inconsistency in the output SPL of the AHWD is quantified and a solution to remove this inconsistency is presented. The collection of meteorological data is discussed and a method to determine refractive conditions is defined.

2.2.1 Data collection

This subsection gives details about the test site, equipment, and procedure used to make measurements. Additionally, the inconsistency in the output SPL of the AHWD is discussed and a method to normalize the output is presented.

2.2.1.1 Set-up and procedure

The experiment was conducted in September and October of 2006 at the Mid-State Airport in Philipsburg, PA. Figure 2.7 shows an aerial view of the airport. Sound was propagated above grass, about 15 m west of the asphalt runway. The AHWD used in the experiment was a current-of-the-shelf model, and was placed at 2.0 m height. An audio file player, amplifier, and generator were used to operate the AHWD. The generator was housed in a high insertion loss enclosure behind the device to reduce noise levels.

Larson Davis model 824 and Brüel & Kjær model 2250 sound level meters (SLMs) were used to measure the unweighted equivalent sound pressure level (L_{pEQ}) in one-third octave bands. The calibration of SLMs was checked each day using a Larson Davis model CAL200 calibrator at 1 kHz and 94 and 114 dB (*re* 20 μPa). During each voice command broadcast, a sound recording was made at three locations simultaneously:

1. 10 m from the source, to be used for output normalization,

2. 500 m from the source, labeled the “stationary” SLM, and

3. between 200 and 1500 m from the source, labeled the “roaming” SLM.

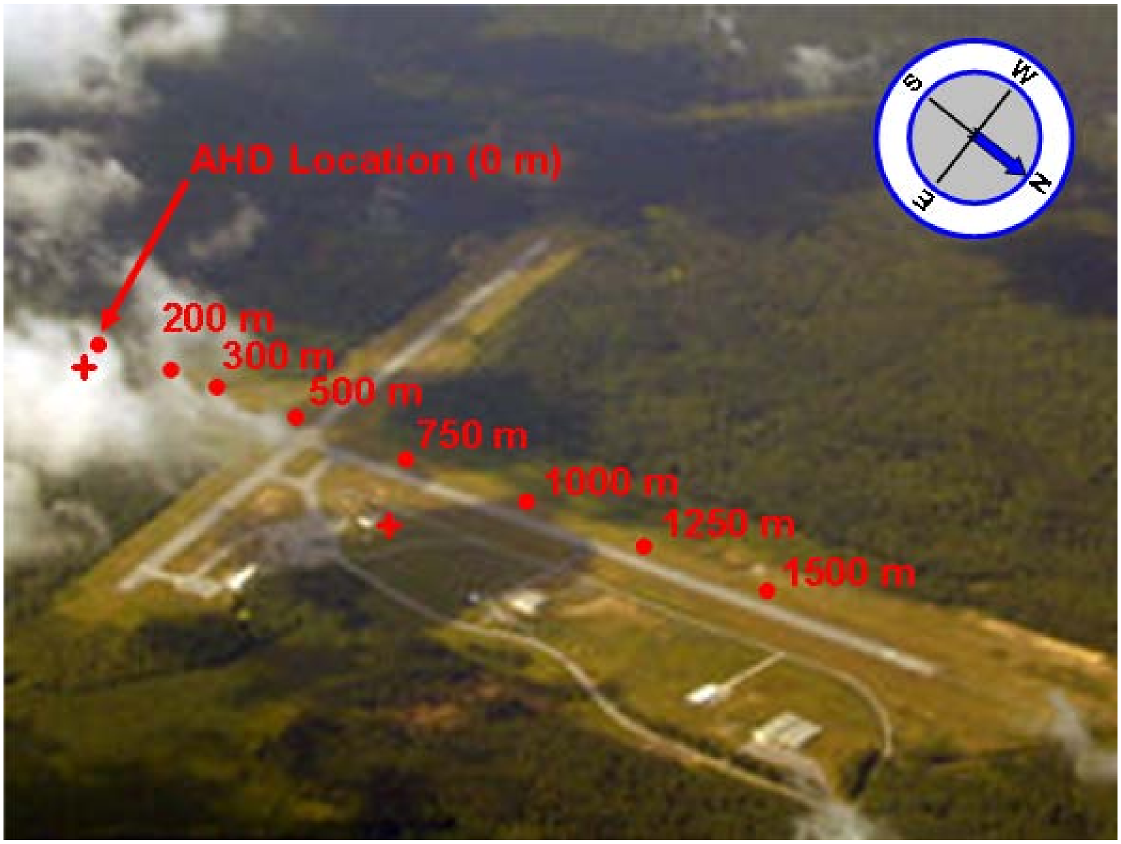

Figure 2.7. Aerial photo of the Mid-State Airport. Listening (•) and weather station (+) locations are marked.

Persons near the activated device wore hearing protection. The voice command was a standard message which was used previously to demonstrate AHWD intelligibility. The text of the voice command read:

> You are in a Naval vessel exclusion zone. Reverse course immediately or I will fire upon you. I say again, reverse course immediately or I will fire upon you.

The voice command was broadcast continuously during each measurement. Each measurement lasted 30 seconds, which is about three repetitions of the message. Measurement times were synchronized using walkie-talkies.

During each test session, the SPL in one-third octave bands was measured by the roaming SLM at 1.5 m height at each of the listener locations marked in Figure 2.7. However, in session 1 the SPL was not measured at 750 m due to battery failure in that SLM. In total, 69 measurements were made. The test sessions lasted a mean of 55 minutes. Testing was repeated on different days, at different times, and in different propagation directions in order to make measurements during various meteorological conditions. This information is displayed in Table 2.2. During sessions 3, 5, 6, and 8 sound was propagated in the reverse direction (i.e., south instead of north). This change in direction resulted in an opposite wind direction than in sessions 2, 4, 7, and 9 which were taken on the same days, because wind direction was typically constant throughout the morning and afternoon. This change in direction was performed to increase the variety of meteorological conditions during measurements.

Table 2.2. Dates, times, and mean relative humidity, temperature, and wind speed during each test session. A variety of temperatures and wind speeds were encountered over the two week test period. RH is relative humidity, T is temperature, and WS is wind speed along the direction of propagation.

Test session	Date	Start time	End time	RH (%)	Mean T (°C) 1.8 m	Mean T (°C) 11.7 m	Mean WS (m/s) 1.8 m	Mean WS (m/s) 11.7 m
1	29 Sept	14:15	14:58	63	11.0	10.3	−3.0	−5.1
2	2 Oct	11:18	12:38	64	15.9	15.6	−1.1	−3.5
3	2 Oct	13:56	15:01	53	20.3	18.6	0.6	2.7
4	3 Oct	10:38	11:35	60	22.1	20.4	0.7	0.2
5	3 Oct	12:27	13:22	57	22.8	21.5	−0.5	−0.5
6	4 Oct	10:54	11:45	88	19.6	17.7	−0.2	−0.8
7	4 Oct	12:49	13:47	80	20.7	19.8	1.9	3.4
8	10 Oct	14:24	15:02	51	21.8	20.0	0.5	1.4
9	10 Oct	15:43	16:36	50	22.0	20.9	−0.3	−1.1
10	10 Oct	20:09	21:05	78	14.0	15.0	0.0	0.0

2.2.1.2 AHWD output normalization

The AHWD was known to have an inconsistent output due to electronics warm-up and fatigue issues during use. Due to this inconsistent output, the L_{pEQ} at 10 m was recorded during each measurement, so that it could be used to normalize the L_{pEQ} at listener locations. This was done so that the received SPLs could be compared without the added variation of changes in source SPL. The normalization procedure was performed in a two step process. First, the mean SPL over the entire experiment was calculated for each one-third octave band measured at 10 m. Second, the difference from the mean of each one-third octave band SPL for measurements at 10 m was added to the measurements at listener locations.

Figure 2.8 shows the mean SPL in one-third octave bands for sessions 1–7

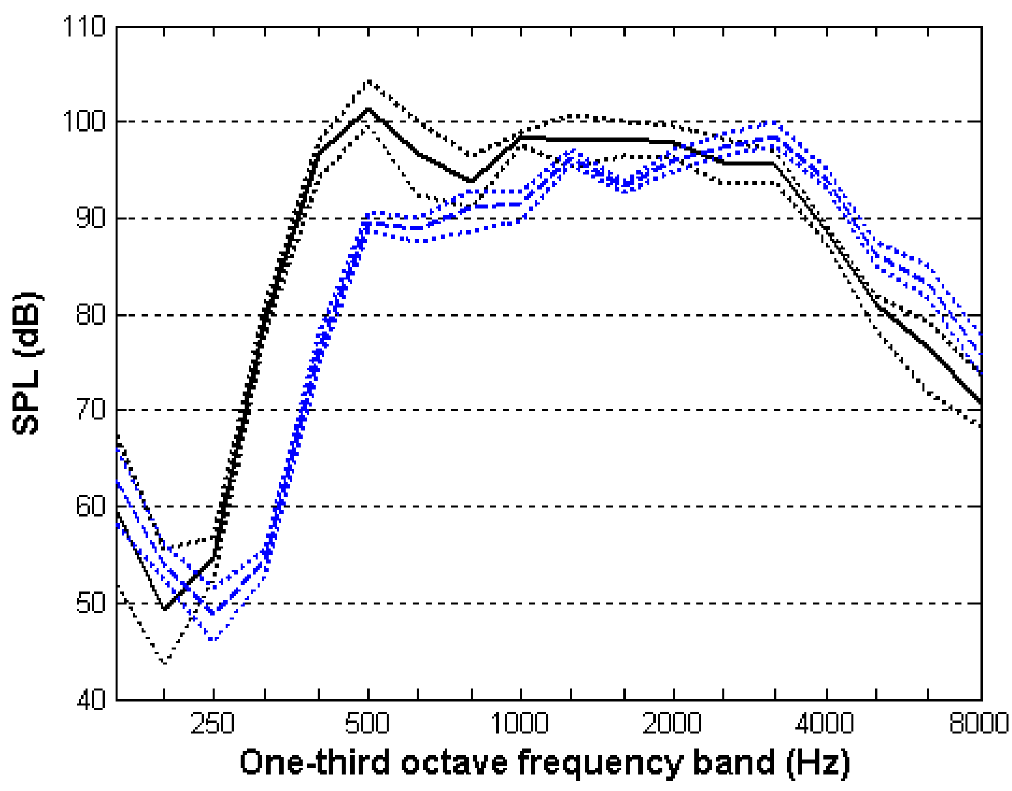

Figure 2.8. Mean SPL at 10 m for sessions 1–7 (solid black line) and 8–10 (blue dashed line). Dotted lines illustrate the maximum and minimum one-third octave band SPLs. The output SPL in each one-third octave band was constant to within 4 dB of the mean SPL in each one-third octave band for both test session groups.

and 8–10. In both session groups, the device output was constant to within 4 dB of the mean SPL in each one-third octave band. However, the L_{pEQ} was 3 dB less in sessions 8–10. Sessions 8–10 occurred on October 10, at the end of a long series of other tests. It was assumed that components of the AHWD were failing from overuse, which reduced the output L_{pEQ} of the AHWD. Figure 2.9 displays the mean voice command SPL in one-third octave bands from the entire experiment. There was significant variation in the SPL in some one-third octave bands of the AHWD during the course of the test: as much as 15 dB at 500 Hz. However, the variation in the overall L_{pEQ} is less than 8 dB. All measurements were normalized to this mean output.

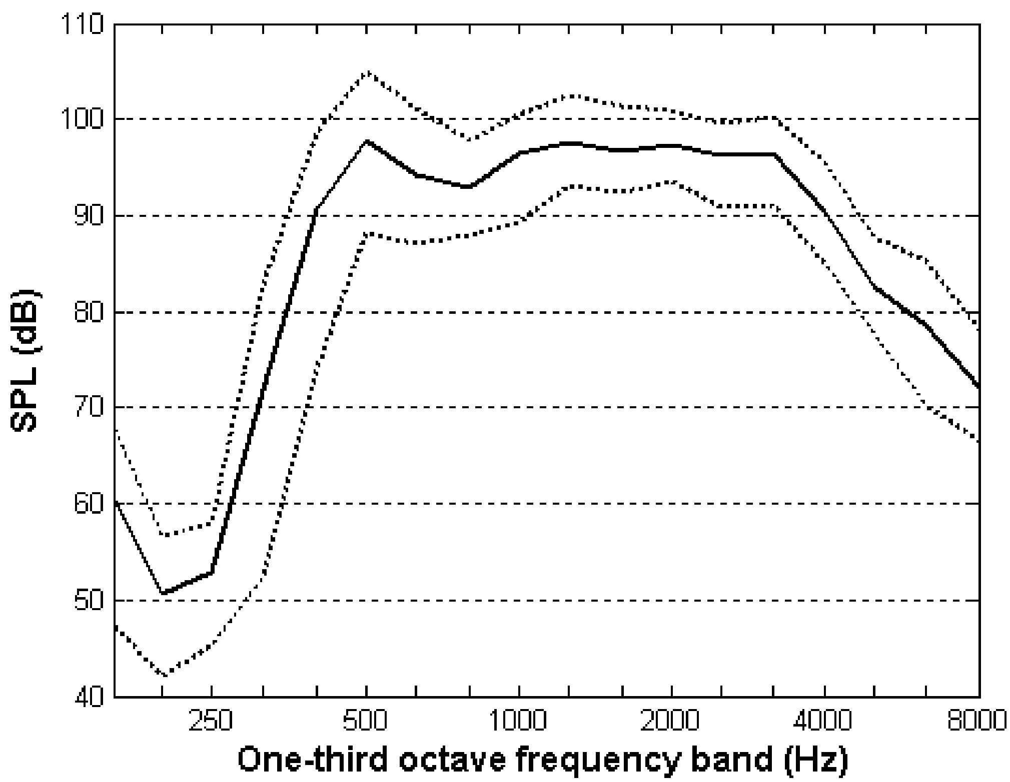

Figure 2.9. Mean SPL in one-third octave bands at 10 m (solid black line) during the experiment and the maximum and minimum one-third octave band levels (black dotted lines). Overall L_{pEQ} varied less than 8 dB.

2.2.2 Sound speed profile calculation

Refraction and turbulence are expected to dominate the variation in measured L_{pEQ} at a listener location. Although turbulence causes a random variation in L_{pEQ}, changes in refractive condition directly correlate to changes in measured L_{pEQ}. Therefore, estimating the type and strength of the refractive condition during a measurement is necessary to determine how L_{pEQ} measurements are affected by changes in refractive condition. In this subsection, wind speed and temperature measurements are discussed. Then, a method for quantifying the refractive condition is introduced. Once the relative type and strength of a refractive condition is known, variations in measured L_{pEQ} can be compared to variations in refractive conditions.

2.2.2.1 Wind and temperature measurements

Ideally, weather stations are vertically aligned to capture the refractive condition at a single location. However, due to local obstructions at the base of the tower along the propagation path, weather stations were placed in multiple locations. Three LaCrosse Technology model WS3610 home weather stations were used to estimate the refractive condition along the sound propagation path. The first weather station ("source") was placed near the AHWD at a height of 1.8 m, the second ("tower") was placed at a height of 11.7 m on a tower along the propagation path, and the third ("field") was placed at a height of 2.1 m near the base of the tower. The weather stations collected the temperature, wind velocity, relative humidity, and absolute pressure in one minute averages. These one minute averages were later re-averaged over 10 minute intervals. Re-averaging reduced the effect of short time-scale turbulence [33] and allows the mean sound speed profile to be estimated. This re-averaged meteorological data is listed in Appendix A.2.

Figure 2.10 shows the 10-minute averaged temperatures during testing. Each point on the graph represents a measurement time. Individual measurement times were separated by intervals of 5–12 minutes. The difference in temperature between weather stations did not change by more than about 1°C during any test session, suggesting that the temperature gradient was stable during each recording session. Relative humidity varied less than about 10% during each session, and is therefore

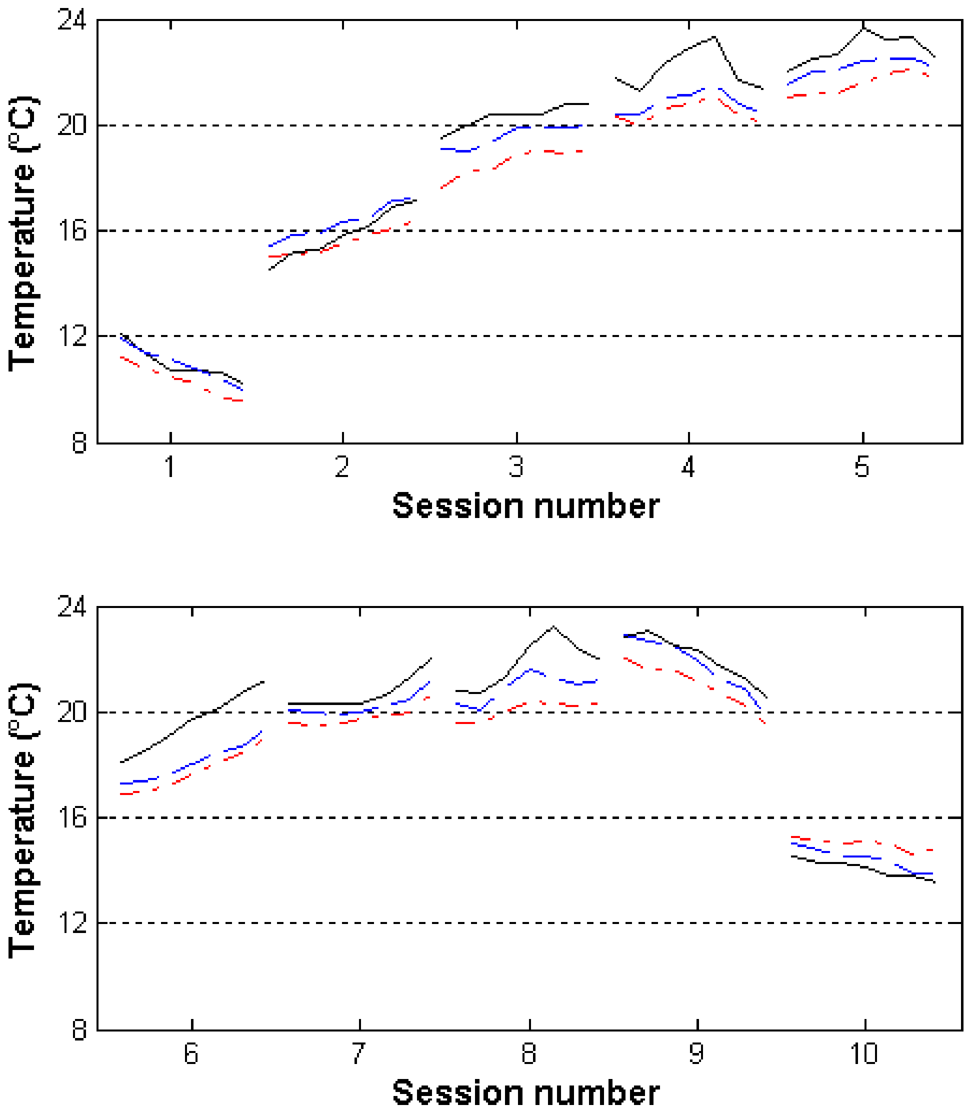

Figure 2.10. 10-minute averaged temperatures recorded by the source (solid black line), field (blue dashed line), and tower (red dot-dash) weather stations. During the day, temperature was greater close to the ground, while after sunset (session 10), temperature was greater on the tower.

not displayed here.

Figure 2.11 shows averaged wind speed along the direction of sound the 10-minute averaged wind speed in the direction of sound propagation. Cross-path wind was ignored since it has been shown to have a negligible effect on refraction [27]. A positive value in Figure 2.11 indicates that the wind speed was in the direction of sound propagation. In sessions 1, 2, 3, 6, 7, and 9, the tower weather station recorded the greatest wind speeds. This was expected because wind speed should increase with height. When there was little to no wind, as in sessions 4, 5, and 10, this trend was not apparent. The wind switched direction in session 8, indicating a significant change in the refractive condition during this session.

The source and tower weather stations were chosen to represent the meteorological condition because they give a better correlation to measured L_{pEQ} (see subsubsection 2.3.2.3, on page 38). Due to their horizontal separation, these two stations were not expected to give as precise a measurement of the meteorological condition as two weather stations placed at the same location. However, in order to draw conclusions about its effect on voice command propagation, only an estimate of the refractive condition is necessary.

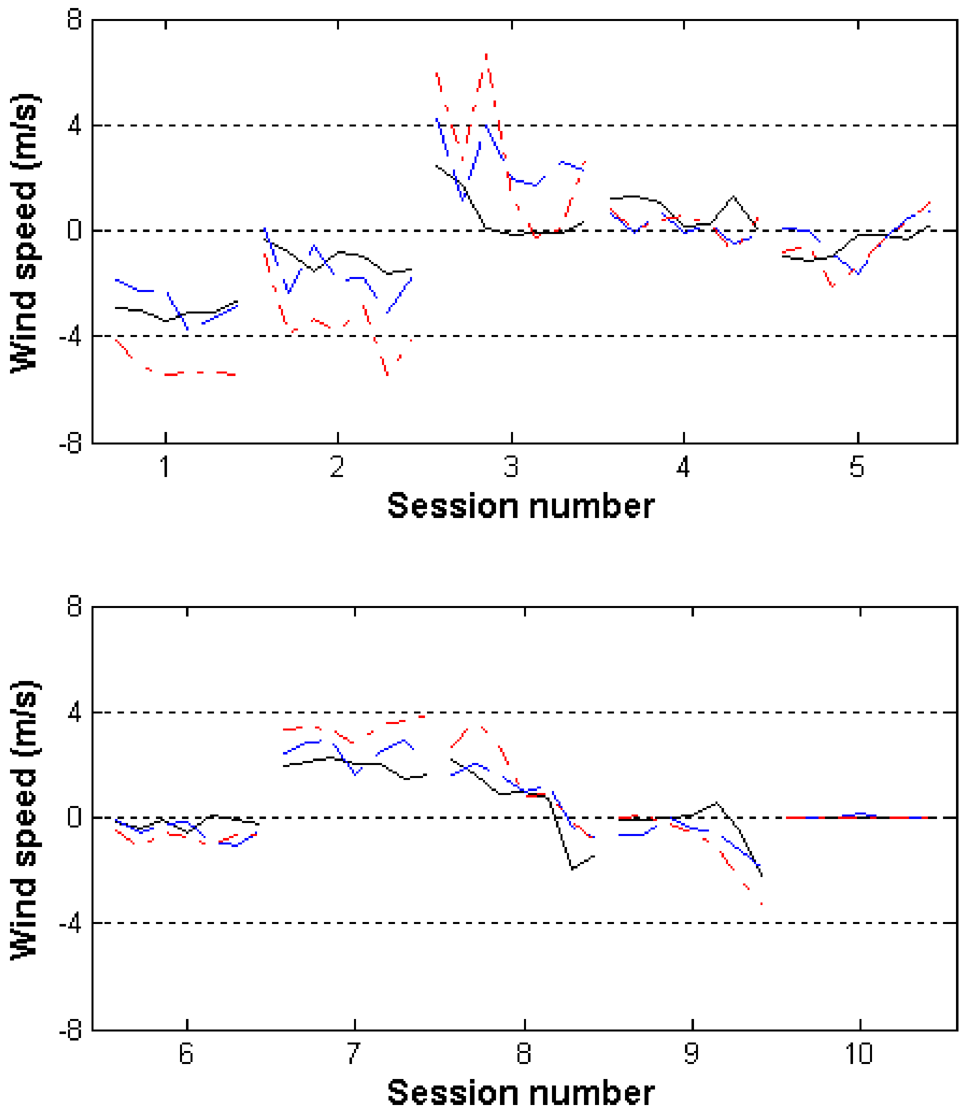

Figure 2.11. 10-minute averaged wind speed, as recorded by the source (solid black line), field (blue dashed line), and tower (red dot-dash) weather stations. A positive value indicates wind speed in the direction of sound propagation. Measurements were made in down- and up-path wind, as well as during conditions of little to no wind.

2.2.2.2 Equations for calculation

For sound propagation over a flat, homogeneous ground surface it can be assumed that the effective sound speed, c_{eff}, is not a function of range, but of height, z, only. The effective sound speed is given as

$$c_{\text{eff}}(z) = c_0(z) + u(z), \tag{2.3}$$

where c_0 is the adiabatic sound speed and u is the horizontal component of the wind velocity along the direction of propagation [27]. Recently, it has been suggested that this approximation is not sufficient for detailed calculations of sound propagation (e.g., computer modeling) [34]. Nevertheless, the error introduced does not change the resulting meteorological condition, which is the main focus of this study.

A realistic profile for the atmospheric surface layer is the logarithmic profile, given by Salomons [27] as

$$c_{\text{eff}}(z) = c + b \ln(z/z_0 + 1). \tag{2.4}$$

The parameter z_0 is the aerodynamic roughness length, given as 0.1 m for grassland; c_0 is the adiabatic sound speed at the ground surface; z is the height above the ground; and b is the strength constant of the logarithmic profile. Salomons gives typical values of $b = 1$ m/s and $b = -1$ m/s for downward and upward refracting atmospheres, respectively [27]. These profiles show a large change in sound speed close to the ground. Figure 2.12 shows examples of these two profiles, and a neutral ($b = 0$ m/s) refracting profile.

The logarithmic profiles are only meaningful as estimations for the boundary layer of the atmosphere. The boundary layer extends up to 100 m during the day, and may reduce to half this height during the night. Since we do not have weather station data at higher heights, we assume that sound interacting with the next atmospheric layer need not be considered. When the effective sound speed is measured at two heights, z_1 and z_2, Equation (2.4) can be used to remove the mathematical dependence on c_0 and find an expression which linearly relates the change in the effective sound speed, Δc_{eff}, to the logarithmic strength constant, b.

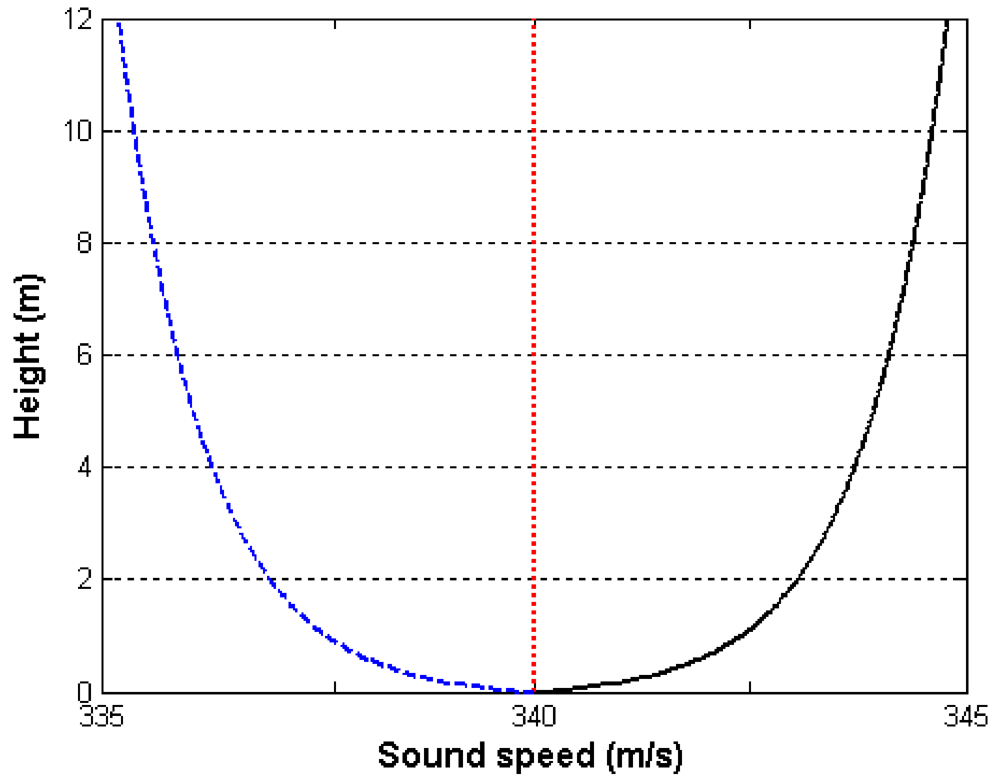

Figure 2.12. Sound speed profiles for a normal downward (solid black line), upward (blue dashed line), and neutral (red dotted line) refracting atmosphere. These logarithmic profiles are meaningful as estimations for the boundary layer of the atmosphere.

For specific measurement heights of $z_1 = 1.8$ and $z_2 = 11.7$ m, this gives

$$b \approx 0.55 \Delta c_{\mathrm{eff}}. \tag{2.5}$$

2.3 Experimental results

In this section, variations in measured voice command SPL are examined after a range of adequate S/N is defined. Variations in SPL between measurements taken days, hours, and minutes apart are investigated. Next, the variation in excess attenuation is calculated. The effect of the meteorological condition on variations in measured voice command SPL and the variation in SPL between frequency bands are examined. Finally, the experimental results are summarized.

2.3.1 Frequency range of adequate signal-to-noise ratio

There must be a significant signal-to-noise ratio (S/N) so that the measured L_{pEQ} between different trials can be compared without error due to environmental noise. Additionally, the range of adequate S/N must be over a significant portion of the speech-important frequency range in order to accurately calculate the intelligibility of a measured voice command at a listener location. For these two reasons, a S/N of at least 6 dB is desired in the most important one-third octave frequency bands, 400–3150 Hz, for the speech intelligibility index (SII) calculation [20] and at least 3 dB is wanted in all other speech-important bands, 160–315 and 4000–8000 Hz. Figure 2.13 shows the mean measured SPL in each one-third octave band at propagation distances of 500, 1000, 1250, and 1500 m. The mean ambient background noise SPL is also shown. There was not a sufficient S/N at and beyond 500 m for frequency bands below 400 Hz and above 4 kHz. This result was a function of the output spectrum of the AHWD at lower frequencies and attenuation from atmospheric absorption at higher frequencies.

The lowest measured voice command SPL cases at 1000 m and beyond did not always meet the criteria of 6 dB S/N at 400 and 3 dB S/N at 4000 Hz. Additionally, the 6 dB S/N was not met at 3150 Hz at 1500 m. However, due to the output spectrum of the voice command, which drops rapidly at 400 and 3150 Hz, the noise introduced by an insufficient S/N in the three frequency bands of 400, 3150, and 4000 Hz for a few of the low-level cases at 1000–1500 m does not adversely affect the calculation of the L_{pEQ}. Therefore, we find that the frequency band from 400–4000 Hz to have a sufficient S/N. The equivalent SPL for this band will be referred to as L_{pEQL} (‘L’ for limited), and will be used to compare variations in received

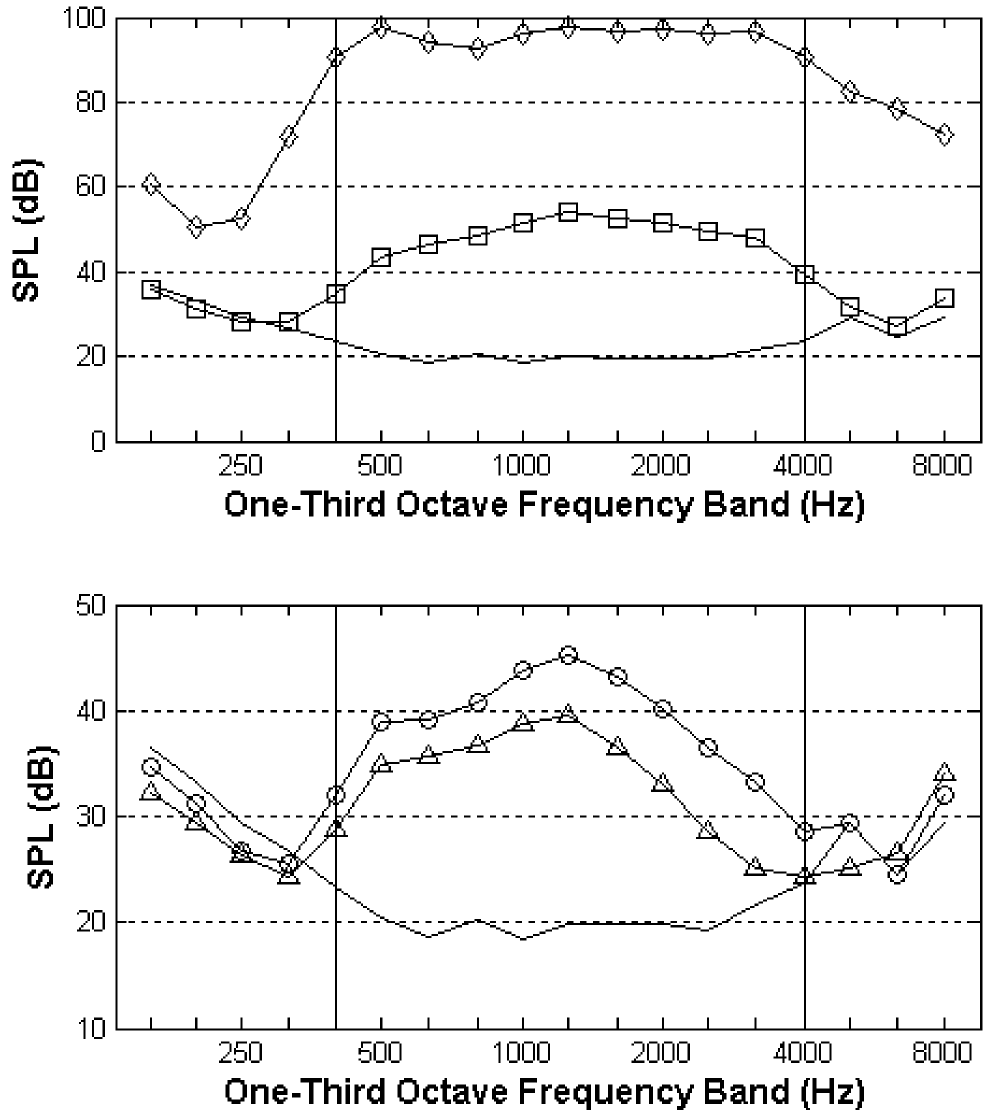

Figure 2.13. Overall mean measured SPL at 500 (◊), 1000 (□), 1250 (○), and 1500 (△) m. The average background noise (solid black line) is also shown. The frequency band of adequate signal-to-noise ratio, 400–4000 Hz, is noted by black vertical lines.

voice command SPLs between the different propagation distances. When the band importance function of the speech intelligibility index (SII) calculation in ANSI S3.5-1997 [20] is integrated, it is found that this frequency range is responsible for a significant majority of the SII value (87%). A voice command meeting these S/N criteria will have a speech intelligibility index (SII) value greater than 0.5, with 95% percent of words understood (PWU) for unknown messages. This indicates a stable and fully intelligible rating that does not change with small (up to 6 dB) changes in the noise SPL (see Section 3.3, on page 63).

2.3.2 Variation in measured voice command L_{pEQL}

Measured voice command SPLs are examined in order to determine the variation found during the experiment. First, variations in measured voice command SPL are examined between measurements made days, hours, and minutes apart. Second, the excess attenuation of all of the measured voice command SPLs is calculated. Third, variations in meteorological condition over the course of the experiment are examined and related to changes in measured voice command SPL. Fourth, frequency dependent variation is examined. Finally, a summary of the results of the variation in measured voice command SPL is given.

2.3.2.1 Time scales of days, hours, and minutes

Figure 2.14 shows measured L_{pEQL} recorded by the roaming SLM. Variation was as much as 30 dB at a single propagation distance, with only 10 measurements during five days. Additionally, variation was not consistent with increasing distance. Table 2.3 lists the total amount of variation in SPL measured at each distance in Figure 2.14, from only 14 dB at 750 m, to 30 dB at 200 m. A greater variation in received SPL was expected at longer distances [16], so it was counter-intuitive that the largest variation was found at 200 m. One explanation for this result is that the meteorological conditions varied more while acquiring data at some distances than at others. Additionally, we took point measurements in time and therefore were not capturing the total (continuous) amount of variation.

The largest variation was measured on a single day, with only a few hours time difference between measurements. Since the SPL was not measured continu-

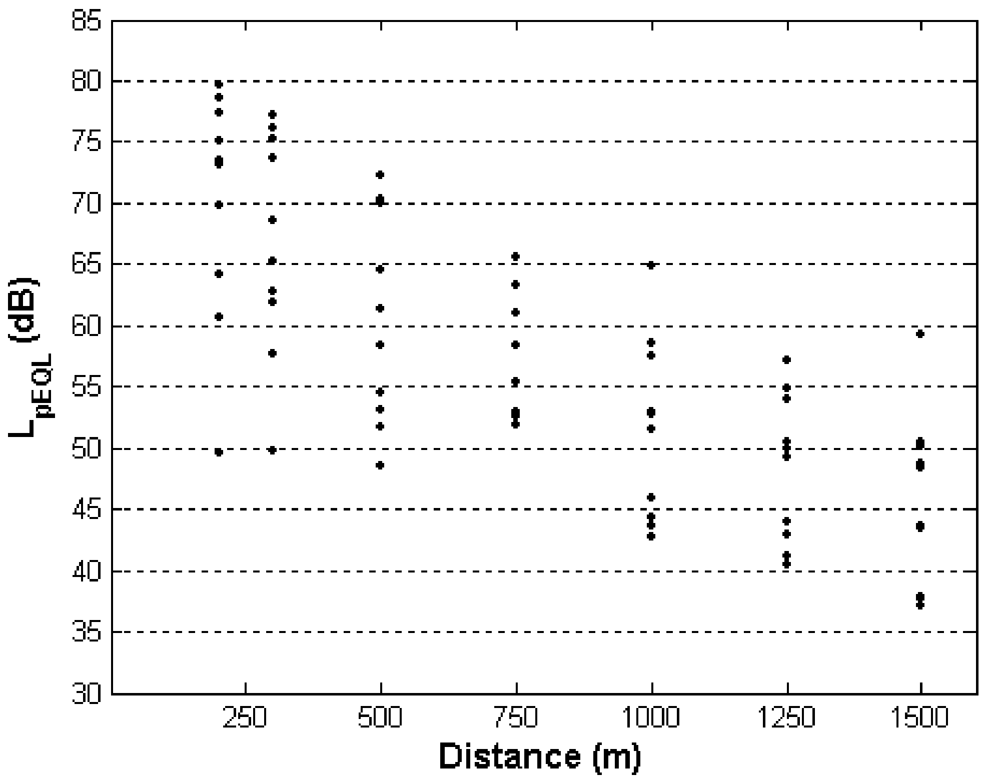

Figure 2.14. Measured L_{pEQL} by the roaming SLM over the course of the experiment. Variation in measured SPLs were as much as 30 dB at a single propagation distance.

Table 2.3. Variation in measured L_{pEQL} at each distance from Figure 2.14. These variations occurred with only 10 measurements at each distance during five days of measurements.

Distance (m)	Variation (dB)
200	30
300	27
500	24
750	14
1000	22
1250	17
1500	22

ously, the total variation during the several hour period cannot be commented on. However, the total variation over a period of time is at least what was shown by two point measurements taken in that time period. Table 2.4 lists a few of these variations. Consistent variations (i.e., at multiple distances between measurement sessions) in measured L_{pEQL} of 12–14 dB or 15–17 dB were seen on October 2 and 10. These changes in measured L_{pEQL} were due to changes in the wind direction relative to sound propagation. Additionally, increases of 25–30 dB were measured between afternoon and early evening on October 10 as a temperature inversion formed and the wind calmed.

When the overall variation in received L_{pEQL} was compared between the stationary and roaming SLM at 500 m, there was an increase in total variation from 24 to 33 dB. This was expected because a larger number of measurements should likely give a larger total variation. Figure 2.15 shows the measured voice command L_{pEQL} recorded by the stationary SLM, separated by measurement session. Table 2.5 lists the variation measured during each test session found in Figure 2.15. Note that during a single testing session lasting only 38 minutes (session 8), the measured L_{pEQL} varied by up to 18 dB! More dramatic perhaps, are the changes in L_{pEQL} recorded over time scales of only several minutes shown in Table 2.6. During session 8, a 17 dB increase in the voice command L_{pEQL} was recorded over a time period of only 6 minutes. This 6 minute increase in L_{pEQL} was attributed to changes in the meteorological conditions that occurred on the same time scale. When the non-averaged weather station data (i.e., one-minute averages) was examined, a 1°C decrease in temperature was recorded by the station closest to the

Table 2.4. Several cases of significant amounts of variation in measured L_{pEQL} which occurred on time scales of hours by the roaming SLM. These are calculated from point measurements in time, so it does not represent the total variation, but the minimum over the time period. The largest variation in measured SPL, 30 dB, occurred as a result of the formation of a temperature inversion.

Date	Approximate 1^{st} record time	Approximate 2^{nd} record time	Difference in record time (hr)	Maximum L_{pEQL} difference (dB)
10 Oct	15:00	16:30	1.5	14
2 Oct	12:30	15:00	2.5	17
10 Oct	16:30	21:00	4.5	30

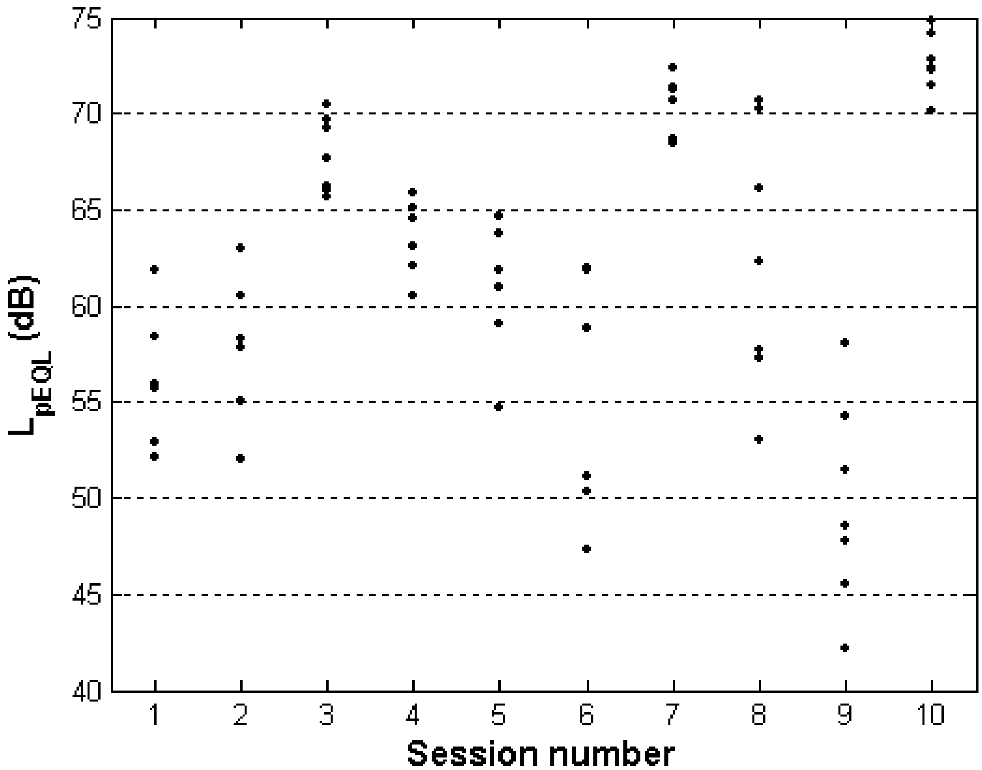

Figure 2.15. Measured L_{pEQL} recorded by the stationary SLM separated by testing session. Variation in measured SPL during a session was as little as 4 dB to as much as 18 dB. The differences in the amount of variation during a session are attributed to changes in meteorological condition.

Table 2.5. Variation in measured L_{pEQL} during each session from Figure 2.15.

Session	Variation (dB)
1	9.7
2	11.0
3	4.8
4	5.4
5	9.9
6	14.6
7	4.0
8	17.6
9	15.9
10	4.6

Table 2.6. Several cases of significant amounts of variation in L_{pEQL} which occurred on time scales of minutes as recorded by the stationary SLM. These variations were the result of changes or consistency in meteorological condition.

Session	Date	1^{st} record time	2^{nd} record time	L_{pEQL} difference (dB)
8	10 Oct	14:50	14:56	16.8
5	3 Oct	12:34	12:42	9.1
7	4 Oct	13:10	13:31	4.0

ground while the temperature recorded by the station in the tower was unchanged. Both weather stations also recorded a wind gust in the sound propagation direction. These temperature and wind changes both cause downward refraction, which should result in higher received SPLs. Therefore, they are believed to be responsible for the 17 dB increase in SPL that was recorded over this 6 minute period of time. It is possible that all of the variation occurs on time scales of minutes, or shorter, but since the SPL was not measured continuously, we do not know.

During session 5, a 9 dB decrease in measured voice command L_{pEQL} was seen in 8 minutes. When unaveraged weather station data was examined there was a negligible change in temperature or wind speed and gust. This indicates that the change in measured L_{pEQL} was not from changes in refractive condition, but from turbulence alone. Turbulence alone has previously been shown to cause variations in received SPL of up to 6 dB standard deviation during conditions of upward refraction [32]; this measurement illustrates this effect. Alternatively, during session 7 there was only 4.0 dB total variation. During this session, there was a steady down-path wind. The variation which occurred between two measurements 20 minutes apart was as much as that which occurred during the entire hour-long session. This small variation illustrates that during conditions of downward refraction, variations in received SPL are less than in conditions of upward refraction. This result of different amounts of variation for upward and downward refracting conditions is discussed further in subsubsection 2.3.2.3, on page 40.

2.3.2.2 Calculation of excess attenuation

Excess attenuation was found by removing the effects of geometrical spreading and atmospheric absorption, which allowed the examination of those effects which remained. The ground effect was assumed to be approximately constant over all trials, leaving only atmospheric turbulence and refraction to contribute to the variations in excess attenuation. The excess attenuation, EA, is given as

$$\text{EA} = L_{\text{p,received}} + 20\log_{10}(r/r_0) + \alpha\, r - L_{\text{p,output}}, \tag{2.6}$$

where r is the propagation distance to the listener location, r_0 is the reference distance where $L_{\text{p,output}}$ was measured, and α is the absorption coefficient in dB/m. Figure 2.16 shows the excess attenuation calculated for each measurement using the Equation (2.6) over the frequency range of 400–2500 Hz. A value of 0 dB in Figure 2.16 indicates that the measured L_{pEQL} was exactly the value predicted by taking into account the attenuation from geometrical divergence and atmospheric absorption, with no net change from other effects; positive values indicate additional attenuation beyond this value. The calculation was not performed for the entire frequency range from 400–4000 Hz because the excess attenuation values at 1250 and 1500 m were incorrect due the low S/N at 4000 Hz. Additionally, 3150 Hz was not included to ensure that this effect was not present. The smallest values of excess attenuation at each distance occurred during session 10, which took place from 20:00 to 21:00. (With the exception of 300 m, where it was second smallest.) This was expected because session 10 was during a downward refracting condition, where measured SPLs were high and the effect of turbulence was low. Table 2.7 lists the variation in excess attenuation at each distance. These values are within 1 dB of those displayed in Table 2.3, on page 31, because atmospheric absorption values did not vary considerably during the experiment. Table 2.8 lists the variation in excess attenuation for the stationary SLM, which is similar to the total variation in received SPL listed in Table 2.5, on page 33.

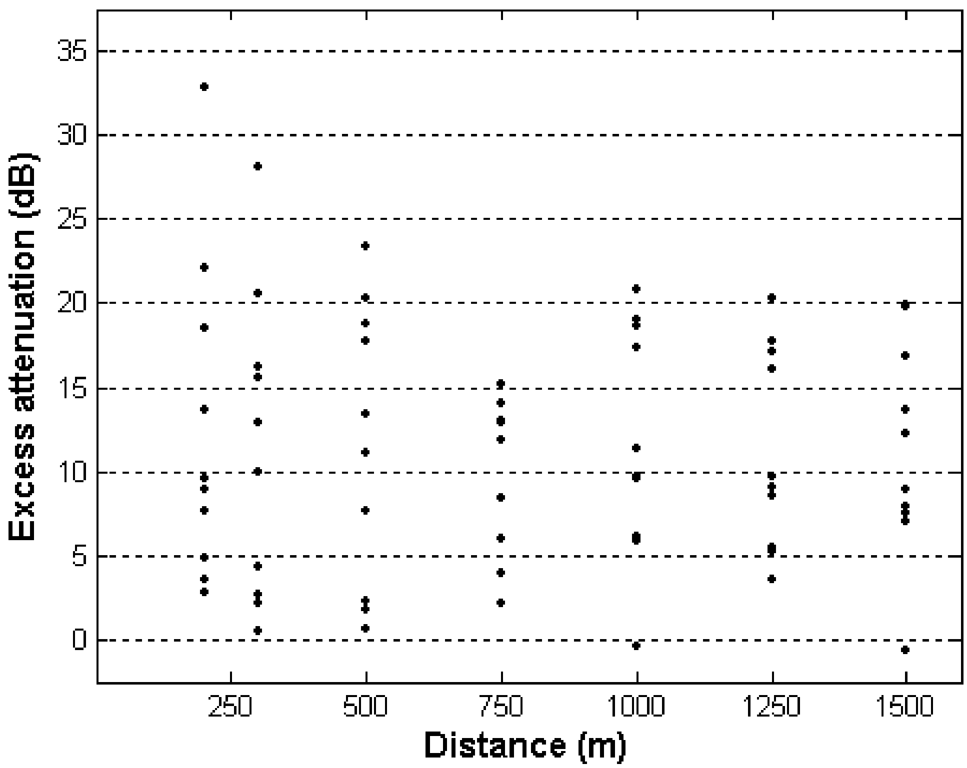

Figure 2.16. Excess attenuation calculated for the band of 400–2500 Hz for each measurement during the experiment recorded by the roaming SLM. Conditions of downward refraction consistently gave lower values of excess attenuation.

Table 2.7. Variation in excess attenuation at each distance from Figure 2.16 for the roaming SLM. These results are similar to those found in Table 2.3, on page 31, because the amount of atmospheric absorption did not change significantly during the experiment.

Distance (m)	Variation (dB)
200	30
300	28
500	23
750	13
1000	21
1250	17
1500	21

Table 2.8. Variation in excess attenuation during each testing session from the stationary SLM (at 500 m). These results are similar to those found in Table 2.5, on page 33, because the amount of atmospheric absorption did not change significantly during the experiment.

Session	Variation (dB)
1	9.1
2	11.0
3	4.7
4	5.5
5	10.4
6	15.0
7	4.3
8	17.3
9	17.3
10	3.8

2.3.2.3 Effect of the meteorological condition

To determine how measured voice command SPLs relate to a meteorological condition, values for the logarithmic strength constant, b, are assigned. First, the source and tower weather stations are chosen to calculate b, based on their better correlation to received SPLs. Second, the distribution of b values during the experiment is shown. Third, received voice command L_{pEQL} is compared to changes in refractive condition. Finally, a summary of the results is given.

Choice of two weather stations

Downward refraction gives higher received SPLs than upward refraction. Therefore, positive b values should give higher received voice command L_{pEQL} than negative b values. To determine whether the tower and source or the tower and field weather stations more accurately predict the refractive condition for sound propagation, L_{pEQL} is split into groups of positive and negative b. Figure 2.17 shows the measured L_{pEQL} from the roaming SLM split into these two groups. A better correlation between downward refraction and higher measured SPLs was found by the source and tower weather stations, shown by the grouping of circles (downward recfraction) and dots (upward refraction). This indicates that these two weather stations gave a better representation of the refractive condition on the sound propagation path. For greater accuracy in future measurements, weather stations should be placed at multiple heights at a single location.

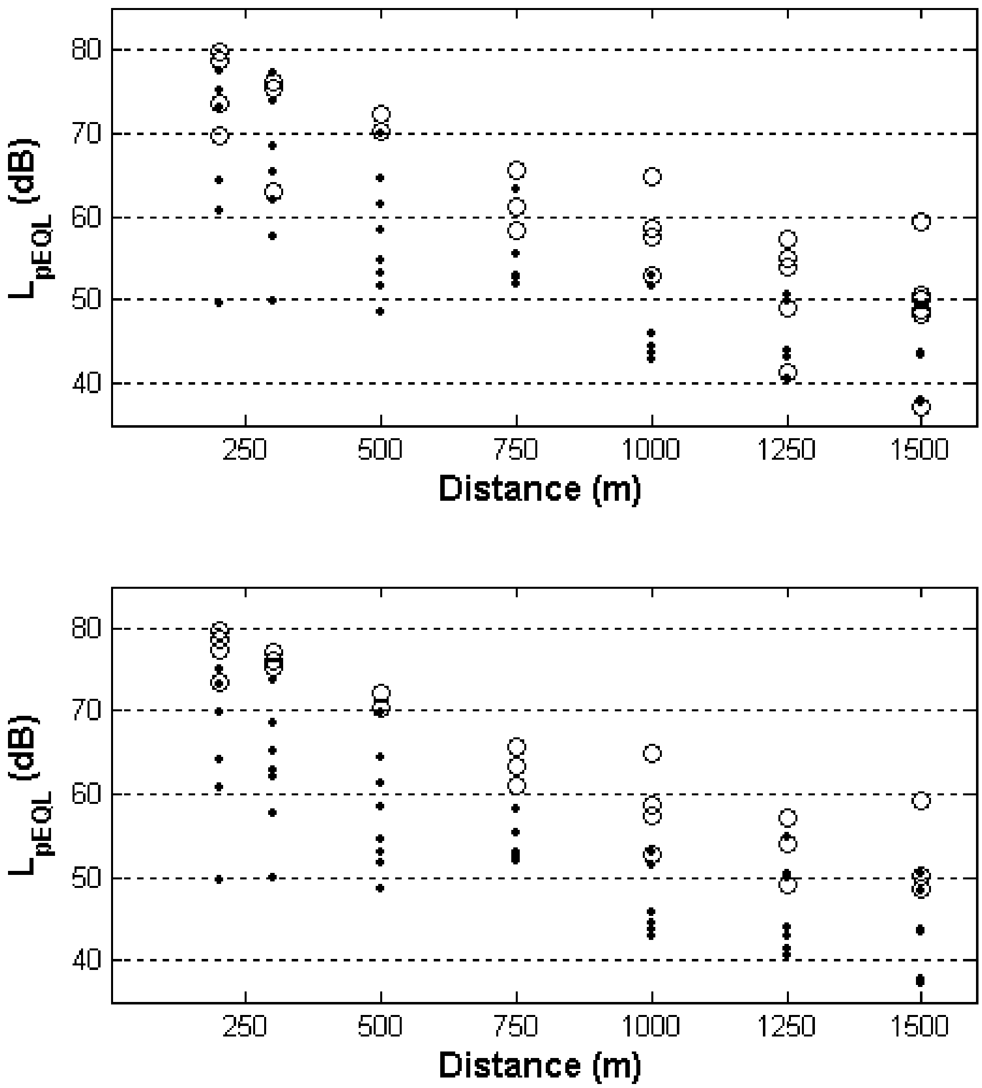

Figure 2.17. Measured L_{pEQL} from the roaming SLM separated into groups of positive (○) and negative (●) b values. The b values were calculated by the field and tower (upper plot) or source and tower (lower plot) weather stations. A better correlation between downward refraction and higher measured SPLs was found for the lower plot.

Distribution of b values

Figure 2.18 displays the distribution of b values during the experiment into 16 bins. The distribution was right-skewed (i.e., the right tail is longer), with the highest number of occurrences at approximately -1 and 0.5 m/s. The high number of occurrences at -1 m/s was expected, because most of the testing is done during the day when there was solar radiation contributing to an upward (negative b) refracting sound speed gradient. Since the testing was performed in such a way to have both up- and down-path wind, it was expected that b values would be distributed around $b = -1$ m/s, a normal b value for upward refraction. The high number of occurrences at about 0.5 m/s is due to the evening measurement session. All seven measurement points during this session were placed in the same bin because refractive conditions were nearly constant during this session.

Separation of measured L_{pEQL} by refractive condition

Measured SPLs were separated into groups of downward and upward refraction to further investigate the difference between these two cases. Figure 2.19 shows the measured voice command L_{pEQL} separated into groups of downward ($b > 0$ m/s) and upward ($b < 0$ m/s) refraction values. A line that approximates the measured L_{pEQL} for a "neutral" refracting atmosphere is also shown. The neutral line was calculated by performing a linear regression on measured L_{pEQL} and b value at each distance and determining the L_{pEQL} at $b = 0$. Figure 2.19 shows that refractive condition separates measured SPLs into two separate groups well, with only about five points overlap between the two groups in both the upper and lower plots. This overlap is within 3 dB of the neutral line, except for a single point at 55 dB SPL and 1250 m in the upper plot and 58 dB in session 8 in the lower plot. Additionally, less variation is shown for measured SPLs in downward refraction than in upward refraction. This result is explored further in Figure 2.20.

In Figure 2.20 measured SPLs are examined in a more statistical manner by plotting them against the percent of data at or below their SPL, a method previously shown by Schomer [14–16]. For example, if you have 50 data points, each point would be placed at an interval of 2% (i.e., at 2%, 4%, 6%, . . .). Additionally, the percentage axis is set up in the same way as normal probability plot paper,

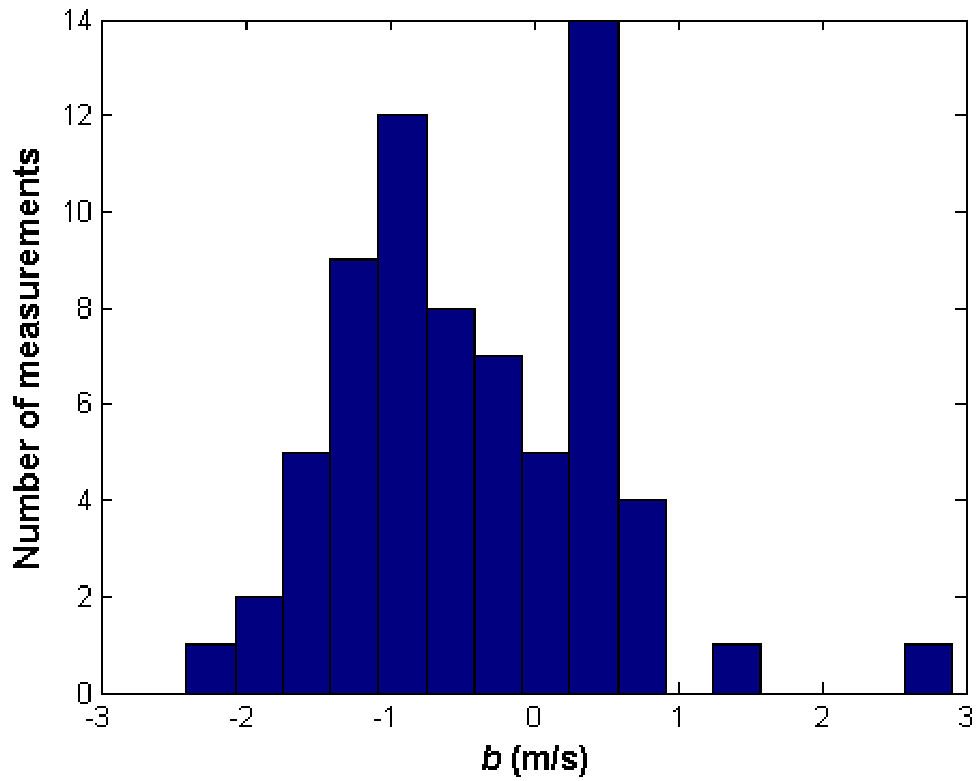

Figure 2.18. Distribution of b values during the experiment. A high number of occurrences around $b = -1$ m/s was expected because most of the measurements were taken during the day. The high number of occurrences at $b = 0.5$ m/s is due to the nighttime session, for which all measurements fell into the same bin.

where the percentage of data contained in each standard deviation of a normally distributed data set is given an equal width. Due to this property, data sets with a normal distribution fit to a straight line, where the slope of the line is the standard deviation of the data set. Figure 2.20 displays the received voice command L_{pEQL} in this way. Separate linear regressions were fit to the higher and lower level data, indicating that these two groups were each normally distributed. The higher level SPLs showed a standard deviation of about 2.5 dB, while the lower level SPLs showed a standard deviation of about 9 dB. Schomer indicates that the high level data represents sound that traveled by a direct path from source to receiver, and has a lower standard deviation. This happens for downward refraction or for receivers close to the source (i.e., out of the shadow zone). Low level data represents sound for which there was not a direct path, indicating upward refraction and that

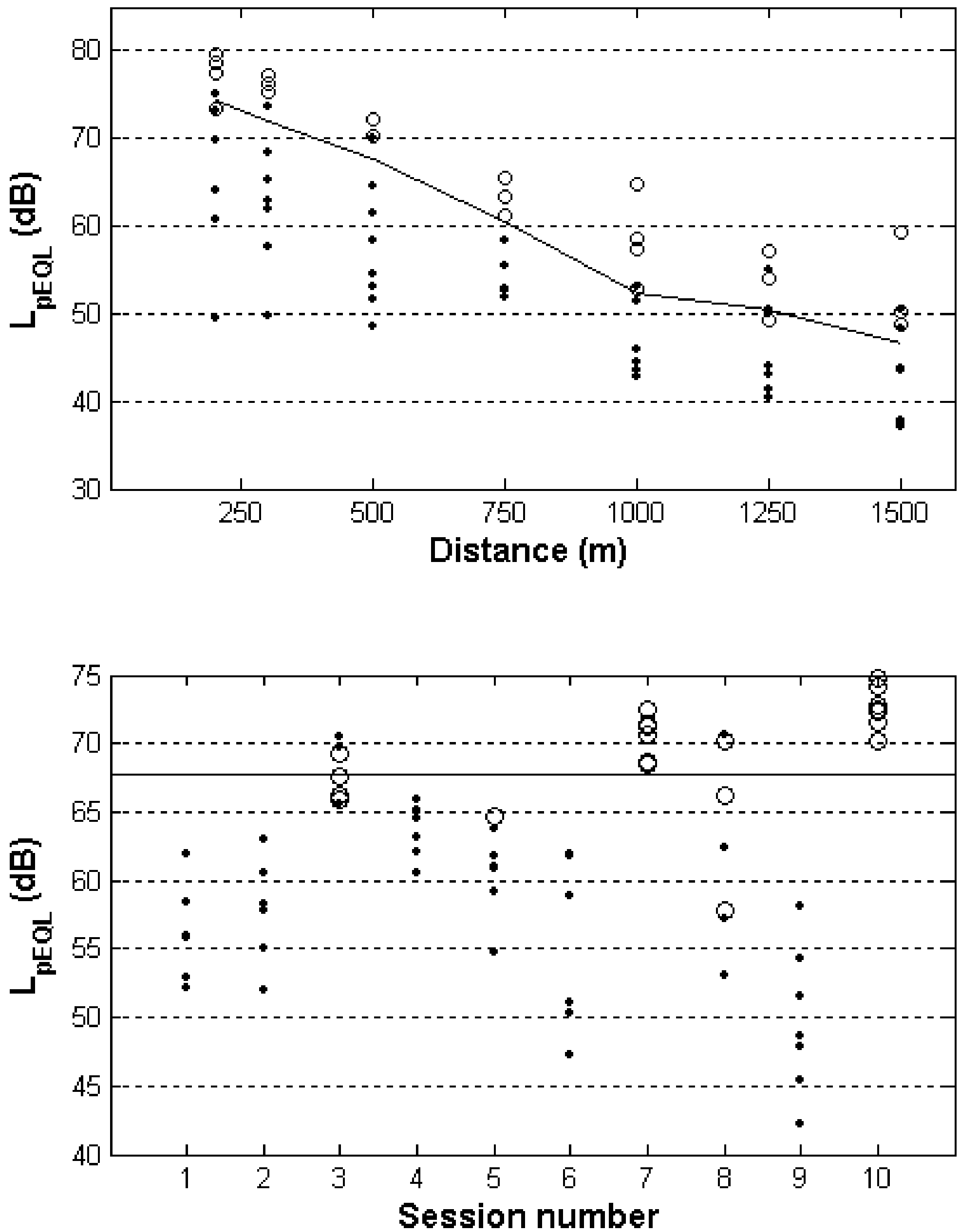

Figure 2.19. Measured L_{pEQL} separated by positive (○) and negative (●) b value by distance for the roaming SLM (above) and by test session for the stationary SLM (below). A neutral line (solid black line) is given for reference. Downward and upward refraction segregate the measured voice command SPLs into two distinct groups, where a larger variation is found for voice commands propagated in conditions of upward refraction.

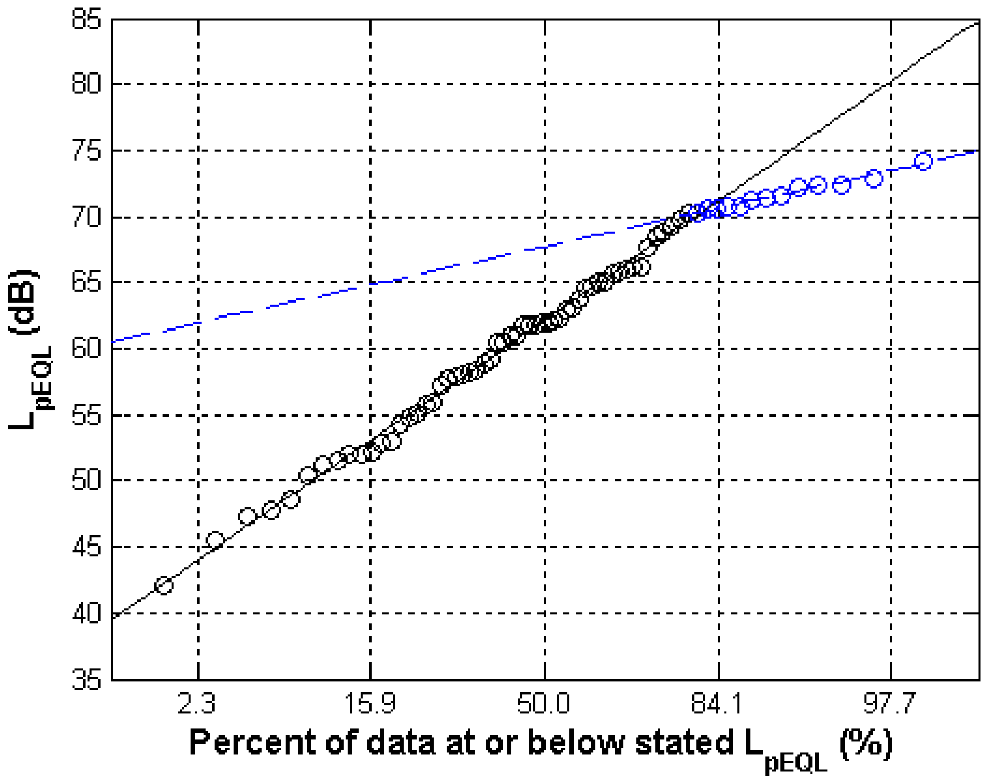

Figure 2.20. Measured L_{pEQL} plotted against the percent of data at or below that level. Low level (black circles) and high level (blue circles) data were fit to linear regressions, indicating that the two groups were normally distributed, where the slope of each line is the standard deviation of that data set. Low level voice command SPLs showed about three times the standard deviation as high level SPLs.

the receiver was in the shadow region. In the shadow region the sound is received by scattering and diffraction which gives a larger standard deviation. The standard deviation for the low level data depends on the variation in test conditions. However, Schomer shows that the high level data consistently give less than a 5 dB standard deviation [15].

When b values are divided into a greater number of groups, it could be expected that the measured SPLs would order themselves from highest to lowest in terms of their b values. However, this is not the case due to variations in measured SPL from atmospheric turbulence, as well as changes in the refractive condition along the sound propagation path. Neither of these two effects are considered in the calculation of b. Figure 2.21 displays the result for b values split into four groups:

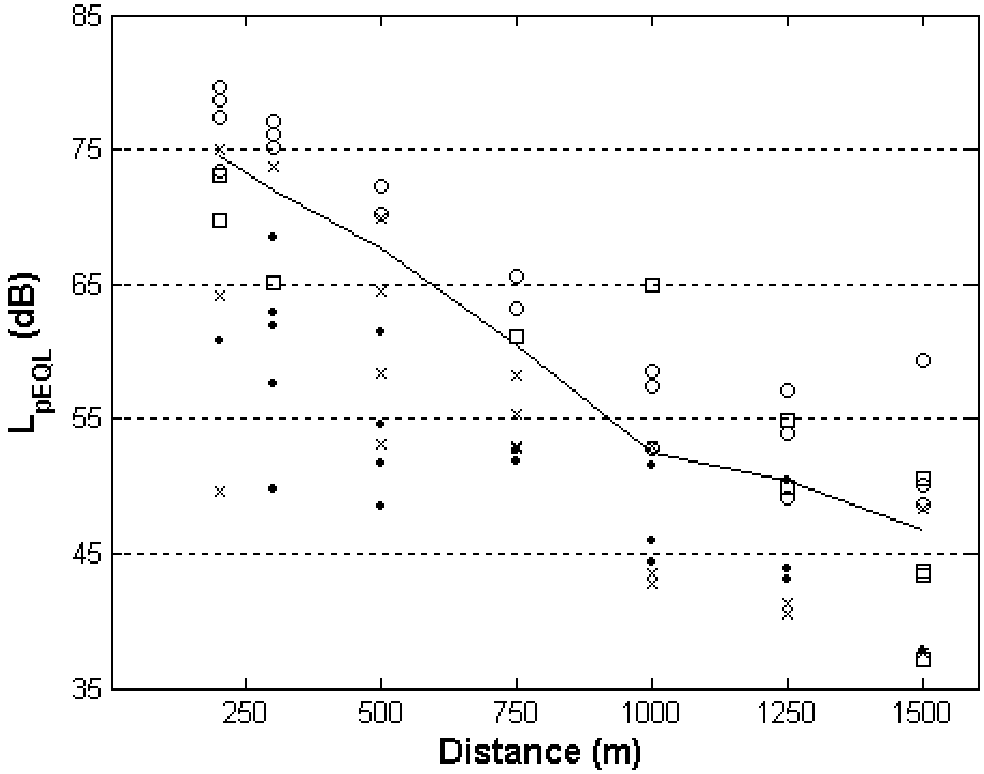

Figure 2.21. Measured L_{pEQL} separated into four groups by b values, calculated for each measurement from the roaming SLM. The calculated neutral line (solid black line) is also shown. The groups are: $b > 0.25$ (○), $|b| < 0.25$ (□), $-1 < b < -0.25$ (×), and $b < -1$ m/s (●). Strong upward refraction, $b < -1$ m/s, and downward refraction, $b > 0.25$, consistently give the lowest and highest received levels, respectively.

$b < -1$, $-1 < b < 0.25$, $|b| < 0.25$, and $0.25 < b$ m/s. Although downward and upward refractive values give the highest and lowest measured L_{pEQL}, respectively, the fluctuations in measured SPL in each group cause overlap between the groups.

The differences between upward and downward refraction

Our measurements indicate that downward and upward refraction are two physically separate phenomena, which each give normally distributed SPLs at a listener location. During conditions of downward refraction, variation in received SPL have a standard deviation of less than 3 dB. However, during conditions of upward refraction, the standard deviation is about 9 dB. This result is in agreement with

Attenborough [33], who writes that

> increases in noise level (say 1–5 dB) are smaller than the decreases (say 5–20 dB).

This trend is commonly supported by experiment (e.g., Schomer [16]).

During cases of downward refraction, it has been shown that for propagation scenarios similar to ours, the top grouping of four ray paths makes the most significant contribution to the received SPL [35]. The fact that there are four ray paths combining at the listener location indicates that variations in phase (due to turbulence) in any single sound ray path have less effect on changing the total received SPL. Additionally, small changes in refractive condition, while downward refraction still prevails, do not change the fact that there are always four main contributing rays to the received SPL [35]. However, for cases of sound propagation during upward refractive conditions, this is not the case. A receiver at a fixed distance near the shadow zone may undergo changes in SPL due to varying strength of the upward refraction, which may result in a direct or indirect sound path. Once the receiver is sufficiently in the shadow zone (which, for normal upward refraction, $b = -1$ m/s, and a source and receiver height of 2 m will happen in less than 100 m [27]) the received SPLs are controlled by atmospheric turbulence. The sound level in the shadow zone (during a given condition) is agreed to be consistent, but the value is dependent on the amount of turbulent scattering and may be as much as 20–30 dB in excess attenuation [27]. This result has been shown to be true in experiment (e.g., Daigle [31]) as well as computer simulations (e.g., Chevret [36], Gilbert [37]).

2.3.2.4 Frequency dependent variation

Intelligibility is frequency dependent, so if certain frequencies undergo larger variations in received SPL from changes in meteorological condition, it may effect intelligibility at a listener location. Figure 2.22 shows the variation in measured voice command L_{pEQL} in one-third octave frequency bands for different propagation distances. Contour lines represent regions of constant variation in SPL for a given frequency and propagation distance. There is a general decrease in variation as distance is increased, similar to the total amount of variation in measured L_{pEQL}

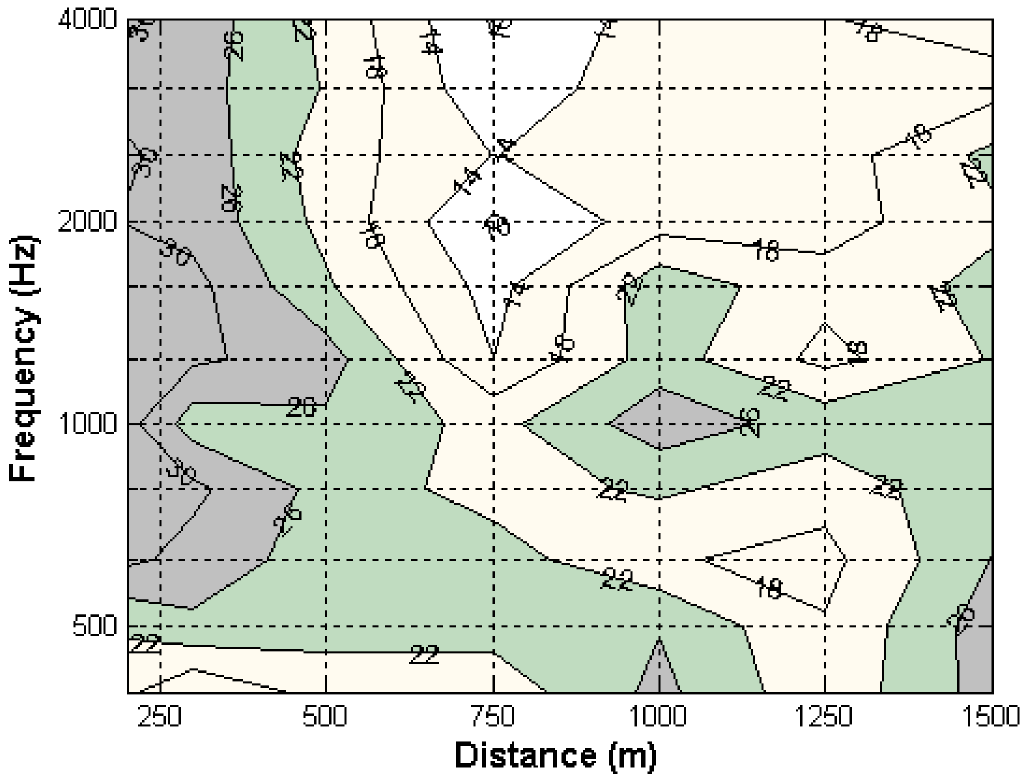

Figure 2.22. Amount of variation in measured L_{pEQL} for a given one-third octave band and propagation distance recorded by the roaming SLM. A decrease in variation with increasing distance is shown, similar to the total variation in measured L_{pEQL} for the experiment.

during the experiment. At any particular propagation distance, variation does not appear to systematically increase or decrease as frequency is increased. The variation in measured SPL displayed in Figure 2.22 is listed in terms of the standard deviation in Table 2.9. The standard deviation is calculated for each one-third octave frequency band and averaged between distances. The standard deviation was constant to within 2–3 dB between individual one-third octave bands. It is suspected that the decrease in standard deviation near the lower and upper frequency limits was a function of the total S/N in the experiment. Both the greatest standard deviation and the greatest S/N was found near 1250 Hz.

Table 2.9. Mean standard deviation over all propagation distances for each one-third octave band. The standard deviation was constant to within 2–3 dB between individual one-third octave bands.

Frequency (Hz)	Standard deviation (dB)	
	Roaming SLM	Stationary SLM
400	6.5	5.5
500	7.4	6.2
630	7.7	7.8
800	8.1	8.3
1000	7.9	8.3
1250	8.0	8.9
1600	7.8	8.2
2000	6.6	7.1
2500	6.8	7.2
3150	6.4	7.1
4000	6.5	6.4

2.3.2.5 Summary of the variation in measured L_{pEQL}

Variations of up to 30 dB were shown at 200 and 300 m propagation distance. This is similar to what was shown by other experiments, where variation of up to 25–30 dB is common for distances at and beyond 200 m [9–18]. It is important to note that 30–35 dB variation in received SPL occurs over the course of a normal day (except in heavily overcast conditions). This result has been shown by L'Esperance [12] and Yoshisha [18] for band-limited noise at as short as 100 m propagation distance above grass and 200 m above concrete. Because AHWDs are used throughout the dinural cycle, variations of more than 40 dB should be expected during normal day-to-day operation.

Variation in measured voice command L_{pEQ} of up to 17–18 dB occured on both time scales of hours and minutes. However, we cannot report on whether all of this variation took place on time scales as short as minutes, because the continuous received SPL was not monitored. The literature does not indicate that such large variations should be expected to occur on time scales as short as several minutes. The variations in voice command SPL are found to be directly related to changes in meteorological condition, indicating that monitoring meteorological conditions is necessary to predict voice command SPLs at listener locations. Additionally, it has been shown that downward and upward refraction have normal distributions with different standard deviations, classified by having direct or indirect sound rays from the source to listener location. During this experiment, the distributions showed a standard deviation of about 2.5 and 9 dB in received SPL for the downward and upward refractive cases, respectively.

Our experiment gave a standard deviation in measured voice command SPL which was nearly constant with frequency, while that reported by other researchers showed an increase in variation with increasing frequency [16, 18, 38–40]. Specifically, Schomer [16] showed an increase in mean octave band standard deviation from 2.8 dB at 125 Hz to 9.2 dB at 8000 Hz using a pink noise source for propagation distances up to 1650 m. It is suspected that this result is a consequence of the difference between using a broadband transient source (i.e., voice commands) or a broadband stationary source; the latter was used by other researchers. It is expected that transient sources will exhibit greater variability than stationary sources. Additionally, in this experiment data was taken in a variety of meteorological conditions so that large variation was induced with a only few number of measurements.

2.3.3 Comparison of measured SPLs to the ISO 9613-2 prediction

Measured SPLs from this experiment are compared with ISO 9613-2 because it is *the standard* for calculating the attenuation of outdoor sound sources; persons attempting to predict device performance would use this standard. First, a detailed outline of the predictive scheme is given. Then, measured SPLs are compared to those predicted. Finally, the capabilities of this standard, and other predictive schemes, for predicting voice command SPL from AHWDs are discussed.

2.3.3.1 ISO 9613-2 calculation

The purpose of ISO 9613-2 is to "predict the levels of environmental noise at a distance from a variety of sources" [19]. This goal is accomplished by providing algorithms to account for the physical effects of geometrical divergence, atmospheric absorption, ground effect, reflection from surfaces, and screening by obstacles. The standard is applied to a limited condition set called "downwind," which is fulfilled by having the

- wind direction within 45 of propagation direction, and the
- wind speed between approximately 1 and 5 m/s at a height of 3 to 11 m.

Alternatively, the downwind condition is established by having a "well-developed moderate ground-based temperature inversion." ISO 9613-2 attempts to predict received SPLs with a small error by only applying to a single, limited set of possible meteorological conditions. The input parameter for the ISO 9613-2 calculation is the sound power level (SWL) of the source. The SWL of the AHWD was calculated following ANSI S12.5 [41]. However, before calculating the SWL, the measured SPL was corrected for the attenuation from the ground effect at 10 m using values from Table 2.1 on page 13. Source SWLs of 96.7, 101.0, 100.8, and 97.1 dB (*re* 1 pW) were used in the ISO 9613-2 calculation for the octave bands of 500, 1000, 2000, and 4000 Hz, respectively.

To perform the prediction using ISO 9613-2, the source SWL, L_W, was used to find the SPL in dB at the (downwind) receiver location,

$$L(DW) = L_W + D_c - A, \tag{2.7}$$

for each octave band. D_c is the directivity correction, which was set to zero because the sound power was calculated assuming an omni-directional source. This was done because only the energy traveling in the direction of sound propagation is important; other energy does not contribute significantly to received SPLs. The parameter A is the total attenuation during propagation, which is separated into five different attenuating effects:

$$A = A_{\text{div}} + A_{\text{atm}} + A_{\text{gr}} + A_{\text{bar}} + A_{\text{misc}}. \tag{2.8}$$

The first effect, A_{div}, is the attenuation due to geometrical divergence, given as

$$A_{\text{div}} = 20 \log_{10}(r/r_o) + 11(\text{dB}), \tag{2.9}$$

where r is the propagation distance and r_o is the distance from the source that the SWL was recorded. The constant, 11 dB, corrects for the difference between decibels referenced to 1 pW for the SWL and 20 μPa for the SPL. The second effect, A_{atm}, is the attenuation due to absorption of sound by the atmosphere, given as

$$A_{\mathrm{atm}} = \alpha\, r/1000, \tag{2.10}$$

where α is the attenuation coefficient, with units of dB/km. For the calculation, 20°C and 70% RH were used to determine α, which were the mean temperature and humidity during downwind measurements. The third effect, A_{gr}, is the attenuation due to the ground, given as

$$A_{\mathrm{gr}} = A_s + A_r + A_m, \tag{2.11}$$

for separate attenuation variables A_s, A_r, and A_m which are based on the source, receiver, and middle ground areas, respectively. This part of the calculation is dependent on whether the ground is hard ($G = 0$), porous ($G = 1$), or a fraction of the two. A_s and A_r are given as

$$A_s = A_r = -1.5 + G\, f(hs, hr, r), \tag{2.12}$$

for 500 and 1000 Hz, and

$$A_s = A_r = -1.5\,(1 - G), \tag{2.13}$$

for 2 and 4 kHz. The function $f(hs, hr, r)$ is given in ISO 9613-2 and is dependent on the frequency band, source height, h_s, receiver height, h_r, and propagation distance, r. A_m is given as

$$A_m = -3\, q\,(1 - G), \tag{2.14}$$

where the variable q is

$$q = 1 - 30\,(h_s + h_r)\,/r. \tag{2.15}$$

For this experiment, $h_s = 2$ m was the source height and $h_r = 1.5$ m was the receiver height. A value of $G = 1$ was used because grass is considered porous ground. The fourth effect, A_{bar}, was zero because there was not any screening by obstacles or reflections from extra surfaces. The fifth effect, A_{misc}, was also zero because there was not any foliage, buildings, etc., in the sound propagation path.

2.3.3.2 ISO 9613-2 results

Figure 2.23 displays the mean L_{pEQL} for values measured by the roaming SLM and the SPL predicted by ISO 9613-2, for conditions that fit and do not fit the downwind criteria. Error bars show the total amount of variation for each of the conditions. The standard agrees with the mean of measured downwind SPLs to a

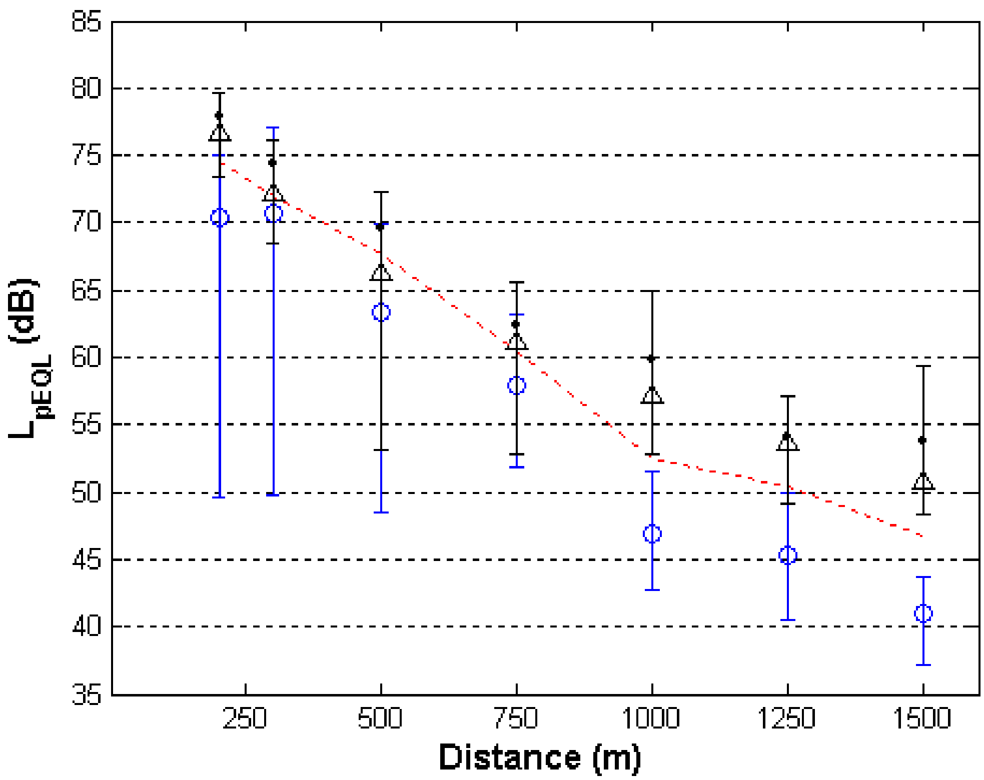

Figure 2.23. Mean values of downwind (•) and non-downwind (○) received L_{pEQL} are compared to the ISO 9613-2 prediction (△). Error bars show the variation in both downwind and non-downwind condition sets. The calculated neutral line (red dotted line) is given for reference. The ISO 9613-2 prediction agrees with the mean of the downwind data set to a mean of 2 dB.

mean error of 2 dB. However, the standard poorly represents the non-downwind class, as expected, with a mean error of about 6 dB. It poorly represents the non-downwind class because downwind and non-downwind classes represent completely different phenomena. Table 2.10 lists the variation in received L_{pEQL} in the downwind data set and the difference between the mean measured L_{pEQL} and ISO 9613-2 prediction. Limiting the choice of measured L_{pEQL} to the downwind condition set reduced the variation in measured L_{pEQL} from a mean of 22 dB to 11 dB. ISO 9613-2 predicted the mean measured SPLs in the downwind class to within about 3 dB at each listener location. This prediction is the same as the estimated error of ±3 dB given in the standard. Surprisingly, other papers have noted the standard to be inaccurate, stating that it gave received SPLs that were considerably too low when a grazing angle over soft ground was present [42, 43], as is the present case for propagation distances of hundreds of meters over grass.

Table 2.10. Variation in measured L_{pEQL} at each distance for the downwind condition set. Also shown is the difference between the mean value of the downwind condition set and the ISO 9613-2 calculation. ISO 9613-2 predicted the mean value of the downwind condition class to within about 3 dB.

Distance (m)	Variation (dB)	Difference (dB)
200	6.2	−1.3
300	7.7	−2.1
500	19.2	−3.3
750	12.9	−1.2
1000	12.0	−2.7
1250	8.0	−0.4
1500	10.9	−3.2

2.3.3.3 Summary of predictive capabilities

A standard must be able to predict SPLs for a variety of meteorological conditions if it will prove useful in the application of predicting SPLs from AHWDs. AHWDs are used during all parts of the day and night, and therefore under many different meteorological conditions. The user of an AHWD must know how the device will perform in all of these different meteorological conditions in order to understand how the range of adequate intelligibility at a listener location changes in time.

Additionally, users of AHWDs need to predict instantaneous levels, so that they will know if a voice command is intelligible to listeners in real-time.

Experimental measurements show that the ISO 9613-2 prediction is accurate to a mean of 5–6 dB from an event SPL, and about 3 dB of the mean measured voice command SPL at a listener location for the downwind meteorological condition class. However, it over-predicts received SPLs for other meteorological conditions. There are not currently any internationally accepted standards which predict received SPLs for a variety of meteorological condition sets. However, there are several other predictive schemes for outdoor sound propagation from a variety of sound sources. These alternate and more sophisticated models include CONCAWE, NORD2000, and HARMONOISE [33]. Additionally, there are several types of computer modeling which are commonly employed. Several of these computer models are compared in a 1995 paper by Attenborough [44]; a more recent list of computational model references is given in a 2007 paper by Prospathopoulos [45].

Wilson [46] uses computer modeling to show that the mean SPL of a meteorological condition can be predicted from mean meteorological data with a maximum of only a few dB error (except in the shadow zone, where the error is much larger). However, predictions of event SPLs typically have much larger errors. When propagating further than 500 m with the receiver near the ground, errors are typically 5–8 dB when using mean meteorological profiles and 8–10 dB when using instantaneous meteorological profiles. In a later paper [34], Wilson shows that the predictive skill for event propagation does not appear to depend strongly on the atmospheric propagation model. This result suggests that due to the variations in received SPLs on short time scales, computer models or other predictive schemes are simply not able to predict instantaneous received SPLs to an accuracy better than 5–8 dB for distances beyond 500 m. Although mean received SPLs ma be predicted accurately, the inherent variability in SPL imposed by propagating sound outdoors means that instantaneous SPLs can only be predicted within some margin of error. This margin of error becomes important when intelligibility must be guaranteed at a listener location in real-time.

Chapter 3

Quantification and variation in voice command intelligibility

3.1 Intelligibility calculation

One metric used to quantify intelligibility is ANSI S3.5-1997 [20]. The purpose of ANSI S3.5-1997 is to define a method for

> computing a measure, called the Speech Intelligibility Index (SII), that is highly correlated with the intelligibility of speech under a variety of adverse listening conditions.

This metric was specifically designed to determine the intelligibility in environments which may have high noise levels. The SII is computed from measurements or estimates of the speech spectrum, noise spectrum, and hearing threshold levels. For the purposes of these calculations, listeners with normal hearing are assumed. Figure 3.1 displays a flow chart of the calculation, which is ultimately dependent on the speech and noise spectra.

The calculation of the SII is a complicated, multi-step process. First, the bandwidth adjustment, B_A, given in Table 3.1, is subtracted from both the background noise level, N, and the speech spectrum level, E, to determine the equivalent noise, N', and speech, E', spectrum levels. Second, the equivalent masking spectrum level, Z, which accounts for the masking of higher frequencies by lower frequen-

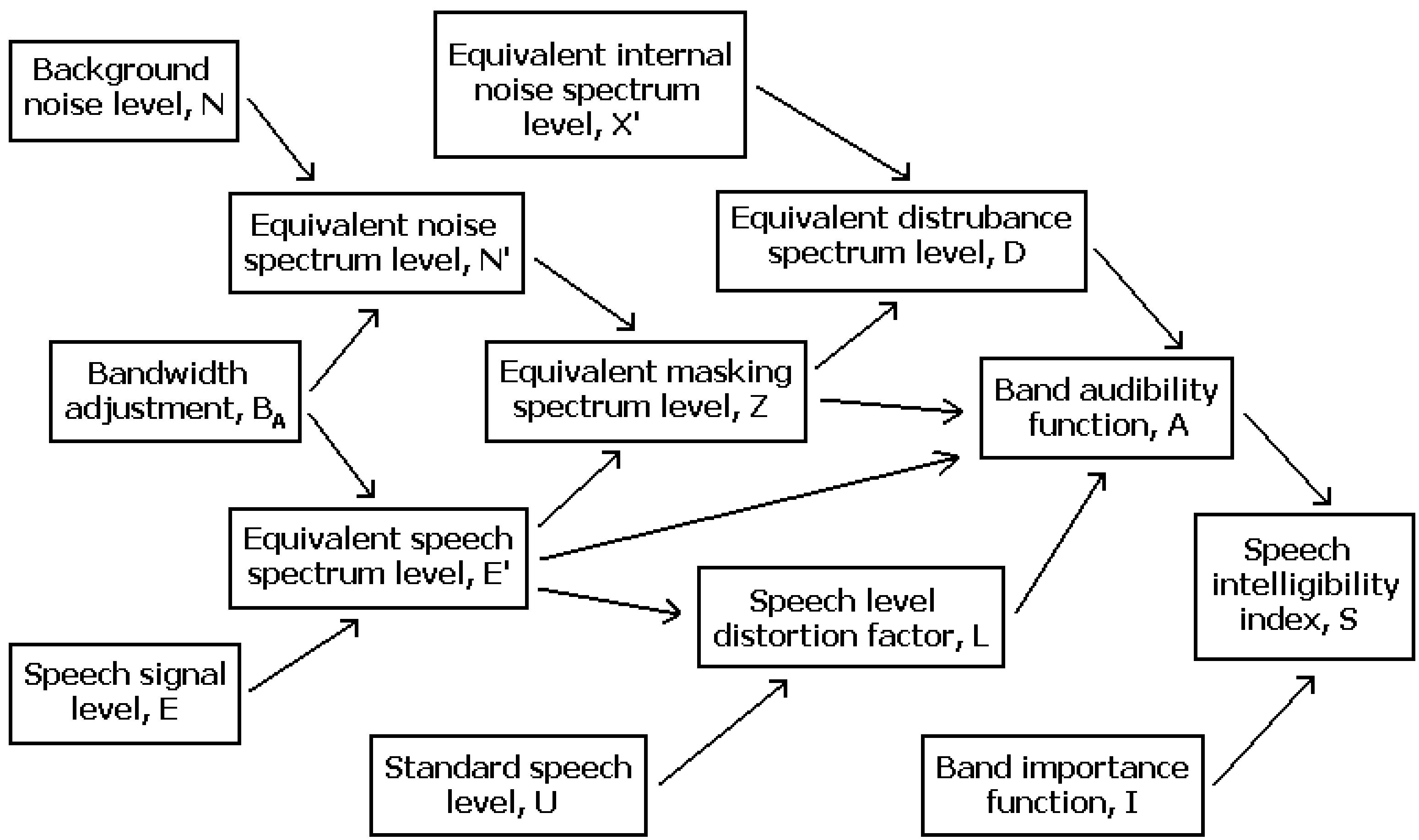

Figure 3.1. Flow chart of the ANSI S3.5-1997 SII calculation. The SII is ultimately dependent on the speech signal and background noise levels.

Table 3.1. Constants used in the SII calculation. F is the center frequency of the one-third octave band, B_A is the bandwidth adjustment, U is the standard speech level for normal vocal effort, and I is the band importance function. The 400–3150 Hz frequency bands have the highest importance in the SII calculation.

F (Hz)	B_A (dB)	U (dB)	I (%)
160	15.65	32.41	1.14
200	16.65	34.48	1.53
250	17.65	34.75	1.79
315	18.65	33.98	5.58
400	19.65	34.59	8.98
500	20.65	34.27	9.44
630	21.65	32.06	7.09
800	22.65	28.30	6.60
1000	23.65	25.01	6.28
1250	24.65	23.00	6.72
1600	25.65	20.15	7.47
2000	26.65	17.32	7.55
2500	27.65	13.18	8.20
3150	28.65	11.55	8.08
4000	29.65	9.33	4.83
5000	30.65	5.31	4.53
6300	31.65	2.59	2.74
8000	32.65	1.13	1.45

cies, is given for each frequency band, i, as

$$Z_i = 10\log_{10}\left(10^{0.1N_i'} + \sum_{k=2}^{i-1} 10^{0.1[B_k + 3.32C_k \log_{10}(0.89F_i/F_k)]}\right), \tag{3.1}$$

where C_k is the slope of each one-third octave frequency band,

$$C_k = -80 + 0.6\left[B_k + 10\log_{10}(F_k) - 6.353\right], \tag{3.2}$$

and F is the center frequency of a one-third octave band, given in Table 3.1. B is the larger value of the equivalent noise spectrum level, N', or the self speech masking level, V. In AHWD use, N' is always larger than V. Third, the speech level distortion factor, L, is calculated from the standard speech level for normal vocal effort, U, given in Table 3.1, and the equivalent speech spectrum level, E', in each one-third octave frequency band using the equation:

$$L_i = 1 - \left(E_i' - U_i - 10\right)/160, \tag{3.3}$$

on which an upper limit of 1 is imposed. Fourth, the equivalent disturbance spectrum level, D, is given as the larger of the equivalent internal noise spectrum level, X', and the equivalent masking spectrum level, Z. In the situation with voice commands in high noise environments, Z is always larger than X'. Fifth, the band audibility function, A, is given as

$$A_i = L_i\,(E_i' - D_i + 15)/30, \tag{3.4}$$

for each one-third octave frequency band. Finally, the speech intelligibility index, S, is defined as

$$S = \sum_{i=1}^{n} I_i A_i, \tag{3.5}$$

where the band importance function, I, is given in Table 3.1. ANSI S3.5-1997 gives different band importance functions in Annex B, depending on the type of speech, which should be chosen to increase the accuracy of the calculation. The band importance function for short passages of easy reading material is used. Table 3.1 shows that frequencies from 400–3150 Hz have the highest importance in the SII calculation. The SII calculation is performed using the Matlab code shown in Appendix B.3.

After the SII is calculated, the percent of words understood (PWU) for an unknown message is found using Figure 3.2, reproduced from ANSI S3.5-1969 [21]. This curve is approximate, and depends on the skill of both talkers and listeners. The PWU is a function of the type of message, and is dependent on syntactic, semantic, linguistic, and contextual constraints. Unknown messages are defined specifically as sentences of 30 words or less. For moderate to high values of SII, Figure 3.2 shows that the PWU is above 90%, or that almost all of the words are understood. However, as the SII value is decreased below 0.5, the PWU begins to decrease rapidly. In this region, the PWU curve drops with an almost constant slope, after which the curve levels off at very low SII values. The PWU for a given SII is found by interpolating along the curve in Figure 3.2. This interpo-

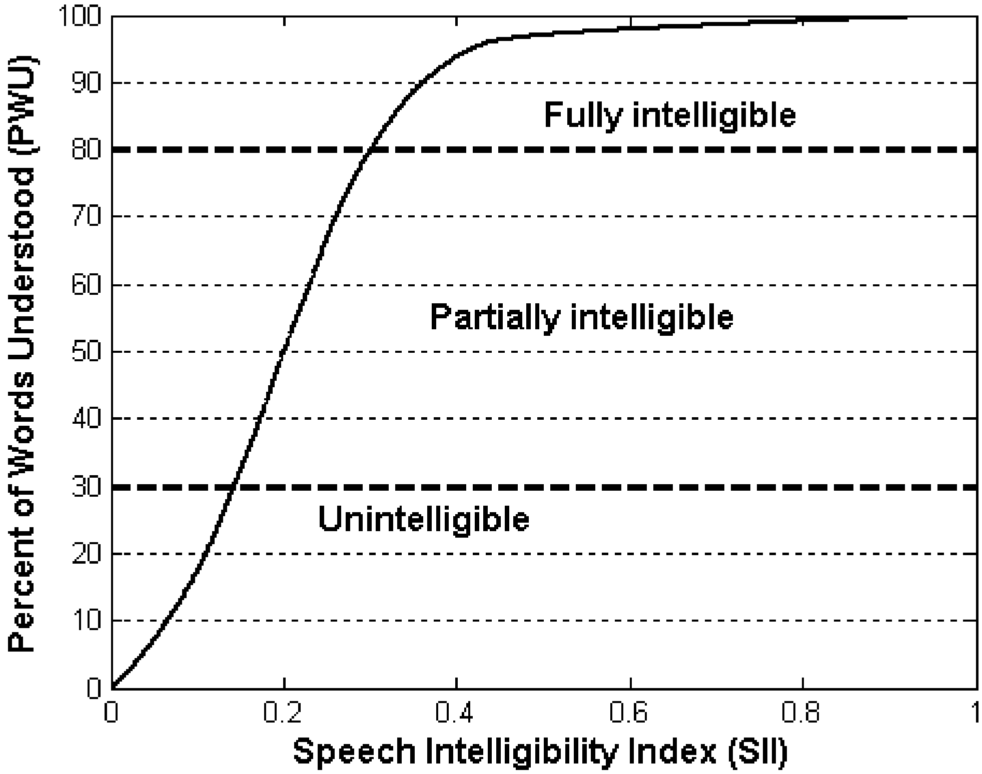

Figure 3.2. Transfer function of SII to PWU for an unknown message from ANSI 23.5-1969 [21]. Cutoffs for the intelligibility ratings given by Crocker [47] are shown by the dashed horizontal lines at 30 and 80 PWU.

lation was performed using Matlab code shown in Appendix B.3. Crocker [47] provides guidelines relating the PWU to an intelligibility rating where 0–30 PWU is unintelligible, 30–80 PWU is partially intelligible, and 80–100 PWU is fully intelligible. Although Crocker developed these guidelines for monosyllabic words, the same guidelines are applied to the subject voice command message since most of the words used in the message are monosyllabic. The boundaries for intelligibility ratings given by Crocker are shown as dashed horizontal lines in Figure 3.2.

3.2 Estimation of signal and noise SPLs for calculations

This section assesses the differences in PWU that arise from two estimations used in the intelligibility calculations of this thesis. The first estimation is that the measured SPL spectra by the roaming SLM can be used to accurately calculate the PWU, instead of an estimate of the speech spectrum level, which corrects the SPL spectra for noise. The second estimation is that a flat noise spectrum accurately represents the PWU which would result from a real noise source (e.g., noise from a vehicle).

3.2.1 Estimation of signal SPLs

It was determined in subsection 2.3.1 that the adequate S/N from the experiment was from 400–4000 Hz. However, the SII is calculated over the 160–8000 Hz frequency band, so it can be expected that for low level received speech signals, noise adversely affects the intelligibility calculation. In order to determine the error in PWU introduced by background noise, the difference between using the measured voice command SPL spectrum (including background noise) and an estimated voice command spectrum which corrects for background noise is determined. To determine the difference, a low level (43.6 dB) voice command spectrum measured at 1000 m was examined. To estimate the voice command spectrum, (i.e., correct the measured spectra for noise), a low frequency roll-off of 15 dB/octave below 500 Hz and a high frequency roll-off of 10 dB/octave above 3150 Hz are imposed. The PWU was calculated for both spectra using a noise SPL incremented in 1/9 dB steps and then averaged over 1 dB. The difference in PWU between the measured and estimated voice command spectra was plotted against the average PWU of the two cases (see Figure 3.3).

The difference in PWU is about 13 PWU at the greatest point, and is found over a wide range of PWU. This large error in PWU indicates that changing the measured voice command SPL spectrum to an estimated voice command SPL spectrum is necessary for this measurement. It is necessary, and creates such a dramatic effect, because the noise SPLs of one-third octave bands outside the 400–

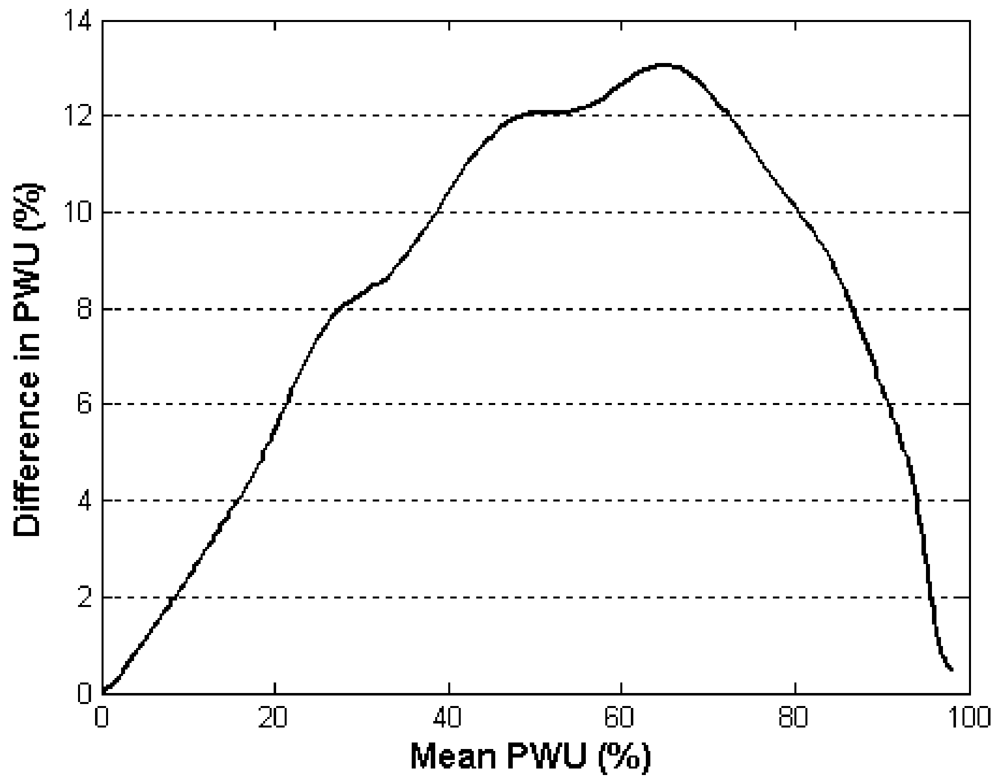

Figure 3.3. Difference in PWU between the measured and estimated voice command SPL plotted against the mean PWU of both cases. A low-level (43.6 dB) spectrum at 1000 m is used for this calculation. There is a significant difference in PWU because the noise SPL outside of the 400–4000 Hz band is comparable (or larger) to the signal SPL inside the 400–4000 Hz band.

4000 Hz band are comparable to the signal SPLs of one-third octave bands inside the 400–4000 Hz band. When the same comparison is performed on a median (52.8 dB) measured voice command SPL spectra at 1000 m, there is less than 0.5% difference in the PWU. For this spectrum, the noise SPLs outside the 400-4000 Hz band are at most 10–20 dB less than the largest signal SPLs inside the band. Therefore, it is only necessary to correct the measured SPL spectra when noise SPLs outside the 400–4000 Hz band are comparable to signal SPLs inside this frequency band, which occurred only for the low-level measured voice command SPLs at and beyond 1000 m.

3.2.2 Estimation of noise SPLs

In scenarios where AHWDs are used, the noise environment may be a car engine, ship engine, or a variety of other sources. Each of these sources has a unique spectral shape. Often, these broadband noise sources have a relatively flat noise spectrum in the speech intelligibility band (160–8000 Hz), but may have an increasing SPL in the lowest one-third octave frequency bands and a decreasing SPL in the highest one-third octave frequency bands. A snow blower recorded during the experiment is an example of this spectrum (see Table 3.2). When the snow blower spectrum is compared to a flat spectrum of the same overall SPL, it exceeds the flat spectrum by as much as 5 dB in the lowest one-third octave bands, and falls below the flat spectrum by 5 to 10 dB in the highest one-third octave frequency bands. The overall SPL of this snow blower is about 62.5 dB. A flat spectrum which gives the same overall SPL has 50 dB SPL in each of the 18 one-third octave bands used in the SII calculation.

Figure 3.4 shows the difference in PWU for the median received voice command at 1000 m between calculations using the flat and snow blower spectra. The noise SPL spectra were incremented in 1/9 dB steps and averaged over 1 dB. The difference in PWU for these two cases reached a maximum of about 5%. As expected, the snow blower gave a lower PWU score, due to the presence of higher SPLs at lower frequencies, which increases the amount of masking. Therefore, the

Table 3.2. Example spectrum of a snow blower taken during the experiment. The SPL of the snow blower in is listed for each one-third octave band. An increase and decrease in SPL from a flat spectrum is shown at the lowest and highest frequencies, respectively.

Center Frequency (Hz)	SPL (dB)	Center Frequency (Hz)	SPL (dB)
160	55.3	1250	50.9
200	52.3	1600	51.6
250	49.6	2000	49.0
315	50.8	2500	50.5
400	52.3	3150	48.9
500	49.6	4000	47.0
630	49.1	5000	44.8
800	44.6	6300	43.6
1000	46.3	8000	41.5

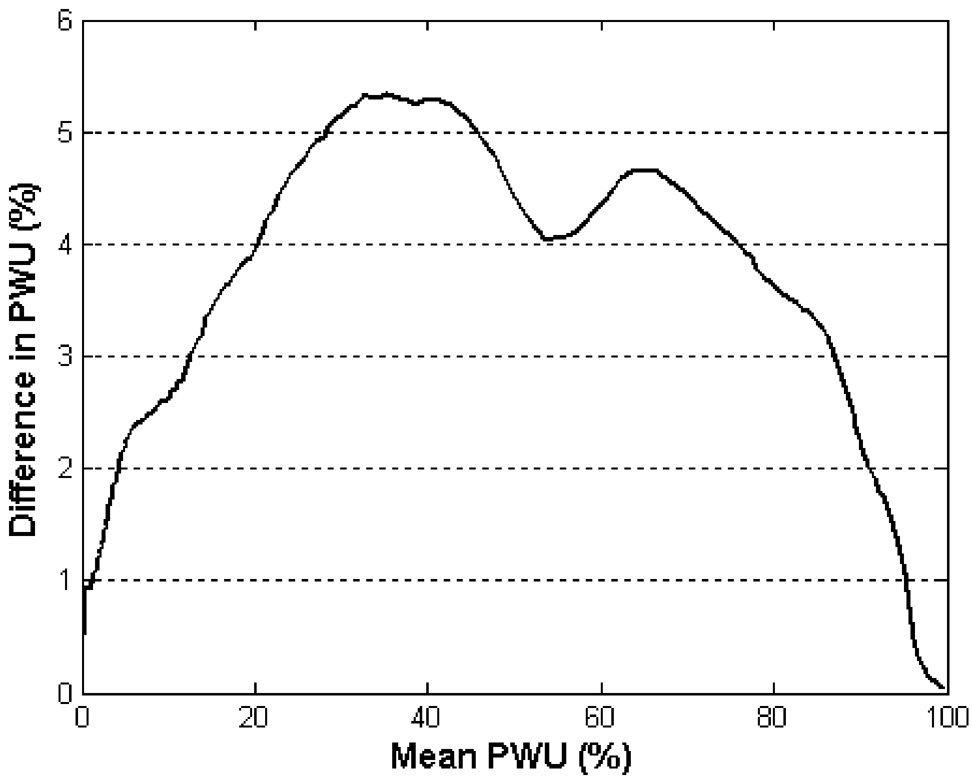

Figure 3.4. Difference in PWU between a flat and snowblower noise spectrum plotted against the mean PWU of both cases. The overall SPL for both cases is equivalent, but the snow blower shows less PWU by a maximum of about 5% due to masking. This difference in PWU is negligible.

difference in PWU caused by using a flat noise spectrum is negligible. However, a calculation of this estimate is important to test when noise sources of different spectral shape are considered.

3.3 Variation in voice command intelligibility

In this section, the variation in intelligibility over the entire experiment is compared with three different noise environments. Then, the variation in intelligibility is compared to changes in noise and signal SPLs. Finally, the results of the calculations are discussed and related to changes in meteorological conditions.

3.3.1 Low, moderate, and high noise environments

In this section, three background noise SPLs are chosen and the PWU is calculated at each of these noise levels for all of the measured voice command SPL spectra recorded by the roaming SLM during the experiment. The three background noise levels are chosen because they are relatively high (76 dB), moderate (64 dB), and low (52 dB) compared to measured voice command SPLs at 750 m. The calculation was performed to confirm that the large (up to 30 dB) variations in received SPL measured during the experiment cause large variations in intelligibility rating. Figure 3.5 shows the calculated PWU at each of the three background noise levels for all of the received SPL data from the roaming SLM. Each of the three areas represents the range of PWU values calculated with a single background noise level. For example, the shaded region corresponds to the range of PWU calculated using a background noise level of 64 dB for all of the received SPL data. The area (vertical hash) above the higher of the two thick, slanted, solid lines is the range of PWU values calculated using a background noise level of 52 dB. The area (horizontal hash) below the lower thick, slanted, solid line is the range of PWU values calculated using a background noise level of 76 dB. Boundaries for the intelligibility ratings are given by the dashed horizontal lines at 30 and 80 PWU.

At 750 m, 52 dB (relatively low noise) resulted in full intelligibility ($>$ 80 PWU) and 76 dB (relatively high noise) resulted in an unintelligible ($<$ 30 PWU) voice command for all measurements. This is expected, and indicates that variation in measured voice command SPL due to changes in meteorological condition has little effect on the intelligibility rating when noise is relatively high or relatively low: the intelligibility rating is stable. However, for 64 dB (a moderate noise level) at 750 m, there is extreme variation in the intelligibility (from 17–94 PWU), which gives the full range of intelligibility ratings from unintelligible to fully intelligible.

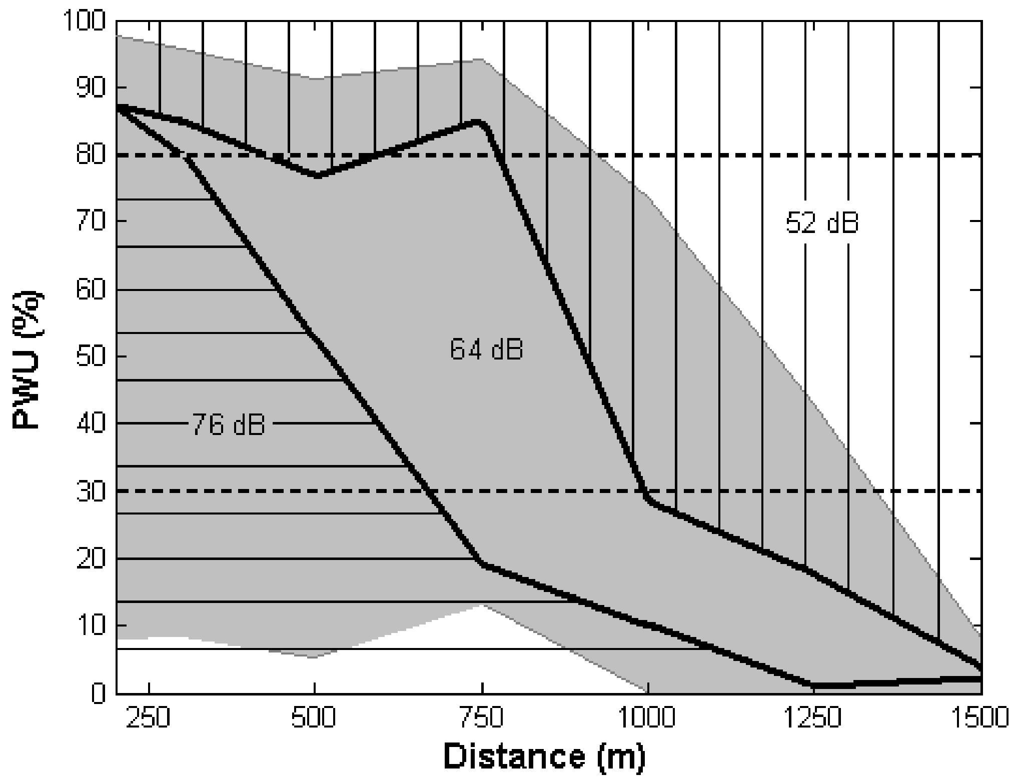

Figure 3.5. PWU calculated for 52 dB (vertical hash), 64 dB (shaded region), and 76 dB (horizontal hash) background noise levels. Dashed horizontal lines indicate the boundaries of intelligibility ratings. At 750 m, relatively high (76 dB) and low (52 dB) noise levels give intelligibility ratings which do not change for different measurement conditions, while a large change in intelligibility is shown from the moderate noise level.

For moderate noise levels, the intelligibility rating of a voice command is highly dependent on variations in received voice command SPL caused by changes in meteorological condition: the intelligibility rating is unstable.

The same result occurred at closer and farther distances. At 200 m propagation distance, the variation in PWU was 90% for both the 76 and 54 dB noise SPLs, and only 10% for the 52 dB noise SPL case. Similarly, at 1500 m propagation distance, the variation in PWU was 90% and 65% for the 52 and 64 dB noise SPLs, respectively, and only 5% for the 72 dB noise SPL. For the 64 dB noise SPL case, there was about a 90% spread in PWU from 200–1000 m propagation distance. Even though the signal level dropped considerably in that distance (the neutral line dropped 22 dB); the variation in measured voice command SPLs over the experiment was still sufficient to give this wide range of PWU. This wide range of PWU indicates that much smaller changes in noise SPL than those used in Figure 3.5 are sufficient to cause large changes in intelligibility.

3.3.2 Changes in signal and noise SPL

In subsection 3.3.1, it was determined that changes in noise SPL which are smaller than 12 dB have large changes in intelligibility. In this subsection, smaller changes in noise SPL are used to examine the effect on the PWU. Changes in both signal and noise SPL are examined. Finally, the effects on intelligibility ratings of variations in signal and noise SPL are examined in terms of the S/N.

3.3.2.1 Changes in noise SPL

Figure 3.6 shows calculated PWU contour lines for a single measured voice command at each propagation distance. The calculation was performed on the voice command closest to the mean of measured SPLs at each distance. Incremental changes in noise SPL of 0.5 dB were used to calculate the PWU, giving a "matrix" of PWU values across the noise SPL–distance plane. Contour lines of constant PWU are shown. Regions of unintelligible ($<$ 30 PWU) and fully intelligible ($>$ 80 PWU) voice commands are indicated on the plot. Vertical space between each of the 30, 55, and 80 PWU contour lines is about 3 dB noise SPL, and is constant over all propagation distances. This indicates that the effect of noise on intelligibility ratings is independent of propagation distance. Additionally, a change in noise SPL of 3 dB causes a voice command with a value of 55 PWU, considered partially intelligible, to change to fully intelligible or unintelligible. This is significant because noise levels may vary by +/- 3 dB on time scales as short as seconds. For example, consider the change in noise SPL from idle to full throttle for a motorized boat. The 55 PWU contour line, found at the center of this middle region, is named the *threshold of intelligibility*. The 55 PWU contour is called the threshold of intelligibility because the intelligibility is unstable and small (3 dB) shifts in noise SPL cause a voice command to become either fully intelligible or unintelligible. The vertical space between the 95 and 80 PWU and the 30 and 10 PWU contours is each about 4 dB, and is constant over all of the propagation

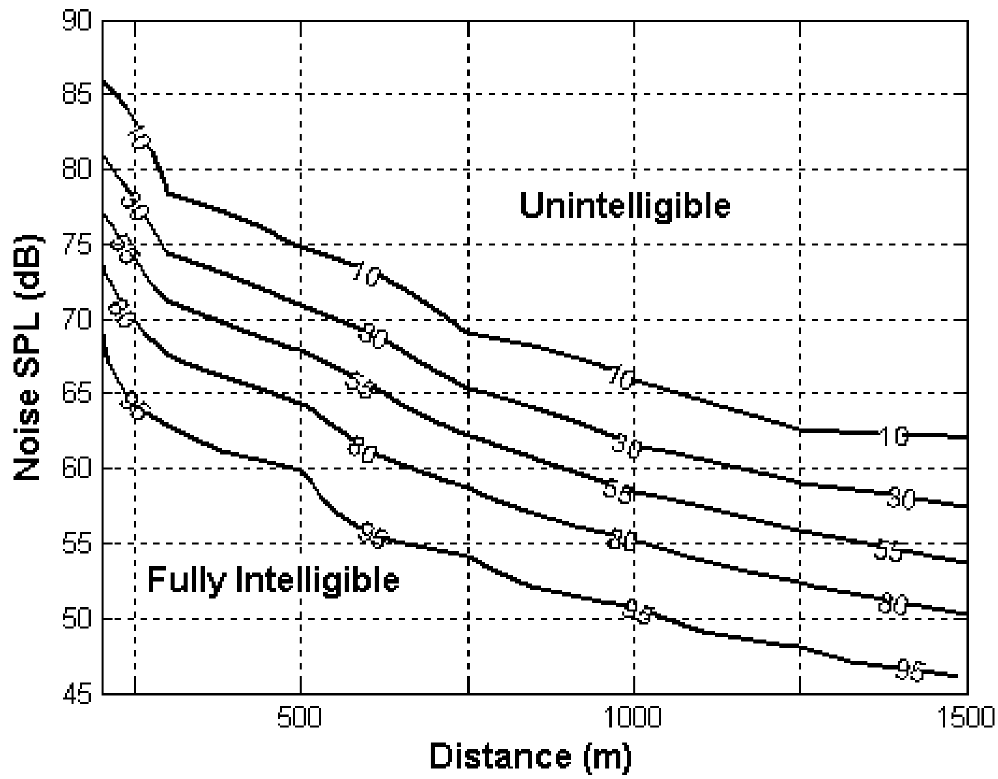

Figure 3.6. PWU contours are calculated for a measured voice command at each propagation distance as noise SPLs are incremented in 0.5 dB steps. The calculation was performed for the voice command closest to the mean of measured SPLs at each propagation distance. The effect of noise on intelligibility ratings was independent of distance.

distances. To induce these smaller changes in PWU outside of the partially intelligible band it is necessary to have a larger change in noise SPL, indicating that the intelligibility rating is more stable in these two regions.

3.3.2.2 Changes in signal and noise SPL

Figure 3.7 shows PWU contour lines from 20–90 PWU in increments of 10% calculated for noise and signal SPL steps of 0.5 dB. The voice command used for this calculation was measured at 1000 m and had a SPL of 52.8 dB. In Figure 3.7, PWU contours appear parallel, indicating that the relative relationship between changes in noise and signal SPL stays constant over the band of loudness where the signal SPL ranges from 40–60 dB. This suggests that the S/N ratio is an ap-

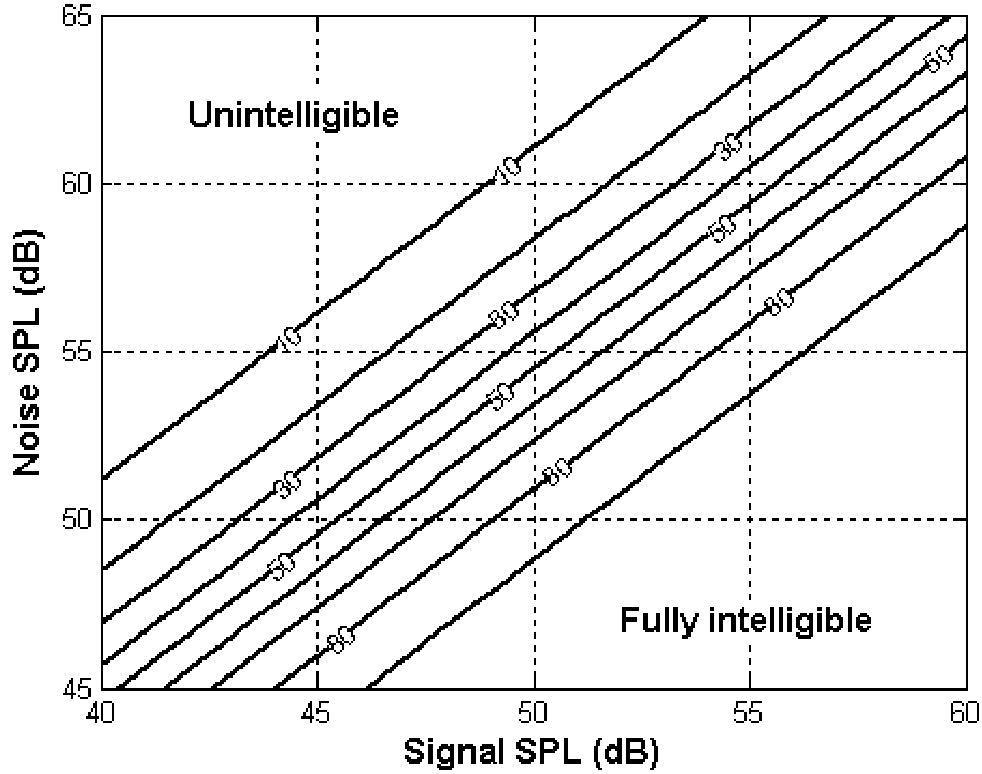

Figure 3.7. PWU contour lines in increments of 10% are shown. These contours were calculated for signal and noise SPL changes in increments of 0.5 dB for a measured voice command at 1000 m propagation distance and SPL of 52.8 dB. The slope of PWU contours is close to unity, indicating that changes in signal and noise SPL hold equal significance.

propriate generalization for assigning intelligibility ratings; this result is explored further in subsubsection 3.3.2.3. Additionally, the slope is close to unity, i.e., an increase or decrease in the noise SPL has the same effect as an equivalent decrease or increase in signal SPL. Therefore, both the signal and noise SPL spectra are equally important to estimate accurately when attempting to predict intelligibility at a listener location because equal changes in signal and noise SPL have the same effect on intelligibility. A 3–4 dB increase or decrease in either the noise or signal SPL from the threshold of intelligibility (55 PWU) causes the intelligibility rating to change from partially intelligible to either unintelligible or fully intelligible. This is significant, as changes in measured voice command SPL during this experiment were as much as 30 dB at a single propagation distance!

The closest spacing of contour lines is inside the partially intelligible band and the relative spacing increases outside of the partially intelligible band. We can take a vertical slice of Figure 3.6 and examine how the PWU changes as noise level changes. If we take the derivative of this slice, the result is the slope of the PWU curve, or change in PWU per dB change in noise. Figure 3.8 shows this slope plotted against the S/N. The change in PWU is calculated using increments of 0.2 dB in noise SPL and is averaged over a 1 dB change in noise SPL. The slope is low when the speech signal is unintelligible, increases to a maximum when the speech signal is partially intelligible and near the threshold of intelligibility, and decreases when the speech signal is fully intelligible. The largest slope is about 8 PWU per dB. Near this maximum value, the slope is relatively constant for a change in S/N of several dB, indicating that changes in S/N are approximately linearly related

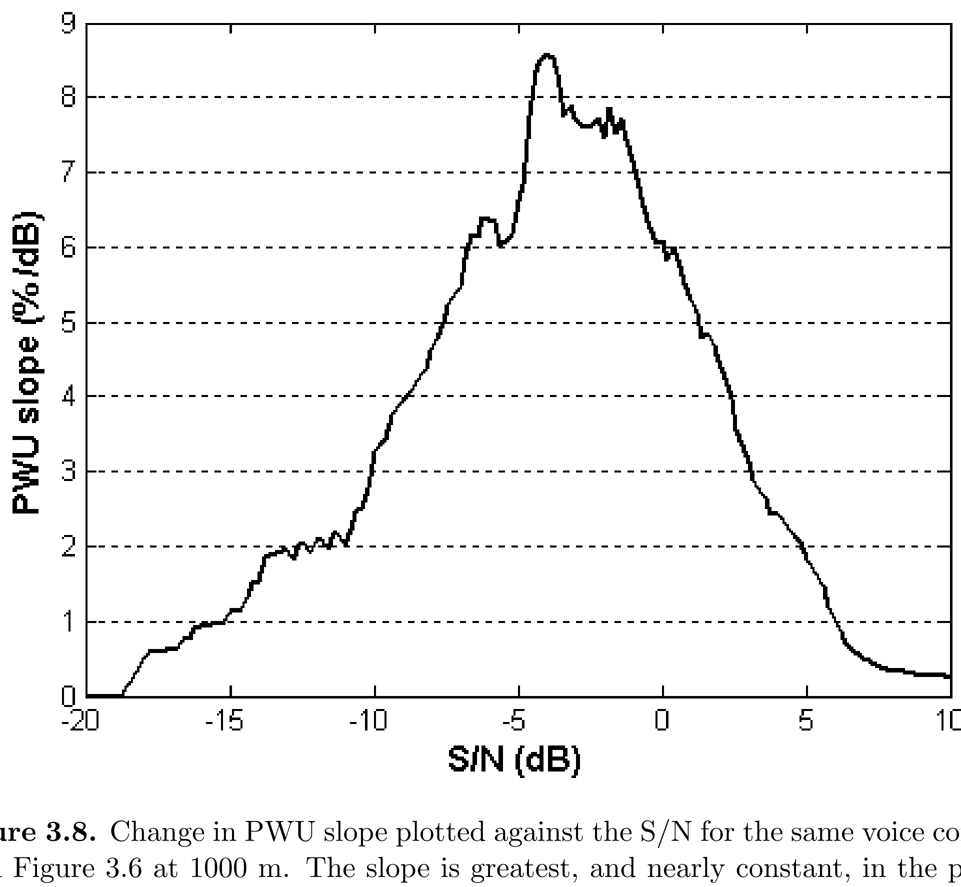

Figure 3.8. Change in PWU slope plotted against the S/N for the same voice command as in Figure 3.6 at 1000 m. The slope is greatest, and nearly constant, in the partially intelligible band.

to changes in PWU in the partially intelligible band. Additionally, the decrease in slope outside of the partially intelligible band indicates that a larger change in S/N is needed to make an equivalent change in PWU.

3.3.2.3 Generalizing to S/N and S/(N+IL)

The PWU calculation shown in Figure 3.7 suggests that the results may be shown in terms of the S/N. This decision is supported by Crocker [47] and Kinsler [48] who show plots relating intelligibility to the S/N. This relationship is explored in Figure 3.9, which shows the same PWU contours calculated for Figure 3.7, replotted against the S/N and signal SPL. As found in Figure 3.9, the PWU contours are approximately constant in S/N from 40–60 dB signal SPL, and a constant

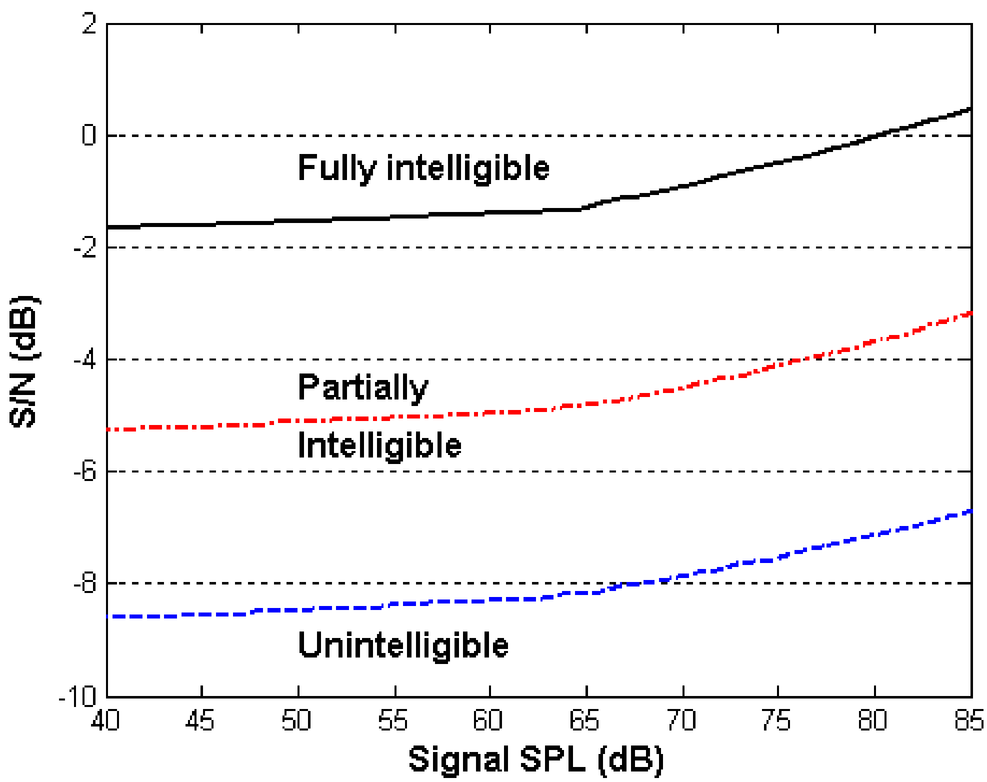

Figure 3.9. PWU calculated as in Figure 3.7 for changes in S/N for a signal measured at 1000 m. The boundaries of intelligibility ratings are indicated on the plot. Above a signal SPL of about 60 dB, a constant S/N no longer approximates the boundaries for intelligibility ratings.

S/N ratio may be used for the prediction of intelligibility in this region of signal SPL. However, as the signal (and noise) SPL is increased, PWU contours curve upward, indicating that for higher signal SPLs, the S/N must be increased in order to keep the same intelligibility rating. This result is different than that suggested by Crocker [47] and Kinsler [48] who show an intelligibility rating calculated from the S/N ratio regardless of signal SPL. These references do not consider the effect on intelligibility caused by such loud speech signals as those which are produced by AHWDs. This result is manifested in the SII calculation as an increase in the speech level distortion factor. Additionally, this result is significant because measured SPLs in the experiment ranged from about 40 dB at 1500 m to about 80 dB at 200 m. Therefore, a constant S/N calculation does not give accurate intelligibility ratings in all AHWD situations, because signal levels at closer distances are too high.

The same calculation as Figure 3.9 is performed for another voice command in Figure 3.10. This voice command was measured at a propagation distance of 200 m, and had a SPL of 73.1 dB. The same trend of a constant, then increasing S/N for a constant PWU is found, as in Figure 3.9. However, the S/N at which the boundaries for the intelligibility ratings occur is shifted by 1 dB. When this calculation is performed for other measured voice commands, a similar result is found. Therefore, it is appropriate to define a range of S/N values, at which cutoffs for intelligibility ratings occur as a function of signal SPLs. For signal SPLs below 60 dB, the boundary for our voice command to be fully intelligible is at about 0 to -1 dB S/N. Additionally, any S/Ns less than -7 to -8 dB are considered unintelligible. The threshold of intelligibility (55 PWU) is found at a S/N between -3 and -5 dB. When signal SPLs extend beyond 60 dB, it appears that an increase in S/N of about 1 dB is necessary for every 10 dB increase in signal SPL. Using this adjustment for high signal SPLs, the S/N at which the approximate cutoffs for these intelligibility ratings occur can be estimated over a large range of signal SPLs. However, it appears that the relationship does not hold for signal SPLs over about 95 dB, due to limitations imposed by the SII calculation. Additionally, the boundaries in terms of a S/N can be generalized to the S/(N+IL) if the insertion loss, IL, is approximated as constant (i.e., frequency independent) in the range from 160–8000 Hz. For a frequency independent insertion loss, the received signal

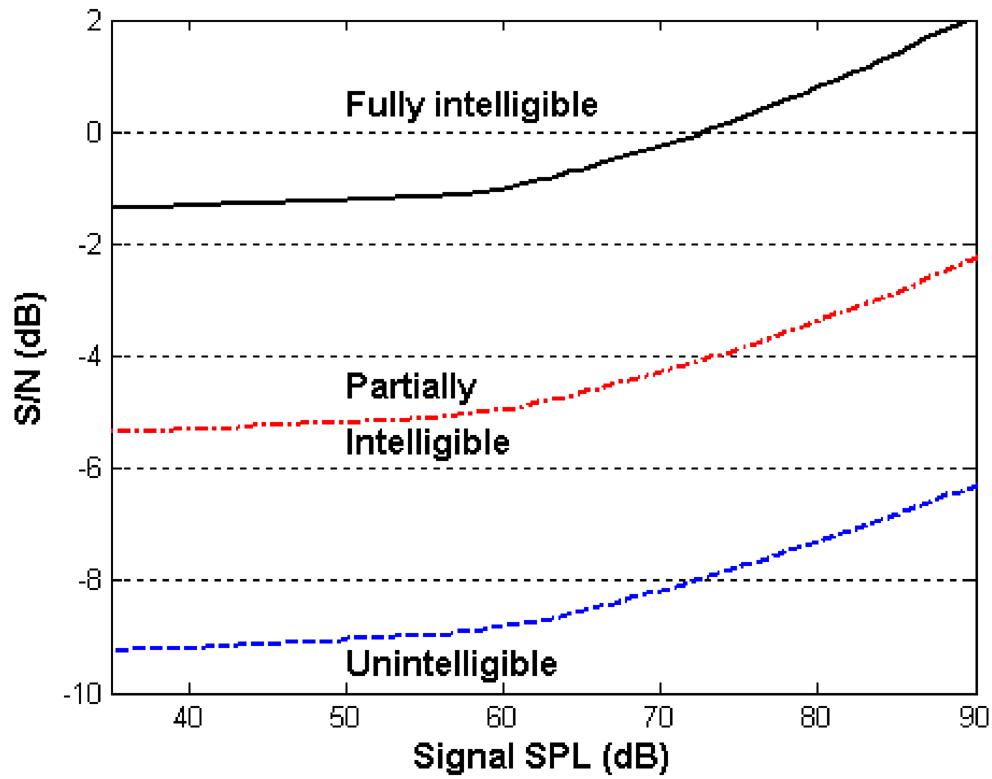

Figure 3.10. PWU contours calculated as in Figure 3.9, now for a signal measured at 200 m. The boundaries of intelligibility ratings are indicated on the plot. These boundaries have a similar location and shape to those in Figure 3.9.

SPL will be perceived as a simple reduction in overall signal SPL, and the spectral shape will not change. Changing the spectral shape of a voice command induces additional changes in the intelligibility calculation.

3.3.3 Summary of the results of intelligibility calculations

Calculations were performed using ANSI S3.5 [20, 21] to determine the speech intelligibility index (SII) and percent of words understood (PWU) for measured voice commands during the experiment. Intelligibility ratings were assigned using a guideline given by Crocker [47]. Several conclusions were drawn about the relationship between AHWD voice commands and noise environments. First, relatively high and relatively low noise environments were shown to give a stable intelligibility rating, which was subsequently unintelligible or fully intelligible, respectively.

Moderate noise level environments gave an unstable intelligibility rating, which resulted in intelligibility ratings from fully intelligible to unintelligible during the experiment. Second, a small (about 3 dB) change in noise SPL was found to be sufficient to cause a voice command to change from partially intelligible to unintelligible or to fully intelligible in the presence of this moderate noise condition. This result was independent of propagation distance.

Third, changes in signal SPL were shown to have a similar effect as changes in noise SPL. Therefore, changes in the signal SPL of about 3 dB for a partially intelligible voice command were sufficient to change it to either unintelligible or to fully intelligible. This is significant because measured voice command SPL was shown to vary by 30 dB at a propagation distance of 200 m. Fourth, it was shown that the variability in PWU is high near the intelligibility threshold, where only a 6–7 dB change in voice command SPL causes a signal that is just fully intelligible to become unintelligible. This change in received voice command SPL has been shown to occur on time scales as short as minutes in subsubsection 2.3.2.1, on page 30.

Finally, a constant S/N was shown to give a constant value of PWU at voice command SPLs less than about 60 dB. This indicates that a boundary in terms of a constant S/N ratio is a good predictor of intelligibility for voice command SPLs below 60 dB at a listener location. These approximate S/N boundaries are listed in Table 3.3, calculated for the voice command used during the experiment. For voice command SPLs above 60 dB, the S/N must be increased in order to keep the same PWU value. The increase in S/N was found to be approximately 1 dB for every 10 dB increase in voice command SPL above 60 dB.

Table 3.3. A constant S/N gave a constant value of PWU for signal SPLs less than 60 dB. These PWU values were used to assign intelligibility ratings for our voice command, which have boundaries at a particular S/N. For higher signal SPLs, the S/N boundary must be increased. Boundaries for other voice commands may be shifted due to differences in spectral content.

Intelligibility rating	S/N (dB)	PWU value (%)
Fully intelligible	> 0	> 80
Partially intelligible	-1 to -7	30 to 80
Unintelligible	< -8	< 30

Chapter 4

Summary and conclusions

4.1 Variation in measured voice command SPL

Measurements of received voice command sound pressure levels (SPLs) from acoustic hail and warning devices (AHWDs) were performed at listener locations up to 1500 m in order to determine how changes in meteorological condition effect variations in received voice command SPL. Weather stations were used to monitor meteorological conditions during the time of each voice command broadcast. Meteorological conditions were used to compare the variations in received voice command SPL to the variations in sound propagation conditions. Variations in measured voice command SPL were compared to the results of other experiments, the international standard for calculating the attenuation of sound outdoors, ISO 9613-2, and to variations in meteorological condition. Variation in measured voice command SPL at a single propagation distance was as much as 30 dB. This result is in agreement with that found in other experiments. Additionally, variations of more than 30 dB should be expected to occur throughout the course of each day at listener locations at and beyond 200 m. This is significant because AHWDs are used throughout the diurnal cycle. ISO 9613-2 was shown to accurately predict the mean of the downwind meteorological condition class within an error of less than 2 dB at each listener location. However, the mean event error was 5–6 dB. These values for mean and event error have been reported as typical for all predictive schemes, including intensive computer modeling, for conditions of neutral or upward refraction at distances beyond 500 m. Predictive schemes cannot gain higher accuracy due to the effects of atmospheric turbulence on received SPLs in neutral and upward refracting conditions.

Variations in measured voice command SPL of as much as 17 dB in a 6 minute time period were shown. The results presented from other experiments did not indicate that such large variations in SPL occur on time scales as short as several minutes. Alternatively, during a condition of low variability, measured voice command SPL varied by only 4 dB over the course of an entire hour. Conditions of high and low variability are characterized by whether the sound path from the source to listener location is indirect or direct, respectively. The type of path can be determined from the meteorological condition and sound propagation distance. For propagation distances beyond 200 m, the direct and indirect paths correspond to downward and upward refraction. Measured voice command SPLs during downward and upward refraction fit normal distributions, where the standard deviation for downward refraction was about 3 dB, compared to a standard deviation of about 9 dB for upward refraction. The standard deviation for upward refracting conditions is dependent on the variation in meteorological conditions during measurement times, while the standard deviation in received SPL for downward refracting conditions was shown in other experiments to be consistently less than 5 dB. Variation in received voice command SPL in individual one-third octave frequency bands did not increase with increasing frequency, as shown in other experiments, but was constant between about 6–8 dB standard deviation from 400-4000 Hz. It was believed that this consistently larger variation was from the use of speech signals, which are a transient instead of a continuous broadband noise source.

4.2 Variation in intelligibility

ANSI S3.5 was used to calculate the speech intelligibility index (SII) and the percent of words understood (PWU) of measured voice commands in order to determine how intelligibility at a listener location varies as a function of received voice command SPL and meteorological condition. Intelligibility ratings were assigned based on PWU value. The relationship between variations in received speech signal SPLs and the respective changes in the intelligibility of those signals has received little, if any, attention from the research community. When background noise levels at a listener location are relatively low or high, the variations in measured SPL imposed by meteorological changes has little effect on the resultant intelligibility rating, which is fully intelligible or unintelligible, respectively. When a moderate background noise level is present, intelligibility ratings are unstable. A change in measured voice command SPL of only 3–4 dB is necessary to cause a partially intelligible voice command to become either fully intelligible or unintelligible. This is significant because measured voice command SPLs were shown to vary by 30 dB at a listener location of 200 m. However, when meteorological conditions are examined, the intelligibility rating is less variable during downward refractive conditions compared to upward refractive conditions.

The intelligibility rating at a listener location can be estimated using a constant signal-to-noise ratio (S/N) for signal SPLs below 60 dB. A S/N greater than -1 dB was found to give a fully intelligible rating for our voice command message, while a S/N less than -7 dB was found to give an unintelligible rating. When signal SPLs are increased beyond 60 dB, the S/N must be increased by approximately 1 dB for every 10 dB increase in signal SPL to ensure the same intelligibility rating for our voice command. Although intelligibility has previously been characterized by a constant S/N, such high speech signal levels were not considered. This result is significant because AHWDs are commonly broadcast into high background noise level environments and/or into high insertion loss enclosures, where signal SPLs above 60 dB must be used.

4.3 Recommendations and future work

An intelligibility rating and the variability associated with that rating may be estimated using the expected S/N at a listener location. The mean received speech signal SPL and it's variability for a given meteorological condition can be estimated based on experimental data or computer simulations. The background noise SPL at a listener location can be estimated based on the scenario (e.g., the listener's mode of transportation). Knowing the approximate S/N and it's variability allows for the estimation of the PWU and intelligibility rating, and some margin of error. Ideally, a database containing this information could be accessed by a simple computer program in real-time. The output of such a program could be as simple as a red, yellow, or green light, indicating to an AHWD operator whether the message is expected to be adequately intelligible for a given propagation distance and noise scenario. To put this plan into effect, the study of the variation in received voice command SPL for different meteorological conditions must be expanded. Received voice command SPL needs to be classified for different meteorological conditions in terms of the expected SPL and the standard deviation at listener locations. Noise sources must also be classified. Additionally, the effect on PWU of a frequency-dependent insertion loss should also be calculated.

The relation of atmospheric sound propagation to intelligibility is a new field of study, so there are many directions that future work may take. First, in relation to atmospheric sound propagation, the received SPL should be measured continuously to see if all of the variations in voice command SPL have time scales as short as minutes. It is possible that considerable variation takes place on time scales of seconds—which are very important for AHWD scenarios. Also, most previous outdoor sound propagation experiments used tonal or continuous broadband noise source, so performing an experiment to determine how the variation in received SPL of speech is related to these other sound sources would allow for the use of the larger set of experimental data to help determine expected SPLs for different meteorological conditions. Additionally, measurements with a wider frequency band of adequate S/N should be made to confirm the result that the variation in received SPL in one-third octave bands of speech signals are independent of frequency, a result which is contrary to that reported for continuous broadband noise sources. Second, in terms of intelligibility, frequency compression of the voice command message should be explored as a possible way to increase intelligibility, based on AHWD frequency output characteristics and/or limitations. Also, individual words, as well as sentences, should be optimized for their intelligibility.

Appendix A

Tables of experimental data

A.1 Measured voice command SPLs

A.1.1 Roaming SLM

The normalized measured voice command SPLs from the roaming SLM are found in Tables A.1 on page 78 and A.2 on page 82.

A.1.2 Stationary SLM

The normalized measured voice command SPLs from the stationary SLM are found in Tables A.3 on page 86 and A.4 on page 91.

A.2 Meteorological conditions during testing

Table A.5, on page 95, lists the source, field, and tower weather station data for the times of voice command propagation. Temperature and wind speed along the direction of propagation have been averaged over ten-minute intervals. The listed pressure and relative humidity are one-minute averages given by the source weather station. Typical differences in pressure and relative humidity between individual weather stations did not exceed 1.0 hPa and 10 %, respectively.

Table A.1: Measured SPLs in one-third octave bands from 160–1000 Hz as recorded by the roaming SLM. D is the propagation distance. The columns numbered 160–1000 are the center frequencies for the SPL (dB) in each one-third octave band.

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
Test Session 1, 9/29											
14:15	200	64.14	48.98	34.87	30.54	30.11	40.57	48.07	50.05	51.64	55.78
14:26	300	61.96	45.10	32.10	27.64	26.10	38.66	45.58	46.60	49.69	53.42
14:35	500	51.63	46.83	41.92	33.26	26.72	32.10	37.76	39.24	40.43	43.19
14:44	1000	44.35	31.40	29.11	22.80	16.80	23.42	30.58	32.28	35.41	37.22
14:51	1500	37.84	39.22	36.97	31.47	25.33	27.10	27.62	27.34	29.04	30.34
14:58	1250	43.89	28.13	27.22	19.12	14.32	23.07	32.36	33.43	35.35	37.91
Test Session 2, 10/2											
11:18	1500	43.41	41.24	28.85	18.37	12.40	21.92	31.38	31.10	32.94	36.51
11:33	1250	43.00	43.30	30.56	20.97	13.94	21.74	29.84	32.06	32.84	36.20
11:45	1000	45.88	45.21	33.77	25.43	17.62	24.17	31.33	31.26	34.58	37.46
11:59	750	51.93	56.52	50.87	37.86	29.35	30.09	36.15	38.00	40.59	44.39
12:09	500	54.59	49.46	40.68	35.12	26.66	31.53	38.85	42.32	44.31	45.78
12:28	300	57.67	47.97	38.72	34.17	28.66	36.68	43.44	41.67	43.35	47.95
12:38	200	60.73	47.91	39.44	35.13	30.44	37.86	45.96	42.87	46.86	51.83

Table A.1—continued on next page

Table A.1—continued from previous page

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
Test Session 3, 10/2											
13:56	1500	50.16	26.67	25.16	24.53	16.70	32.84	40.80	37.39	40.63	42.20
14:07	1250	54.93	27.71	28.34	29.54	21.71	33.25	44.96	43.25	46.50	47.30
14:18	1000	58.64	28.36	29.19	31.28	27.46	46.36	54.90	47.16	48.28	48.71
14:36	750	63.25	27.88	28.11	26.27	21.99	37.55	50.24	49.31	54.51	55.53
14:45	500	69.96	27.82	26.21	26.07	24.00	41.04	54.77	56.74	60.30	61.12
14:54	300	73.69	33.94	33.44	34.53	26.09	42.27	55.66	58.61	63.41	64.82
15:01	200	77.43	31.02	27.37	30.02	27.74	45.15	58.20	64.00	67.03	67.73
Test Session 4, 10/3											
10:38	1500	48.37	39.38	37.73	31.59	21.31	27.09	37.77	38.62	41.70	41.22
10:50	1250	50.47	32.78	35.78	28.24	20.86	25.52	36.07	36.80	42.33	43.29
10:58	1000	53.00	34.16	36.10	30.98	20.11	26.64	37.20	37.02	41.62	45.80
11:07	750	58.30	35.90	37.85	33.63	23.46	30.15	40.56	43.04	46.65	50.12
11:17	500	64.48	46.68	46.68	41.46	33.30	36.41	45.94	50.09	52.91	54.50
11:25	300	68.50	36.06	34.02	29.16	21.84	35.52	46.56	45.39	49.78	55.95
11:35	200	69.75	37.81	32.02	28.00	25.01	36.96	47.98	52.08	53.94	56.74
Test Session 5, 10/3											
12:27	1500	43.69	30.01	28.32	18.02	9.39	20.48	30.68	30.48	32.58	34.29
12:34	1250	49.93	32.30	35.49	23.82	12.81	25.63	36.64	36.67	38.12	40.74
12:42	1000	51.51	36.45	38.52	31.73	19.73	29.05	39.64	40.68	41.64	40.79

Table A.1—continued on next page

Table A.1—continued from previous page

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
12:58	750	52.60	30.25	32.74	27.10	13.51	25.61	37.96	40.62	42.26	41.04
13:06	500	58.44	29.98	29.83	20.05	13.95	27.96	40.91	44.28	45.49	45.82
13:14	300	65.17	38.71	38.93	30.03	21.63	35.99	46.33	51.64	51.46	52.76
13:22	200	73.47	41.82	37.40	26.13	24.82	42.56	52.39	59.67	58.70	60.90
Test Session 6, 10/4											
10:54	1500	37.58	32.30	28.49	23.29	10.80	16.68	27.99	31.01	27.56	26.99
11:05	1250	40.46	36.40	30.81	19.61	14.97	21.84	30.64	33.85	30.71	29.52
11:14	1000	42.80	42.00	28.62	21.12	13.63	25.19	33.61	34.65	32.42	32.19
11:24	750	55.39	39.72	32.61	23.75	18.15	29.43	39.86	46.39	44.26	43.36
11:32	500	61.36	37.43	29.91	28.08	28.15	35.62	44.94	48.44	48.90	49.71
11:39	300	62.85	37.10	26.94	22.98	17.74	35.20	45.88	50.23	50.85	51.05
11:45	200	75.07	40.79	28.11	24.02	27.58	45.30	55.65	59.48	60.85	62.26
Test Session 7, 10/4											
12:49	1500	48.67	29.74	33.96	22.31	15.68	21.88	31.71	38.32	39.62	40.35
12:56	1250	49.16	31.70	37.08	29.33	18.74	25.29	35.03	37.72	37.90	39.54
13:02	1000	57.46	28.56	29.71	16.33	12.05	27.37	41.32	48.16	49.76	47.63
13:10	750	61.09	32.76	35.98	32.46	25.76	34.79	40.45	51.55	52.25	51.47
13:19	500	70.25	33.87	35.66	26.89	19.13	34.37	47.26	56.36	58.47	59.24
13:31	300	75.23	36.06	33.82	27.37	23.34	35.99	46.33	54.33	57.30	59.27
13:47	200	78.63	42.08	38.74	29.94	23.76	37.93	49.70	59.55	63.70	65.39

Table A.1—continued on next page

Table A.1—continued from previous page

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
Test Session 8, 10/10											
14:24	1500	50.50	39.36	32.05	40.88	47.89	38.54	38.14	39.31	44.09	45.60
14:31	1250	53.93	27.81	18.12	24.23	30.29	29.48	39.24	41.10	47.64	47.13
14:37	1000	52.83	30.59	20.39	25.95	32.97	34.71	37.37	38.14	42.28	46.87
14:43	750	52.76	28.69	21.09	23.62	28.82	28.03	35.03	37.04	40.33	44.08
14:50	500	53.06	29.71	14.02	22.95	31.11	32.79	38.48	39.22	41.57	44.81
14:56	300	77.15	37.62	25.99	29.60	32.12	43.92	49.79	56.85	61.16	67.66
15:02	200	73.13	48.64	39.12	43.38	52.81	50.51	49.17	52.44	53.87	59.93
Test Session 9, 10/10											
15:43	1500	37.11	15.12	12.03	16.25	32.79	30.41	24.78	24.47	23.37	32.10
15:50	1250	41.24	11.43	7.32	12.24	28.36	26.80	28.36	26.48	27.97	37.15
16:00	1000	43.57	27.10	23.67	22.94	39.08	31.56	29.10	29.73	28.32	39.30
16:07	750	52.91	27.29	22.96	25.53	40.56	32.33	29.86	29.46	34.33	46.71
16:15	500	48.51	19.66	12.98	15.16	29.69	29.12	31.68	32.88	35.60	42.21
16:22	300	49.82	36.75	24.45	26.90	35.33	32.10	32.21	33.01	32.84	43.66
16:36	200	49.58	31.24	24.21	19.57	33.74	31.98	35.21	33.16	34.85	41.54
Test Session 10, 10/10											
20:09	1500	59.30	27.41	26.47	29.13	39.06	44.41	52.94	50.53	48.33	52.89
20:18	1250	57.19	32.76	35.56	40.90	48.68	40.79	46.68	42.57	44.21	53.72
20:27	1000	64.89	39.86	44.79	38.70	52.49	50.46	53.20	46.83	51.04	60.60

Table A.1—continued on next page

Table A.1—continued from previous page

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
20:37	750	65.62	28.76	26.38	27.85	41.56	45.18	53.66	53.33	52.74	61.69
20:47	500	72.26	36.18	36.95	37.07	48.46	47.19	55.59	54.75	58.08	67.54
20:56	300	76.18	34.54	29.99	30.40	44.92	46.75	57.37	61.80	63.70	67.32
21:05	200	79.68	39.14	32.44	36.48	51.33	47.30	53.21	59.28	62.14	72.75

Table A.2: Measured SPLs in one-third octave bands from 1250–8000 Hz as recorded by the roaming SLM. D is the propagation distance. The columns numbered 1250–8000 are the center frequencies for the SPL (dB) in each one-third octave band.

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
Test Session 1, 9/29											
14:15	200	64.14	55.61	54.81	56.16	54.92	56.12	49.59	40.88	35.38	36.29
14:26	300	61.96	55.49	53.03	53.78	52.00	52.60	45.44	35.85	33.32	32.59
14:35	500	51.63	44.32	43.74	43.95	40.83	39.33	31.92	32.68	24.59	17.49
14:44	1000	44.35	38.06	35.64	34.10	29.38	28.97	30.53	37.44	34.36	22.09
14:51	1500	37.84	29.48	26.75	24.64	25.56	24.79	23.92	25.35	25.25	17.28
14:58	1250	43.89	37.48	34.15	31.03	27.41	26.52	24.89	23.84	23.41	15.07
Test Session 2, 10/2											

Table A.2—continued on next page

Table A.2—continued from previous page

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
11:18	1500	43.41	38.23	35.50	32.23	26.12	22.14	23.47	29.75	36.92	51.57
11:33	1250	43.00	37.00	35.08	32.84	27.28	25.38	20.02	16.03	22.72	41.31
11:45	1000	45.88	39.96	38.62	37.03	32.10	29.75	33.99	45.90	28.69	45.57
11:59	750	51.93	45.99	43.95	44.20	39.51	36.85	29.66	24.89	25.35	42.67
12:09	500	54.59	46.74	46.87	47.02	44.32	42.91	35.77	25.10	33.27	47.39
12:28	300	57.67	50.63	50.11	50.42	48.03	47.42	41.03	31.35	31.03	43.02
12:38	200	60.73	53.76	52.09	52.26	51.42	52.29	46.16	37.74	31.40	40.61
Test Session 3, 10/2											
13:56	1500	50.16	45.32	42.02	35.73	30.89	28.28	27.86	21.78	24.94	38.84
14:07	1250	54.93	49.69	46.42	41.50	36.67	32.75	28.67	29.81	24.77	42.58
14:18	1000	58.64	49.66	47.68	43.70	39.00	32.68	25.18	20.59	20.50	35.14
14:36	750	63.25	58.15	55.74	52.08	48.04	43.60	33.79	24.43	23.18	39.11
14:45	500	69.96	64.57	62.34	59.64	58.54	56.91	47.35	37.86	25.33	36.81
14:54	300	73.69	66.91	66.25	65.36	64.13	61.87	55.26	43.93	36.58	41.70
15:01	200	77.43	71.58	70.43	68.04	67.24	65.31	58.39	47.88	39.66	36.81
Test Session 4, 10/3											
10:38	1500	48.37	41.98	38.30	34.30	29.02	25.95	26.74	26.43	37.00	47.15
10:50	1250	50.47	45.06	42.17	39.36	35.00	34.39	27.75	21.60	30.01	43.07
10:58	1000	53.00	47.50	45.46	43.33	39.61	39.33	37.45	30.55	32.46	53.09
11:07	750	58.30	52.81	51.99	49.07	46.13	43.00	36.15	25.74	27.68	47.06

Table A.2—continued on next page

Table A.2—continued from previous page

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
11:17	500	64.48	57.66	57.61	56.03	54.78	54.47	46.00	35.05	38.14	52.50
11:25	300	68.50	62.63	61.30	59.99	59.82	60.59	53.56	43.18	35.33	48.83
11:35	200	69.75	59.38	60.94	62.40	61.70	63.66	59.31	51.25	46.95	49.33
Test Session 5, 10/3											
12:27	1500	43.69	37.69	35.28	32.14	30.13	30.03	35.52	22.31	21.34	39.96
12:34	1250	49.93	44.52	42.46	39.29	38.41	37.44	35.35	32.09	23.20	41.21
12:42	1000	51.51	47.05	43.55	41.10	36.71	32.95	26.80	25.99	25.76	38.69
12:58	750	52.60	47.52	44.52	43.71	41.66	38.73	35.68	24.01	19.40	34.78
13:06	500	58.44	52.60	50.67	50.31	49.94	48.39	40.32	29.31	20.70	35.61
13:14	300	65.17	59.21	56.60	56.67	57.18	56.19	48.57	37.30	31.03	38.25
13:22	200	73.47	66.04	64.74	66.54	66.32	64.42	57.63	47.50	39.56	38.34
Test Session 6, 10/4											
10:54	1500	37.58	31.27	27.43	26.88	22.40	21.24	15.55	17.82	29.05	18.93
11:05	1250	40.46	34.35	29.45	28.82	26.03	23.63	24.88	26.13	34.72	22.53
11:14	1000	42.80	36.55	33.11	32.24	30.55	27.26	22.99	26.40	35.70	23.21
11:24	750	55.39	49.49	46.57	46.50	45.40	44.09	36.03	25.86	36.13	29.61
11:32	500	61.36	55.67	52.48	52.68	52.79	51.71	43.59	33.66	36.69	35.10
11:39	300	62.85	56.18	52.93	54.26	55.23	54.25	47.18	38.00	37.05	36.24
11:45	200	75.07	68.55	66.24	67.47	67.14	66.57	60.98	52.28	47.15	44.24
Test Session 7, 10/4											

Table A.2—continued on next page

Table A.2—continued from previous page

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
12:49	1500	48.67	45.03	37.75	36.23	32.41	28.04	28.80	41.73	36.99	44.84
12:56	1250	49.16	44.21	40.06	40.00	37.92	36.39	28.82	20.05	30.02	40.49
13:02	1000	57.46	53.36	47.15	44.19	43.25	38.54	32.98	31.03	27.41	38.86
13:10	750	61.09	56.05	53.02	50.23	49.18	43.68	36.36	24.98	28.20	33.46
13:19	500	70.25	66.15	63.02	61.35	58.65	54.66	47.20	35.89	36.81	39.46
13:31	300	75.23	68.05	66.91	68.81	69.04	66.01	58.71	49.92	42.25	49.33
13:47	200	78.63	73.27	70.76	71.14	71.05	67.48	62.36	53.86	44.30	45.03
Test Session 8, 10/10											
14:24	1500	50.50	41.75	39.67	34.03	27.89	24.16	24.47	16.53	20.52	38.13
14:31	1250	53.93	45.71	46.99	43.43	36.53	29.31	26.48	30.29	18.22	35.51
14:37	1000	52.83	45.25	46.63	43.23	38.88	34.92	22.43	27.97	13.45	27.30
14:43	750	52.76	44.49	46.09	45.73	44.10	40.15	30.42	20.72	14.22	36.46
14:50	500	53.06	44.76	46.87	44.54	43.14	40.48	31.47	21.03	15.16	33.78
14:56	300	77.15	68.74	73.30	70.02	65.24	62.14	54.28	41.78	30.54	36.93
15:02	200	73.13	60.31	64.97	66.18	67.16	66.36	60.35	51.41	44.64	40.56
Test Session 9, 10/10											
15:43	1500	37.11	28.37	27.79	23.18	17.23	14.48	16.66	27.35	17.56	35.42
15:50	1250	41.24	32.88	33.50	30.86	24.91	20.41	17.53	9.96	12.35	33.05
16:00	1000	43.57	34.95	35.08	34.47	28.85	25.00	21.48	28.12	13.41	29.04
16:07	750	52.91	44.11	47.41	46.16	41.90	36.32	27.09	21.43	16.40	33.15

Table A.2—continued on next page

Table A.2—continued from previous page

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
16:15	500	48.51	39.95	41.50	40.48	38.74	35.18	26.37	37.08	25.31	27.15
16:22	300	49.82	41.74	42.11	41.53	40.70	38.61	30.51	22.61	14.64	21.26
16:36	200	49.58	41.40	42.39	41.50	40.48	39.33	31.67	22.91	16.35	11.83
Test Session 10, 10/10											
20:09	1500	59.30	50.65	49.81	44.38	40.24	30.96	20.07	20.05	12.26	6.79
20:18	1250	57.19	47.71	48.90	45.08	40.94	35.83	22.65	18.85	12.29	6.84
20:27	1000	64.89	58.81	57.54	48.33	44.32	42.09	29.56	17.01	11.97	6.79
20:37	750	65.62	57.60	56.47	53.20	53.44	47.08	36.75	22.21	10.93	7.58
20:47	500	72.26	67.70	63.99	57.97	55.85	55.50	41.96	29.34	15.06	5.99
20:56	300	76.18	72.52	69.60	63.59	61.49	59.16	51.68	38.53	26.49	12.94
21:05	200	79.68	72.20	75.60	70.61	62.35	65.69	61.60	49.20	44.13	32.73

Table A.3: Measured SPLs in one-third octave bands from 160–1000 Hz as recorded by the stationary SLM. D is the propagation distance. The columns numbered 160–1000 are the center frequencies for the SPL (dB) in each one-third octave band.

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
Test Session 1, 9/29											

Table A.3—continued on next page

Table A.3—continued from previous page

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
14:15	500	52.86	51.64	48.03	43.67	39.31	40.41	46.17	48.05	47.38	49.36
14:26	500	58.36	50.93	47.11	43.16	39.38	42.37	48.68	51.25	51.99	54.15
14:35	500	52.17	50.69	47.03	42.42	38.80	40.09	44.46	45.43	44.55	47.15
14:44	500	55.77	46.67	42.96	38.80	35.42	40.10	47.54	47.85	47.44	50.69
14:51	500	55.97	54.67	51.27	47.50	43.38	42.35	47.09	47.98	48.68	51.11
14:58	500	61.91	41.12	37.28	33.23	32.83	44.36	51.28	53.96	54.95	57.17
Test Session 2, 10/2											
11:18	500	58.28	43.80	40.77	37.64	36.06	43.14	50.18	51.76	51.83	54.38
11:33	500	63.00	36.30	33.39	28.49	30.81	43.82	53.11	54.42	57.07	59.83
11:45	500	52.06	39.89	35.67	32.16	29.87	35.59	42.49	41.98	42.75	46.51
11:59	500	60.53	46.74	46.29	39.50	36.62	43.04	49.19	49.99	50.34	53.49
12:09	500	55.04	44.14	39.96	37.44	34.41	39.00	45.04	46.62	46.31	48.72
12:28	500	57.84	49.71	46.42	43.52	40.32	43.45	48.88	47.14	49.47	52.28
12:38	500	51.97	47.33	43.96	40.34	37.93	39.74	44.16	43.13	42.67	45.83
Test Session 3, 10/2											
13:56	500	65.98	48.58	45.80	42.10	38.64	44.44	52.66	54.92	55.76	59.33
14:07	500	65.67	46.88	43.54	40.21	37.64	44.53	52.79	54.55	55.32	60.28
14:18	500	69.28	49.14	45.76	41.51	37.99	50.51	59.56	62.14	62.30	64.24
14:36	500	66.17	39.94	36.78	34.74	34.74	46.66	53.96	56.81	56.20	59.23
14:45	500	70.52	35.64	30.82	27.68	32.53	48.67	58.31	63.07	62.98	64.89

Table A.3—continued on next page

Table A.3—continued from previous page

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
14:54	500	69.70	48.15	44.79	39.78	38.37	49.12	58.30	60.02	61.63	63.76
15:01	500	67.64	39.39	35.08	31.03	31.70	46.85	56.80	60.72	59.59	61.58
Test Session 4, 10/3											
10:38	500	65.05	42.72	38.92	36.48	34.72	41.10	48.96	53.05	54.05	57.33
10:50	500	64.60	37.59	36.14	33.06	32.10	41.59	51.07	53.53	55.93	59.45
10:58	500	63.09	45.82	43.52	41.20	39.44	43.34	49.92	52.53	52.97	56.47
11:07	500	65.89	49.52	46.40	44.52	44.36	46.82	53.49	56.80	56.22	59.70
11:17	500	65.08	48.64	45.73	42.97	40.66	44.93	51.86	55.01	54.95	57.68
11:25	500	60.50	39.94	36.74	35.37	31.76	40.42	46.35	49.48	49.46	54.02
11:35	500	62.10	42.75	39.96	36.88	34.26	40.38	46.85	49.25	48.96	52.69
Test Session 5, 10/3											
12:27	500	61.82	31.57	27.40	23.58	27.11	39.77	47.28	47.96	48.37	53.23
12:34	500	63.81	35.73	32.92	29.64	29.36	41.69	48.91	49.90	51.42	54.23
12:42	500	54.74	30.18	26.33	22.55	22.56	34.64	41.65	41.99	41.43	45.20
12:58	500	60.93	28.70	24.82	20.79	24.17	38.07	44.95	46.31	47.44	51.55
13:06	500	59.11	26.93	21.21	18.32	21.32	34.63	42.56	43.22	45.34	49.36
13:14	500	61.02	33.22	31.44	31.35	27.45	36.68	44.89	45.94	46.50	50.47
13:22	500	64.65	34.42	29.02	23.86	25.32	36.94	45.23	47.99	50.85	54.73
Test Session 6, 10/4											
10:54	500	51.13	34.06	31.07	25.98	19.38	29.51	37.41	39.35	37.86	40.07

Table A.3—continued on next page

Table A.3—continued from previous page

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
11:05	500	47.32	32.87	27.50	24.08	23.39	28.46	34.85	33.60	34.38	38.09
11:14	500	50.37	37.05	24.97	17.08	20.06	32.16	38.52	38.65	39.15	41.13
11:24	500	61.97	36.65	32.19	27.33	29.23	39.95	47.35	47.19	48.34	52.60
11:32	500	61.84	32.46	27.92	29.81	35.53	40.81	48.06	48.14	48.72	52.08
11:39	500	58.86	28.61	23.51	21.06	22.74	35.68	43.16	43.25	44.10	48.01
11:45	500	61.81	32.60	29.02	24.66	28.09	41.68	48.54	47.07	47.95	52.61
Test Session 7, 10/4											
12:49	500	71.22	38.24	33.03	28.57	27.46	39.60	49.42	52.71	56.27	63.74
12:56	500	71.42	42.11	38.58	34.34	32.18	39.36	50.74	56.10	60.04	66.53
13:02	500	68.72	36.54	31.83	26.10	23.99	38.44	48.23	54.06	56.53	61.31
13:10	500	68.44	39.34	35.56	33.00	33.30	39.43	48.27	54.46	58.39	62.39
13:19	500	70.70	39.88	35.13	31.06	27.07	40.42	51.53	55.93	58.73	62.92
13:31	500	72.41	39.61	34.52	32.67	27.07	38.58	48.78	53.10	55.57	61.23
13:47	500	70.69	41.07	36.00	31.65	26.93	34.11	43.62	48.18	52.53	59.66
Test Session 8, 10/10											
14:24	500	70.66	39.67	36.23	36.70	33.07	29.64	41.87	49.40	56.84	62.54
14:31	500	66.16	32.13	26.76	21.00	16.07	23.87	36.48	42.01	49.60	55.75
14:37	500	57.75	31.37	24.00	19.70	23.00	32.65	34.55	34.95	40.14	45.09
14:43	500	57.27	30.15	25.07	19.29	11.53	16.99	29.43	33.91	39.64	44.17
14:50	500	53.01	31.36	25.76	21.51	17.10	18.78	30.16	33.22	37.45	40.96

Table A.3—continued on next page

Table A.3—continued from previous page

Time	D (m)	L_{pEQL} (dB)	160	200	250	315	400	500	630	800	1000
14:56	500	70.23	30.42	29.10	26.54	19.21	22.64	35.41	42.64	51.55	58.85
15:02	500	62.33	45.81	41.77	36.87	37.01	35.95	34.12	35.85	40.08	46.02
Test Session 9, 10/10											
15:43	500	47.82	24.48	18.43	12.24	12.01	14.68	24.73	26.89	31.63	35.19
15:50	500	51.51	27.99	24.49	21.73	17.77	18.17	26.22	28.96	35.05	38.86
16:00	500	54.25	36.76	32.95	28.07	24.19	19.69	27.84	32.24	36.49	42.80
16:07	500	58.07	32.49	25.79	23.70	20.49	20.87	28.01	31.02	39.87	44.07
16:15	500	48.57	27.93	22.45	17.37	13.14	13.00	24.95	25.97	35.70	36.22
16:22	500	45.50	45.02	31.78	30.69	21.80	18.45	22.29	22.21	30.57	33.05
16:36	500	42.17	36.98	33.07	28.53	23.98	20.57	21.10	20.31	26.35	29.26
Test Session 10, 10/10											
20:09	500	70.19	34.89	28.81	24.35	23.80	26.81	37.86	44.46	49.10	57.44
20:18	500	72.29	38.00	36.20	36.59	33.54	30.13	41.43	43.33	55.06	62.85
20:27	500	71.51	46.11	49.39	40.29	36.02	31.20	38.46	41.63	51.06	59.99
20:37	500	72.41	31.88	29.11	26.08	22.32	29.64	44.20	50.03	56.42	63.39
20:47	500	72.86	40.18	36.55	33.28	32.90	36.11	50.29	50.69	59.17	66.55
20:56	500	74.79	34.62	30.31	29.15	27.59	37.13	50.85	59.56	62.75	67.00
21:05	500	74.20	30.72	35.23	31.20	30.35	31.47	45.97	54.04	61.19	67.19

Table A.4: Measured SPLs in one-third octave bands from 1250–8000 Hz as recorded by the stationary SLM. D is the propagation distance. The columns numbered 1250–8000 are the center frequencies for the SPL (dB) in each one-third octave band.

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
					Test Session 1, 9/29						
14:15	500	52.86	50.06	48.73	47.01	43.05	39.35	28.50	23.01	27.80	42.89
14:26	500	58.36	54.97	53.49	51.72	48.07	45.64	33.47	29.81	24.94	31.08
14:35	500	52.17	47.76	47.15	46.85	43.41	39.90	29.57	28.92	19.52	17.04
14:44	500	55.77	51.77	51.09	49.59	46.97	42.46	31.81	29.11	18.76	13.15
14:51	500	55.97	51.59	49.14	49.34	46.71	43.42	33.75	25.69	21.88	17.86
14:58	500	61.91	57.63	54.86	54.04	51.25	47.51	36.10	28.51	21.00	10.57
					Test Session 2, 10/2						
11:18	500	58.28	56.23	54.24	52.98	51.39	49.62	39.76	33.36	31.54	45.83
11:33	500	63.00	60.31	59.07	57.89	55.82	53.32	42.27	31.03	31.59	46.62
11:45	500	52.06	48.75	46.08	45.33	43.20	41.18	35.14	42.17	31.73	44.91
11:59	500	60.53	56.04	55.52	55.51	51.86	48.49	39.05	27.59	32.27	44.78
12:09	500	55.04	49.39	49.30	48.91	46.23	43.77	34.83	25.63	32.65	46.56
12:28	500	57.84	53.40	52.14	51.41	47.28	45.23	36.59	28.18	30.15	44.22
12:38	500	51.97	47.43	45.75	44.54	41.86	39.78	31.78	23.56	27.89	43.49

Table A.4—continued on next page

Table A.4—continued from previous page

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
Test Session 3, 10/2											
13:56	500	65.98	61.33	60.73	59.70	56.16	52.13	41.79	31.36	27.24	38.96
14:07	500	65.67	61.14	60.05	58.29	54.60	51.97	42.98	31.82	23.46	38.22
14:18	500	69.28	64.75	62.11	59.97	55.99	53.15	42.94	30.84	22.69	39.52
14:36	500	66.17	61.27	60.28	58.96	55.75	53.12	42.00	37.56	23.36	39.17
14:45	500	70.52	65.82	63.16	61.05	58.67	56.28	45.06	36.66	23.97	35.84
14:54	500	69.70	64.74	62.44	60.99	58.49	54.92	45.40	35.31	22.58	37.70
15:01	500	67.64	62.81	59.38	58.35	53.33	50.81	38.87	38.30	22.27	36.54
Test Session 4, 10/3											
10:38	500	65.05	61.06	60.73	60.72	57.50	54.90	46.52	40.10	36.30	44.35
10:50	500	64.60	61.57	58.77	57.92	55.14	53.54	44.62	41.34	39.74	45.57
10:58	500	63.09	58.69	57.48	56.80	54.61	52.72	42.55	40.06	34.37	44.78
11:07	500	65.89	62.03	60.60	59.20	54.91	52.52	42.77	33.50	39.66	49.65
11:17	500	65.08	59.98	59.20	58.46	56.54	54.85	44.10	34.68	35.24	48.35
11:25	500	60.50	55.84	53.29	53.74	51.62	49.67	40.77	37.39	32.40	43.18
11:35	500	62.10	55.67	56.09	56.65	54.67	53.65	43.58	33.22	38.21	43.16
Test Session 5, 10/3											
12:27	500	61.82	55.14	53.07	53.16	50.86	48.97	41.00	29.03	22.86	39.40
12:34	500	63.81	57.28	55.88	54.19	52.46	51.31	42.70	36.22	25.34	42.67
12:42	500	54.74	46.77	45.25	45.73	43.63	42.78	36.29	34.31	23.21	40.35

Table A.4—continued on next page

Table A.4—continued from previous page

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
12:58	500	60.93	53.10	52.29	51.29	49.05	49.13	41.67	42.96	28.95	40.50
13:06	500	59.11	51.58	49.93	50.04	48.65	47.95	40.04	30.49	22.51	38.96
13:14	500	61.02	53.15	52.36	51.48	48.97	48.77	40.64	38.56	25.71	40.92
13:22	500	64.65	56.61	56.78	56.42	53.90	51.21	42.72	39.14	25.35	39.76
Test Session 6, 10/4											
10:54	500	51.13	42.40	42.86	43.19	41.48	41.86	37.14	39.42	37.65	23.88
11:05	500	47.32	39.95	38.79	37.65	36.56	36.09	34.85	39.55	38.09	28.69
11:14	500	50.37	42.59	41.43	39.72	38.59	38.16	35.99	40.24	38.92	30.55
11:24	500	61.97	54.14	53.00	52.82	51.23	51.28	42.88	39.18	40.63	36.68
11:32	500	61.84	53.79	52.13	51.43	51.05	50.51	42.32	33.05	37.63	35.56
11:39	500	58.86	49.93	49.70	49.42	48.22	48.08	40.59	37.89	38.79	35.94
11:45	500	61.81	53.71	51.53	51.35	50.25	49.79	41.68	38.57	35.93	40.07
Test Session 7, 10/4											
12:49	500	71.22	67.51	63.88	57.17	57.08	58.09	46.41	36.37	43.16	42.77
12:56	500	71.42	67.79	62.26	58.18	56.87	54.96	45.17	36.49	41.48	43.16
13:02	500	68.72	64.45	61.86	55.01	53.55	52.53	42.27	37.35	40.50	43.54
13:10	500	68.44	63.31	59.23	56.04	55.11	53.54	45.21	37.96	41.56	43.25
13:19	500	70.70	65.01	63.47	60.89	56.81	55.33	45.71	37.19	38.70	42.05
13:31	500	72.41	64.07	61.93	60.09	55.91	54.23	45.49	39.23	37.43	45.47
13:47	500	70.69	62.76	60.51	57.65	53.83	52.64	44.49	41.24	36.67	45.67

Table A.4—continued on next page

Table A.4—continued from previous page

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
Test Session 8, 10/10											
14:24	500	70.66	61.65	58.27	57.55	56.56	53.41	43.75	31.53	21.34	33.68
14:31	500	66.16	57.07	55.24	54.53	57.37	55.13	46.69	32.83	22.56	38.32
14:37	500	57.75	46.85	47.22	48.09	48.01	46.14	39.97	28.18	19.77	33.18
14:43	500	57.27	45.09	45.87	47.44	50.25	49.38	41.01	29.09	19.61	33.04
14:50	500	53.01	43.46	42.34	42.71	43.49	42.27	34.70	25.53	18.84	35.56
14:56	500	70.23	61.94	61.48	58.68	61.28	59.43	50.83	38.62	24.99	39.12
15:02	500	62.33	47.88	49.97	52.81	56.60	55.64	48.50	38.13	23.34	36.18
Test Session 9, 10/10											
15:43	500	47.82	37.89	37.63	37.34	38.36	36.68	29.55	40.31	27.71	40.41
15:50	500	51.51	40.94	41.17	41.74	42.26	39.88	32.27	39.21	27.64	38.91
16:00	500	54.25	44.81	43.00	43.02	44.31	41.26	32.85	39.48	27.55	41.59
16:07	500	58.07	48.53	49.08	48.94	50.72	46.65	38.38	41.93	28.75	34.62
16:15	500	48.57	38.59	37.65	37.93	39.86	37.28	30.78	40.30	31.18	31.81
16:22	500	45.50	35.65	34.17	35.00	35.41	33.01	27.03	40.17	30.28	27.82
16:36	500	42.17	30.63	28.56	29.07	29.91	27.77	25.39	39.44	25.94	20.59
Test Session 10, 10/10											
20:09	500	70.19	62.18	63.18	62.67	57.21	56.13	53.90	37.19	28.68	15.54
20:18	500	72.29	66.33	63.30	63.22	61.79	57.22	50.65	37.28	25.74	12.31
20:27	500	71.51	64.26	64.48	64.11	61.89	59.53	50.16	36.28	29.13	13.05

Table A.4—continued on next page

Table A.4—continued from previous page

Time	D (m)	L_{pEQL} (dB)	1250	1600	2000	2500	3150	4000	5000	6300	8000
20:37	500	72.41	67.08	61.02	55.47	61.70	62.07	51.66	39.59	32.49	17.02
20:47	500	72.86	66.82	59.85	58.50	58.17	58.45	49.36	35.08	22.81	12.34
20:56	500	74.79	68.33	63.32	59.80	59.90	58.94	50.34	35.70	22.76	12.56
21:05	500	74.20	65.14	62.22	57.84	60.78	58.36	49.57	36.83	26.16	12.24

Table A.5: Measured data from the weather stations. T and W denote the ten-minute averaged temperature and wind speed along the direction of propagation, respectively. Subscripts S, F, and T indicate data from the source, field, and tower locations, respectively. P is the pressure and RH is the relative humidity.

Time	T_S (°C)	T_F (°C)	T_T (°C)	W_S (m/s)	W_F (m/s)	W_T (m/s)	P_S (hPa)	RH_S (%)
Test Session 1, 09/29								
14:15	12.1	11.9	11.2	−2.95	−1.83	−4.12	944.0	55
14:26	11.4	11.4	10.8	−2.99	−2.25	−5.11	944.1	58
14:35	10.7	11.1	10.5	−3.39	−2.29	−5.41	944.5	60
14:44	10.7	10.8	10.2	−3.11	−3.80	−5.40	944.5	60
14:51	10.6	10.4	9.7	−3.09	−3.23	−5.40	944.7	67
14:58	10.2	10.0	9.6	−2.63	−2.85	−5.43	945.0	68

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Table A.5—continued from previous page

Time	T_S (°C)	T_F (°C)	T_T (°C)	W_S (m/s)	W_F (m/s)	W_T (m/s)	P_S (hPa)	RH_S (%)
Test Session 2, 10/2								
11:18	14.5	15.4	15.0	−0.29	0.05	−0.92	954.9	68
11:33	15.2	15.8	15.1	−0.84	−2.32	−3.86	954.8	69
11:45	15.3	15.9	15.2	−1.56	−0.60	−3.35	954.9	65
11:59	15.8	16.3	15.5	−0.80	−1.90	−3.80	954.9	64
12:09	16.2	16.5	15.8	−0.98	−1.80	−2.86	954.9	63
12:28	16.9	17.1	16.1	−1.59	−3.09	−5.47	954.8	57
12:38	17.1	17.2	16.4	−1.43	−1.69	−4.03	954.7	59
Test Session 3, 10/2								
13:56	19.5	19.1	17.6	2.47	4.19	5.94	954.7	55
14:07	20.0	19.0	18.3	1.70	1.11	2.65	953.6	52
14:18	20.4	19.3	18.3	0.09	3.98	6.62	953.6	50
14:36	20.4	19.9	18.9	−0.14	1.94	1.29	953.5	47
14:45	20.4	19.9	19.0	−0.07	1.71	−0.24	953.5	46
14:54	20.8	19.9	18.9	−0.05	2.60	0.12	953.4	47
15:01	20.8	20.0	19.1	0.34	2.28	2.71	953.1	44
Test Session 4, 10/3								
10:38	21.8	20.4	20.3	1.19	0.61	0.84	953.7	55
10:50	21.3	20.4	20.0	1.32	−0.11	0.00	953.7	57
10:58	22.3	21.0	20.6	1.09	0.75	0.40	953.6	55

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Table A.5—continued from previous page

Time	T_S (°C)	T_F (°C)	T_T (°C)	W_S (m/s)	W_F (m/s)	W_T (m/s)	P_S (hPa)	RH_S (%)
11:07	22.9	21.1	20.8	0.13	−0.09	0.57	953.6	55
11:17	23.3	21.5	21.0	0.22	0.26	0.22	953.5	51
11:25	21.7	20.8	20.4	1.28	−0.51	−0.82	953.5	56
11:35	21.4	20.4	20.1	−0.01	−0.20	0.54	953.6	57
Test Session 5, 10/3								
12:27	22.0	21.5	21.0	−1.00	0.12	−0.84	952.4	56
12:34	22.5	22.0	21.2	−1.15	0.01	−0.54	952.1	58
12:42	22.7	22.1	21.2	−0.96	−0.93	−2.09	952.0	53
12:58	23.6	22.4	21.6	−0.20	−1.66	−1.37	951.8	53
13:06	23.2	22.5	21.9	−0.15	−0.41	−0.43	951.8	51
13:14	23.3	22.5	22.1	−0.32	0.47	0.33	951.8	50
13:22	22.5	22.2	21.8	0.23	0.77	1.15	951.6	51
Test Session 6, 10/4								
10:54	18.1	17.3	16.9	−0.13	−0.11	−0.48	950.0	89
11:05	18.5	17.4	17.0	−0.44	−0.60	−1.16	949.8	87
11:14	19.1	17.6	17.2	−0.08	−0.28	−0.60	949.8	87
11:24	19.7	18.0	17.6	−0.56	−0.18	−0.73	949.6	85
11:32	20.1	18.4	18.0	0.11	−0.92	−1.06	949.4	84
11:39	20.7	18.7	18.4	−0.12	−1.07	−0.61	949.4	82
11:45	21.2	19.3	19.0	−0.24	−0.49	−0.62	949.5	80

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Table A.5—continued from previous page

Time	T_S (°C)	T_F (°C)	T_T (°C)	W_S (m/s)	W_F (m/s)	W_T (m/s)	P_S (hPa)	RH_S (%)
Test Session 7, 10/4								
12:49	20.3	20.1	19.6	1.96	2.46	3.37	949.8	80
12:56	20.3	20.0	19.5	2.15	2.81	3.44	949.8	81
13:02	20.3	19.9	19.5	2.30	2.92	3.33	949.8	79
13:10	20.3	20.0	19.7	2.03	1.61	2.76	949.7	79
13:19	20.6	20.2	19.8	2.03	2.55	3.53	949.5	77
13:31	21.3	20.5	20.0	1.44	2.91	3.64	949.2	77
13:47	22.1	21.3	20.7	1.63	2.06	3.92	948.7	75
Test Session 8, 10/10								
14:24	20.8	20.3	19.6	2.21	1.66	2.72	947.4	47
14:31	20.7	20.1	19.6	1.63	2.03	3.65	947.3	50
14:37	21.3	20.9	20.0	0.92	1.59	2.79	947.3	47
14:43	22.5	21.6	20.4	0.99	0.98	0.78	947.2	45
14:50	23.2	21.3	20.3	0.76	1.20	0.89	947.2	43
14:56	22.4	21.0	20.2	−1.92	−0.32	−0.14	947.0	45
15:02	21.9	21.2	20.3	−1.37	−0.83	−0.88	946.8	46
Test Session 9, 10/10								
15:43	22.8	22.9	22.0	−0.11	−0.62	0.01	947.0	45
15:50	23.1	22.7	21.6	−0.10	−0.63	0.07	947.1	44
16:00	22.5	22.5	21.6	−0.03	0.03	−0.26	947.0	45

Table A.5—continued on next page

Table A.5—continued from previous page

Time	T_S (°C)	T_F (°C)	T_T (°C)	W_S (m/s)	W_F (m/s)	W_T (m/s)	P_S (hPa)	RH_S (%)
16:07	22.3	21.9	21.1	0.10	−0.40	−0.57	947.1	47
16:15	21.7	21.2	20.7	0.58	−0.53	−1.03	947.3	48
16:22	21.3	20.9	20.2	−0.46	−1.21	−2.32	947.3	49
16:36	20.5	19.7	19.4	−2.31	−1.92	−3.35	947.4	50
Test Session 10, 10/10								
20:09	14.5	15.0	15.3	0.00	0.00	0.00	947.4	77
20:18	14.3	14.8	15.1	0.00	0.00	0.00	947.3	77
20:27	14.3	14.5	15.0	0.00	0.00	0.00	947.4	78
20:37	14.1	14.5	15.1	0.00	0.16	−0.02	947.2	78
20:47	13.8	14.4	15.0	0.00	0.00	0.00	947.2	78
20:56	13.8	13.9	14.6	0.00	0.00	0.00	947.2	77
21:05	13.6	13.9	14.9	0.00	0.00	0.00	947.2	77

Appendix B

Matlab code

B.1 Atmospheric absorption code

absorption.m

```
function [alpha]=absorption(f,temp,ps,hr)

%  Created by Amanda Hanford, April, 2005
%  Edited by Jason Bostron, 2007-2008
%  Calculates the absorption, alpha (db / 100 m), based on the
    % pressure, ps (atm),
    % temperature, temp (C) and
    % relative humditiy, hr (%) for
    % a frequency vector, f (Hz)

% Equations from:
    % Bass, et al., ``Atmospheric absorption of sound: Further
     % developments'' JASA 97(1) 680-683 (1995).
    % Bass, et al., ``Erratum: Atmospheric absorption of sound:
     % Further developments [J. acoust. Soc. Am. 97, 680-683
     % (1995),],'' JASA 99(2) 1259 (1996).

t0=293.15;  % reference atmopsheric temperature
```

```
t01=273.16; % triple-point isotherm temperature
t=t01+temp; % convert to a temperature in K
    %equation 1 from bass, (saturation vapor pressure)
lgpsat=10.79586*(1-(t01/t))-5.02808*log10(t/t01)+1.50474...
  *10^-4*(1-10^(-8.29692*((t/t01)-1)))-4.2873*10^-4...
  *(1-10^(-4.76955*((t01/t)-1)))-2.2195983;
ps0=1; % reference value of atmospheric pressure in atms
psat=ps0*10^lgpsat; % saturation vapor pressure

for i = 1:length(hr);
   %equation 6 from bass, (absolute humidity in %)
   h = hr(i)./ps.*psat;
   %equation 4 from bass, (relaxation frequency in oxygen)
   Fro = (1/ps0).*(24+4.04*10^4.*h.*((0.02+h)./(0.391+h)));
   %equation 5 from bass, (relaxation frequency in nitrogen)
   Frn = (1/ps0).*(t01./t).^.5.*...
     (9+280.*h.*exp(-4.17.*((t0./t).^(1/3)-1)));
   F = f./ps;
   %equation 3 from bass, erratum,
    % (absorption, a, has units of nepers / m)
   a(i,:)=ps.*F.*F.*( 1.84*10^-11.*((t./t0).^.5)*ps0 ...
     +((t./t0).^-(5/2)).*(0.01275.*(exp(-2239.1./t)...
     ./(Fro+(F.*F./Fro))) + 0.1068.*(exp(-3352./t)...
     ./(Frn+(F.*F./Frn)))));
   alpha(i,:)=20.*log10(exp(1)).*a(i,:).*100;
    % (has units of dB / 100 m)
end
```

B.2 Ground effect code

DBGroundImpedance.m

```
function deltaL=DBGroundImpedance(zs,zr,EFR,R,temp,f)
```

```
% Created by Andrew Barnard
% Lightly edited and heavily commented by Jason Bostron, 2008
% This function calls 'calcFd.m', which in turn calls 'erfz.m'
% Calculates the change in SPL (dB), given:
    % source height, zs (m)
    % receiver height, zr (m)
    % range, R (m)
    % effective flow resistivity, EFR (kPa*s/m^2) and
    % temperature, temp (C) for
    % a frequency vector, f (Hz)

% Equations from:
    % Erik M. Salomons. computational atmospheric acoustics.
      % Kluwer Academic Publishers, Boston: 2001.
% and the equation for impedance, Z, is from:
    % M. E. Delany and E. N. Bazley, ``Acoustical properties
      % of fibrous absorbent materials,'' Appl. Acoust. 3(2),
      % 105-116 (1970).


% Compute Ground Impedance (Delany & Bazley Model)
R1=sqrt(R.^2+abs(zs-zr).^2); R2=sqrt(R.^2+abs(zs+zr).^2);
  % based on geometry in Figure 3.2, given on pg 23
theta=atan(R./(zr+zs)); % angle of reflection with ground
c0=331.5;  % speed of sound (m/s) at 273.15 (K)
temp=temp+273.15; % conversion of temperature from (C) to (K)
c=c0*sqrt(temp./273);
  % calculation of sound speed at the given temperature
k=2.*pi.*f./c; % calculatin of the wavenumber, k (1/m)

flowR=EFR*1000; % conversion of units to (Pa*s/m^2)
Z=(1+0.0511.*(flowR./f).^0.75)+j*(0.0768.*(flowR./f).^0.73);
```

```
  % impedance
Rp=(Z.*cos(theta)-1)./(Z.*cos(theta)+1); % pg 134, (D.59)
d=sqrt(j.*k.*R2./2).*(1./Z+cos(theta)); % pg 133, (D.57)
Fd=calcFd(d); % see function 'calcFd.m'
Q=Rp+(1-Rp).*Fd; % pg 134, (D.58)
deltaL=10.*log10(abs(1+Q.*(R1./R2).*exp(j.*k.*(R2-R1))).^2);
  % pg 25, (3.7)
```

calcFd.m

```
function Fd=calcFd(d)

% Created by Andrew Barnard
% Lightly edited and commented by Jason Bostron, 2008
% This function calls 'erfz.m'
% Calculates equation (D.60) given in Salomons' book, pg 134

% Find Fd by using erfz when abs(d)<=10
   % and approximation when abs(d)>10
[val,lowind]=min(abs(abs(d)-10));
if lowind>1
  if abs(d(lowind))>10 & lowind~=1
    lowind=lowind-1;
  end
    Fd=zeros(size(d));
    ERFCC=1-erfz(-j.*d(1:lowind)); % see 'erfz.m'
    e=exp(-d(1:lowind).^2); % part of the variables in (D.60)
    Fd(1:lowind)=1+j.*d(1:lowind).*sqrt(pi).*e.*ERFCC;
      % pg 134, (D.60)
end
if lowind<length(d)
  for ii=lowind+1:length(d)
    totalSum=0;
```

```
    numVec=[];
    for m=1:12 % summation given for large d on pg 134, (D.63)
      numVec=[numVec,2*m-1];
      summand=prod(numVec)./(2.*d(ii).^2).^m;
      totalSum=totalSum+summand;
    end
    H=((-imag(d(ii)))>=0); % Heaviside step function
    Fd(ii)=2.*j.*d(ii).*sqrt(pi).*exp(-d(ii).^2).*H-totalSum;
      % (D.64)
  end
end
```

erfz.m

```
function f = erfz(zz)

% From Matlab file exchange: <http://www.mathworks.com
  % /matlabcentral/fileexchange
  % /loadFile.do?objectId=3574&objectType=file>

%ERFZ  Error function for complex inputs
%   f = erfz(z) is the error function for the elements of z.
%   Z may be complex and of any size.
%   Accuracy is better than 12 significant digits.
%
%   Usage:  f = erfz(z)
%
%   Ref: Abramowitz & Stegun section 7.1
%   equations 7.1.9, 7.1.23, and 7.1.29
%
%   Tested under version 5.3.1
%
%   See also erf, erfc, erfcx, erfinc, erfcore
```

```
%   Main author Paul Godfrey <pgodfrey@intersil.com>
%   Small changes by Peter J. Acklam <jacklam@math.uio.no>
%   09-26-01

   error(nargchk(1, 1, nargin));

   % quick exit for empty input
   if isempty(zz)
      f = zz;
      return;
   end

   twopi = 2*pi;
   sqrtpi=1.772453850905516027298;

   f = zeros(size(zz));
   ff=f;

   az=abs(zz);
   p1=find(az<=8);
   p2=find(az> 8);

if ~isempty(p1)
   z=zz(p1);

   nn = 32;

   x = real(z);
   y = imag(z);
   k1 = 2 / pi * exp(-x.*x);
   k2 = exp(-i*2*x.*y);
```

```
   s1 = erf(x);

   s2 = zeros(size(x));
   k = x ~= 0;          % when x is non-zero
   s2(k) = k1(k) ./ (4*x(k)) .* (1 - k2(k));
   k = ~k;              % when x is zero
   s2(k) = i / pi * y(k);

   f = s1 + s2;

   k = y ~= 0;          % when y is non-zero
   xk = x(k);
   yk = y(k);

   s5 = 0;
   for n = 1 : nn
      s3 = exp(-n*n/4) ./ (n*n + 4*xk.*xk);
      s4 = 2*xk - k2(k).*(2*xk.*cosh(n*yk) - i*n*sinh(n*yk));
      s5 = s5 + s3.*s4;
   end
   s6 = k1(k) .* s5;
   f(k) = f(k) + s6;
   ff(p1)=f;
end

if ~isempty(p2)
   z=zz(p2);
   pn=find(real(z)<0);

   if ~isempty(pn)
      z(pn)=-z(pn);
   end
```

```
   nmax=193;
   s=1;
   y=2*z.*z;
   for n=nmax:-2:1
       s=1-n.*(s./y);
   end

   f=1.0-s.*exp(-z.*z)./(sqrtpi*z);

   if ~isempty(pn)
      f(pn)=-f(pn);
   end

   pa=find(real(z)==0);
%  fix along i axis problem
   if ~isempty(pa)
      f(pa)=f(pa)-1;
   end

   ff(p2)=f;
end

f=ff;

return

   %a demo of this function is
   x = -4:0.125:4;
   y = x;
   [X, Y] = meshgrid(x,y);
   z = complex(X, Y);
   f = erfz(z);
   af = abs(f);
```

```
%let's truncate for visibility
p = find(af > 5);
af(p) = 5;
mesh(x, y, af);
view(-70, 40);
rotate3d on;

return
```

B.3 Intelligibility code

CalcSII.m

```
function SII=CalcSII(SPL,background,f)

% Created by Andrew Barnard
% Commented by Jason Bostron, 2008
% Calculates the speech intelligibility index, SII, given:
    % the sound pressure level, SPL (dB),
    % the background noise sound pressure level (dB)
    % both are vectors of the center frequencies of one-third
    % octave bands given by the frequency vector, f (Hz)

% Given variables from ANSI S3.5-1997:
    % XXref is the ``Reference internal noise spectrum level''
    % UU is the ``Standard speech spectrum level
      % for normal vocal effort''
    % BA is the ``Band width adjustment''
      % the above three items are from Table 3,
      % for oto-band calculations
    % II is the ``band importance function'' for
      % ``short passages'' (Table B.2)
```

```
% Equations from:
    % Methods for Calculation of the Speech Intelligibility
      % Index. American National Standards Institute. ANSI
      % S3.5-1997. Acoustical Society of America, New York: 1997.


% Calculate SII from from the source and noise SPL spectra:
XXref=[0.6,-1.7,-3.9,-6.1,-8.2,-9.7,-10.8,-11.9,-12.5,-13.5,...
    -15.4,-17.7,-21.2,-24.2,-25.9,-23.6,-15.8,-7.1];
TT=zeros(1,18)-1.7;
  % sect 5.1.5, (-1.7 for binaural listening, instead of monaural)
XX=XXref+TT; % eqn (10)
UU=[32.41,34.48,34.75,33.98,34.59,34.27,32.06,28.3,25.01,23,...
    20.15,17.32,13.18,11.55,9.33,5.31,2.59,1.13];
II=[.0114,.0153,.0179,.0558,.0898,.0944,.0709,.066,.0628,.0672,...
    .0747,.0755,.082,.0808,.0483,.0453,.0274,.0145];
BA=[15.65,16.65,17.65,18.65,19.65,20.65,21.65,22.65,23.65,...
    24.65,25.65,26.65,27.65,28.65,29.65,30.65,31.65,32.65];
NN=background-BA; % eqn (18), (note NN = N', etc.)
EE=SPL-BA; % eqn (17)
VV=EE-24; % eqn (5)
BB=max(NN,VV); % section 4.3.2.2
CC=-80+0.6.*(BB+10.*log10(f)-6.353); % eqn (7)
ZZ(1)=BB(1); % section 4.3.2.4
for jj=2:18 % section 4.3.2.5, eqn (9)
  ZZ(jj)=10.*log10(10.^(NN(jj)./10)+sum(10.^...
  (0.1.*(BB(1:jj-1)+3.32.*CC(1:jj-1)...
  .*log10(0.89.*f(jj)./f(1:jj-1))))));
end
DD=max(ZZ,XX); % section 4.5
LL=1-(EE-UU-10)./160; % eqn (11)
inds=find(LL>1); LL(inds)=1;
  % limits defined by section 4.6 as <= 1
```

```
KK=(EE-DD+15)./30; % eqn (12)
indsL=find(KK<0); indsH=find(KK>1); KK(indsL)=0; KK(indsH)=1;
  % limits defined by section 4.7.1 as from 0 to 1
AA=LL.*KK; % eqn (13)
SII=sum(II.*AA); % eqn (1) or (14)
```

CalcPercentWords.m

```
function Pwords=calcPercentWords(SII,type)

% Created by Andrew Barnard
% Small edits and comments by Jason Bostron, 2008
% Estimates the percent of words understood, PWU, given
    % the speech intelligibility index, SII, and
    % the type of message, known or unknown
  % based on the figure in ANSI S3.5-1969

% Equations from:
    % Methods for Calculation of the Articulation Index.
      % American National Standards Institute. ANSI S3.5-1969.
      % Acoustical Society of America, New York: 1969.


% Estimate the percent of words understood from the SII:
switch type
  case 'known' % transfer function for known messages
   AIplot_known_SII=[0,.04,.07,.095,.12,.14,...
     .16,.18,.21,.27,.4,.48,.68,1];
  case 'unknown' % transfer function for unknown messages
   AIplot_known_SII=[0,.065,.11,.142,.173,.20,...
     .23,.26,.30,.36,.44,.5,.7,1];
end
AIplot_known_words=[0,10,20,30,40,50,60,70,80,90,96,97,98.5,100];
```

```
interpSII=[0:.001:1];
  % extrapolate curve for points given in 'interpSII':
interpWords=interp1(AIplot_known_SII,...
     AIplot_known_words,interpSII,'cubic');

[val,ind]=min(abs(SII-interpSII)); Pwords=interpWords(ind);
  % based on the input SII,
    % find the closest PWU value in the extrapolation
```

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