Sound control in windy weather

Master Thesis

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Electronic Engineering and IT

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AALBORG UNIVERSITY
STUDENT REPORT

Electronic Engineering and IT
Aalborg University
http://www.aau.dk

Title:
Sound control in windy weather

Theme:
Signal Processing and Acoustics

Project Period:
MSc, 10th Semester 2019

Project Group:
Jonas Buchholdt

Participants:
Jonas Buchholdt

Supervisor:
Sofus Birkedal Nielsen

Number of Pages: 40

Date of Completion:
?th June 2019

Abstract:

Will come later

Preface

This report is composed by Jonas Buchholdt during the 10th semester of Electronic Engineering and IT at Aalborg University. The general purpose of the report is *Signal Processing and Acoustics* .

For citations, the report employs the Harvard method. If citations are not present by figures or tables, these have been made by the authors of the report. Units are indicated according to the SI standard.

Aalborg University, February 26, 2019

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Glossary

FOH Front Of House. 9, 21

PA Public Address System. 7, 8

SPL Sound Pressure Level. 7, 8, 9, 10, 11, 17, 20

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Chapter 2

Analysis of sound propogation in outdoor venue

2.1 Live venue sound challenges

This section explore the challenges of producing sound in an outdoor environmental. The challenge of producing a good sound experience for the audience highly depend on the calibration method and the atmosphere condition. It is well known that acoustically wave propagation is strongly affected by the inhomogeneous atmosphere doing the outdoor sound propagation. This inhomogeneous atmosphere shifts the calibration of the sound system which affect the intelligibility. section 2.1.1 gives an overview of the need of controled acoustics at live venue.

2.1.1 Acoustics as live venue

An outdoor Public Address System (PA) system is an important sound reinforcement concept today. It is used to address information, music or just entertainment where the number of audiences is large, sometimes more than 10.000 audiences. The number of the audience makes it difficult to address the information to the large number of audience without reinforcement of the information. The reinforcement is nearly always done from a stage with a PA system. The stage lifts the artist while the PA system is designed to cover the audience area with sound. The optimal PA system covers the area with a linear frequency spectrum in the audible frequency range and a homogeneous Sound Pressure Level (SPL). Today, the used speaker is a line source array flown in both side of the stage and is therefore only close to the audience in front of the stage. The line source array is an array of small identically wide speakers attached to each other to form a vertical line of speakers. An example of a line source array can be seen in Figure 2.1

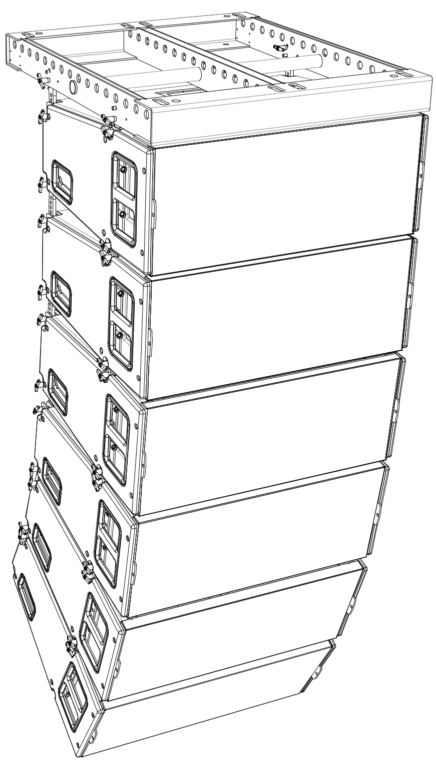

Figure 2.1: The figure shows an illustration of a KUDO line source array from L-Acoustics []

Every speaker or a small group of the line source array can be controlled individually, both in sound coverage area angle and SPL. The benefit of the line source array module design is that the coupling between the line source element can be controlled. With an optimized control system of the line source array, the audience area can be covered with sound such all can hear the information. An optimized line source array has, for example, an optimized main lobe such that the lower part of the main lobe lays flat along the audience area. The following Figure 2.2 shows a graphical illustration of the outdoor PA venue concept.

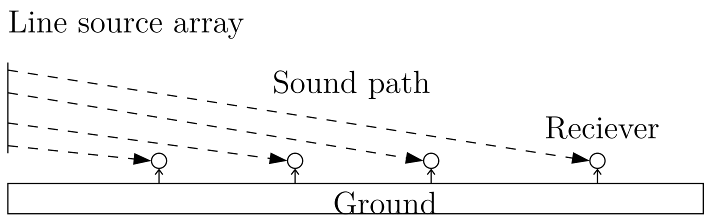

Figure 2.2: The figure illustrate the concept of outdoor PA venue

As shown in Figure 2.2 the distances from one element in the line source array to the receiving audience dependent on the audience position. This indicates that the signal to every line source element has to be adjusted with respect to the coverage area. This is necessary because the wave amplitude decay with distances and is illustrated in section 2.2. The adjustment is not as simple as just supply the upper speaker with more power. A sound wave is a mechanical movement of the particle in the air, which condensate and compression the air molecule, then low pressure and high pressure respectively. The movement of the molecule depends on the medium, and in this thesis, the medium is limited to air. The sound pressure is the local pressure divination of the instantiates atmospheric pressure. The atmospheric pressure, therefore, set a lower bound on the condensation while wery high pressure makes the wave ??. To communicate the information without introducing distortion by the lower limit, the maximum amplification is therefore limited by the lower bound of the atmospheric pressure. Luckily the pressure near the ground is typically 101.325 kPa or a maximum sound pressure of 194 dB SPL . The movement of the particle in the air depends on the medium in the air. The medium in the air is not constant and varies over time with respect to pressure, wind, humanity and temperature. The analysis starts with the experience for live concert of the author section 2.1.2, next section 2.3 address the impact of homogeneous atmospheric effect on sound propagation. Then section 2.3 address the impact of inhomogeneous atmospheric effect on sound propagation.

2.1.2 Author experience of live concert

The Author of the thesis has experience with live concert both as an audience and as a sound engineer. The aspect of being the sound engineer and an audience to a live concert is very different. As a sound engineer, the area for controlling the sound is a secured area with a tent as protection. The tent roof often shadows for the high frequency and the walls make standing waves of the low frequency because the distance between parallel tent walls fits with the wavelength for the low frequency. The control area is defined a the Front Of House (FOH). The FOH is often equipped with an additional speaker and the sound engineer does not fully know how it sounds outside the FOH but base there mix on experience. The aspect of being an audience depends on where the audience is with respect to the stage. In close hand to the stage the SPL is high and often to high especially in the low frequency. The low frequency is often made as a vertical array at the ground or two end-fire arrays and shall be able to exhibit all audience by an audible low frequency spectrum. Therefore the SPL just in front of the sobwoofer has a wery high SPL. This position is not comfortable to be at in longer period and the high SPL mask the higher frequency. The optimal audience position is in the centre of the stage and not as long from the stage as the delay towers. The average SPL is often less than 102 dB SPL since the sound engineer try to keep a maximum average SPL at 102 dB SPL just in front of the FOH. Moreover, it is the stereo sweet spot. This position is the only position where the stereo image is optimal. The stereo perspective problem is a hot topic nowadays, both L-Acoustics [L-Acoustics, 2019] and D&B Audiotechnik [d&b audiotechnik, 2019] have made there own solution to the problem. The idea is to fly many small line source array above the stage and assign every musician to there own line source array. The concept minimises the interference between two line source array playing the same mono signal. Between the delay line towers, the low frequency spectrum is still good and audible but something happens to the high frequency. Often the high frequency designer for few second and gets back. This phenomenon altering through the full concert. Behind the delay towers, the line source array in the delay tower reproduces the sound such that the audience in the back also gets the high frequency spectrum. The question is why does the high frequency disappear for a short period when the low frequency does not? This thesis will focus on answer this question. l

2.2 Ideal geometric spreading loss

When a line source generates a sound wave, the wave field exhibits two fundamental difference spatially directive regions, near-field and far-field. In near-field, the wave propagates as a cylindrical wave wherein the far-field the wave propagates as a spherical wave. When the wave propagates as a cylindrical wave, the wave propagates only in the horizontal plane and therefore the attenuation is 3 dB SPL per doubling of distance. For a spherical wave propagation, the wave propagates in all direction, therefore the attenuation is 6 dB SPL per doubling of distance. The near field and far-field attenuation are based on non-absorption homogeneous atmospheric conditions. The border between the near-field and far-field depends on the hight of the array and the frequency. The distance can be calculated with Fresnel formula Equation 2.1, where the wavelength λ is approximated to $\frac{1}{3f}$ [Bauman et al., 2001]

$$d_B = \frac{3}{2} f \cdot H^2 \sqrt{1 - \frac{1}{(3f \cdot H)}} \tag{2.1}$$

Where:

d_B	is is the distance from the array to the end of near field	[m]
f	is the frequency	[kHz]
H	is the hight of the array	[m]

In equation Equation 2.1 it can be calculated that less than 80 Hz radiate directly intro spherical wave on the exit of the speaker. The following Figure 2.3 shows a horizontal cut of the near-field, far-field from a line source array.

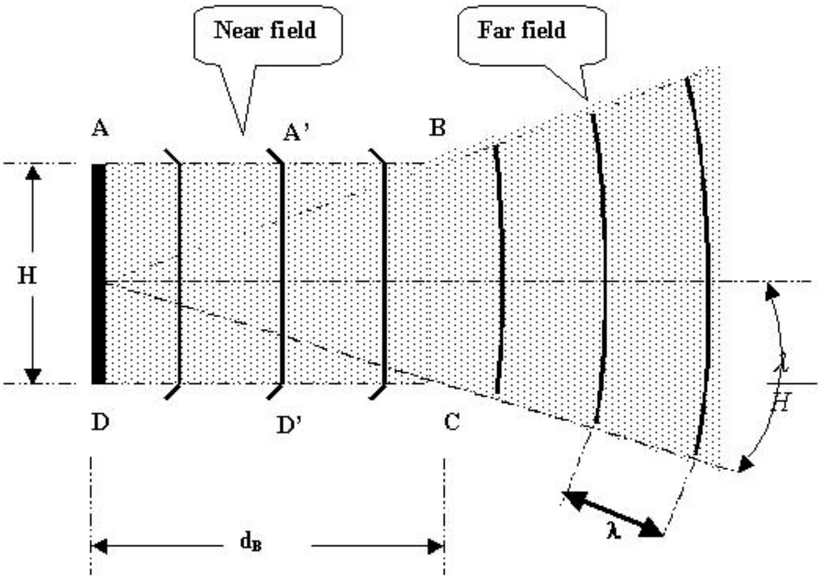

Figure 2.3: The figure shows horizontal cut of a SPL radiation pattern of a line source array [Bauman et al., 2001].

2.3 Homogeneous atmospheric conditions

The aim of this section is to analyse the sound wave propagation in homogeneous atmospheric conditions. It is well known that the sound wave propagation is highly depending on the atmospheric conditions. The propagation depends on the atmospheric pressure, wind, temperature and humanity, where the two latter moreover is frequency dependent. The attenuation difference in frequency for temperature and humanity can be above 80 dB SPL [Corteel et al., 2017]. The following sections introduce a brief discussion of homogeneous atmospheric conditions effect on sound propagation.

2.3.1 Humanity and temperature impact

The temperature and humanity have two impacts on wave propagation, speed of sound and a lowpass effect. The following description starts with the latter.

Lowpass effect The effect of humanity and temperature act as a lowpass filter, where the low frequency remains without any additional attenuation. In other words, attenuation in the high frequency range per doubling of distance depends not only on the spreading loss but also on temperature and humanity. Therefore, for long distance, the atmospheric conditions have a high influence on the frequency spectrum delivered to the audience. Humanity and temperature attenuation are already well studied and standardised. Standard [ISO 9613-1:1993] gives an overview of calculating the frequency attenuation with respect to the distance, temperature and humanity. The article [Corteel et al., 2017] gives some examples of attenuation at a distance of 100 m. The article shows, if humanity increases proportional to the temperature, the lowpass effect is small. If the change in temperature and humanity is the opposite of each other, for example, the high temperature but dry, the attenuation in high frequency is significant. The following Figure 2.4 shows the worst-case scenario from [Corteel et al., 2017].

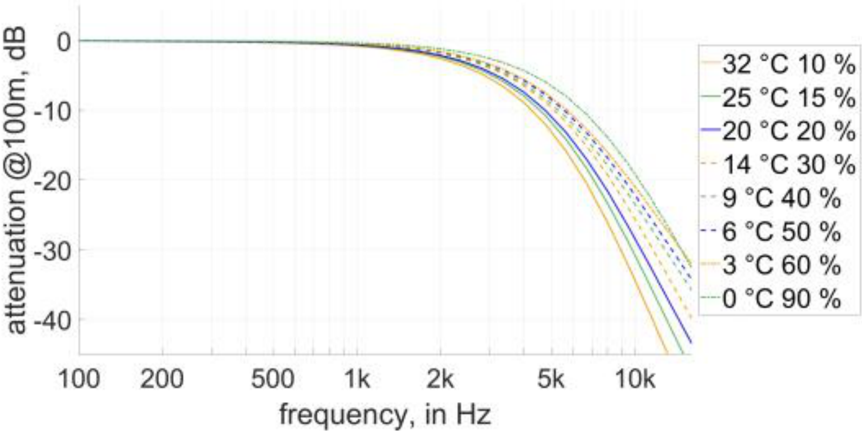

Figure 2.4: The graph shows the attenuation in dB with respect to frequency, humanity and temperature [Corteel et al., 2017].

Speed of sound The second consequence is the speed of sound. At temperature range from 0 °C to 40 °C the speed of sound with respect to humanity change is sparse and mostly depend on temperature change. At 0 % humanity, the speed of sound only depends on the temperature. At humanity higher that 0 % the sound speed increase with respect to humanity, depends on temperature. At 0 °C the speed of sound increases with approximately 0.8 m/s while for 30 °C speed of sound increases with approximately 2.7 m/s [Wong and Embleton, 1985] [Bohn, 1987]. For only temperature differences, the speed of sound increases approximately by 0.6 m/s for every increasing degree Celsius. The wave propagation speed start at 331.5 m/s at 0 °C and 0 % humanity. The following Figure 2.5 shows the speed of sound with respect to humanity and temperature.

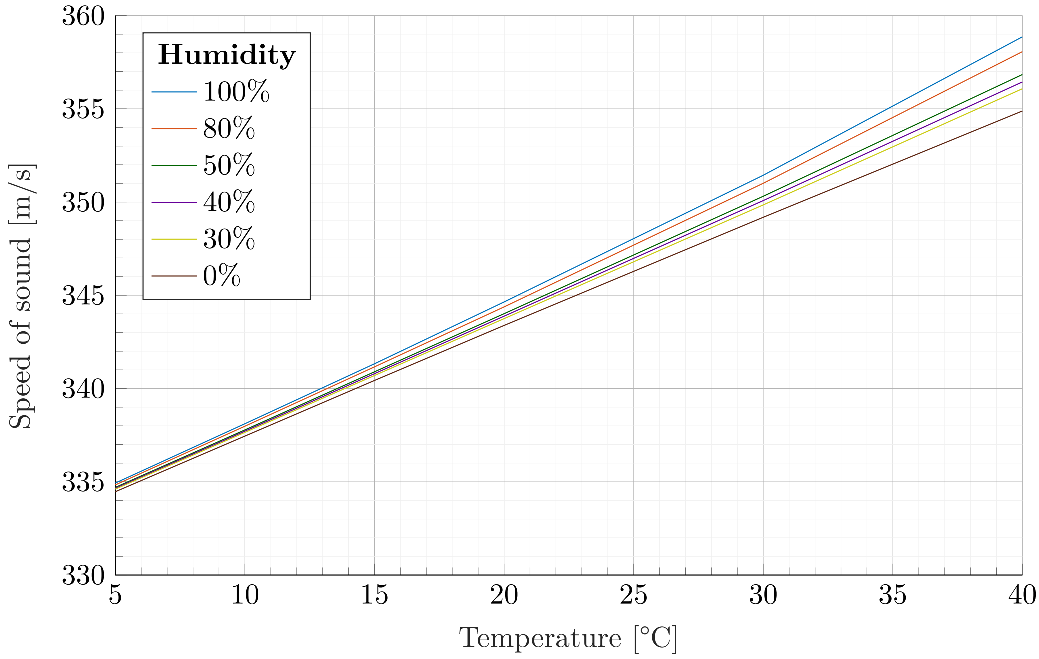

Figure 2.5: The figure shows the increese of sound speed with respect to humanity and temperature [Bohn, 1987]

2.3.2 Wind impact

The wind impact is complex and is not homogeneous with respect to sound source. The impact is depending on the angle of the wind direction with respect to the direction of sound propagation.

Parallel to sound propagation When the wind flows in the same direction as the sound wave propagation, the wind flow in m/s is an addition to the speed of sound. When the wind flows in the opposite direction it is a negative addition. In other cases, the influence is complex since the wind deflect the sound waves.

oblique- and crosswind The effect of oblique- and crosswind on sound wave propagation is rarely studied, and the effect seems to be unclear. Few author have addressed the problem in a simulation of traffic noise and by practical experience [de Oliveira, 2012], [Hornikx and Renterghem, 2017], [Ballou, 2008]. They claim that the crosswind effect refracts the wave in the wind direction. Furthermore, they claim that the effect is not linear in frequency. The author of [Ballou, 2008] indicates that the frequency dependency might be due to the directionality of the high frequency drivers. Since the study of crosswind effects is rare, a geometric calculation of the effect is developed. The geometric calculation will only be done for crosswind which mean that the wind is orthogonal the the frontal direction of the speaker. It will be based on the directional speaker with 90° angle, so 45° angle from frontal direction as the Figure 2.6 shows.

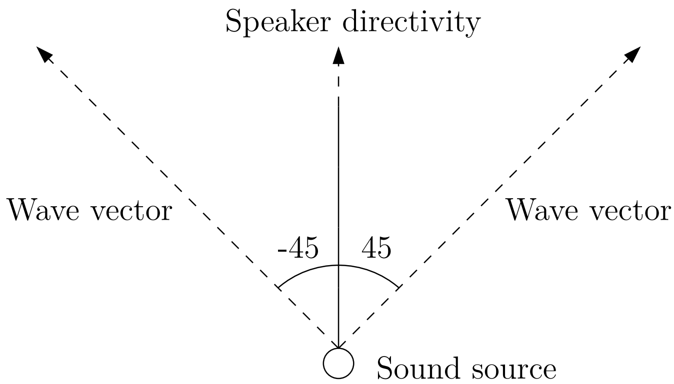

Figure 2.6: The figure shows a geometrical interpolation of a wave moved by the wind

The calculation will calculate the refraction of the two outer wave angle in Figure 2.6. For simplicity the outer wave angle direction is defined as wave vector. It is assumed that the speed of sound is 343 m/s with 20 °C, dry and no influence of wind. A interpolation of the wave vector refraction with present of crosswind is that the time the wave uses for travelling 1 m can be used to find the how much the wind have mowed the air particle in the wind direction. The following Equation 2.4 calculated the cross movement of the air particle as the wave have travelled 1 m.

$$d = v \cdot \frac{1}{c} \tag{2.2}$$

Where:

d	is the cross distance the wave have moved in the wind direction after the wave have travelled 1 m	[m]
v	is the speed of wind	[m/s]
c	is the speed of sound	[m/s]
1	is the travelling distance of the wave	[m]

The cross distance is defined as the wind vector. The wave speed depend on the angle the the wind, therefore the wave speed will change with the refraction. The following Equation 2.3 calculate the speed of sound with respect to the angle to the wind

$$c = c_r + v \cdot sin(\theta) \tag{2.3}$$

Where:

θ	is the angle of the wave with respect to the wind	[°]
c_r	is the reference speed of sound with 20 °C, dry and no influence of wind	[m/s]

The wind gradient with present of wind after the wave have travelled 1 m became as following eq:ana:wind_turn.

$$d = v \cdot \frac{1}{c_r + v \cdot sin(\theta)} \tag{2.4}$$

As the wave refract in the direction of the wind, the wave speed increases. Therefore the travelling time for 1 m decay which do that the travelling distance of the wind vector decays. In the mean time the frontal direction will also decay. A discrete geometrical interpolation of of the descried phenomena is shown in Equation 2.4.

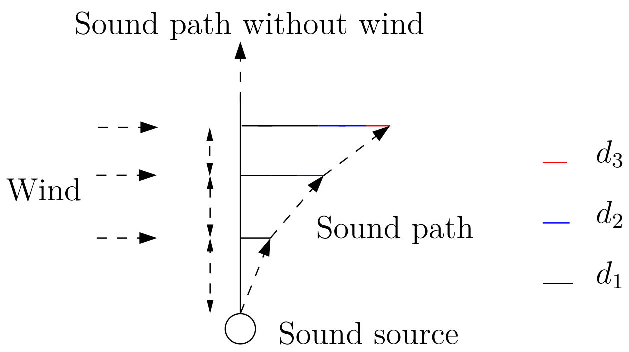

Figure 2.7: The figure shows a geometrical interpolation of a wave moved by the wind

To calculate the resulting wave vector, the following Figure 2.8 illustration of the wave refraction is used.

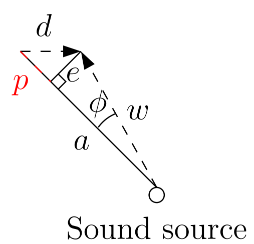

Figure 2.8: The figure shows a geometrical calculation scheme of calculate the resulting wave direction at crosswind

Where:

d	is the resulting wind vector with a wave length of 1 m	[m]
w	is the resulting wave vector	[m]
a	is the wave vector without wind	[m]
p	is the orthogonal projection of the wind vector intro a	[m]
e	is the projection p added with the wind vector d	[m]
ϕ	is the angle between a and w	[°]

The procedure of calculating the resulting wave vector w, is to project the wind vector d intro the direction of the wave vector a without wind. With the projector p the orthogonal e in Figure 2.8 can be calculated with simple addition. The length of a is unknown but can be calculated within the unit circle, since the length of the resulting wave vector always is 1 m. By taking *argsin* to the length of e, the length of a is calculated. The resulting wave direction is then an addition between a and e.

The used calculation script is as Code snippet 2.1.

Code snippet 2.1: The speaker coverage area simulation code | crosswind_geo.m

```
d(:,i) = [v * (1/(c_r+v*sin(theta(i)))) * sin(wind); v *
    (1/(c_r+v*sin(theta(i)))) * cos(wind)];
p(:,i) = (d(:,i)' * (-a_direction(:,i)))/norm(a_direction(:,i))^2 *
    (-a_direction(:,i));
e(:,i) = d(:,i) - p(:,i);
phi(i) = asin(norm(e(:,i)));
a(:,i) = a_direction(:,i) * cos(phi(i));
w(:,i) = a(:,i) + e(:,i);
theta(i+1) = sign(w(1,i)) * acos(((w(:,i)'*front)) /
    (norm(w(:,i))*norm(front)));
a_direction(:,i+1) = w(:,i);
```

A simulation of the speaker coverage area is shown in Figure 2.9

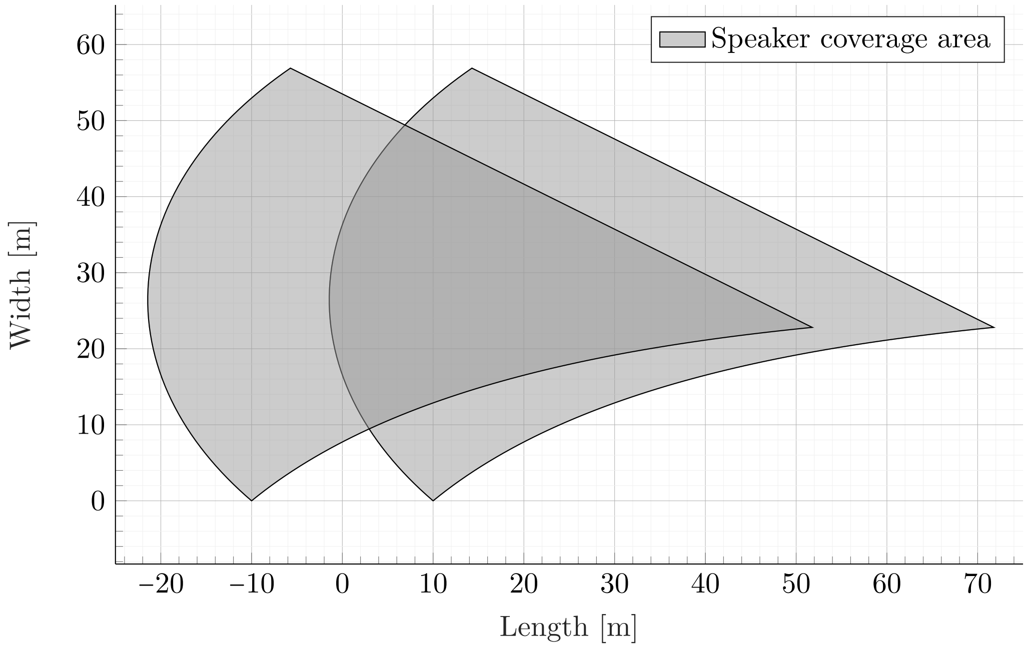

Figure 2.9: The graph shows the coverage area of two speaker with 90° angle and a crosswind from left with a speed of 10 m/s and a wave propagation time of 189.3 ms

It can be seen in Figure 2.9 that the coverage area distance is reduces to 53 m when the speaker have an angle of 90° and the the wind speed is 10 m/s. Another important aspect which is changed is the wave travelling distance from the speaker to the audience. Without wind the distance along the first ariavle wave is 53 m. When the wind is present, the sound ariving to the audiance at 53 m is the wave vector, which have traveled longer that the wavev arriving to the audiance without wind. The wave traveling is increased by 6 m. This increase in length introduce attenuation in the SPL arrival to the audience.

2.3.3 Pressure impact

The influence of atmospheric pressure change is low compared to the effect of wind, humanity and temperature. The average attenuation from 4.0 kHz to 16.0 kHz with fixed temperature was 2 dB SPL while going from 54.02 kPa to 101.33 kPa. The atmospheric pressure then only have a negligibility influence on sound propagation and is generally not frequency dependent.

2.3.4 Ground absorption

In a concert area, ground absorption is complex. The concert area doing the concert is packed by audience, and is therefore not easy to calculate. On the other hand, the line source array is flown and therefore positioneded higher than the audience. The reflection of the high frequency is assumed to be neglible and therefore full absorbtion of the audience. The low frequency driver, also called subwoofer is posisioned in front of the stage on a line, often with a maximum distance of 2.8 m from acoustical center to acoustical center. The distance between the low frequency driver is determinde by the half wavelength of the highest frequency, such that they radiate a plan wave [Bauman et al., 2001]. Higher distance between acoustical center will cause interference in the low frequency in the audience area. The absorption from the audience in the low frequency is assumed to be low since the size of the audience is much smaller than the wave length.

2.3.5 Homogeneous speed equation

The following Equation 2.5 calculate the speed of sound based on homogeneous temperature and wind speed.

$$c = c_0\sqrt{1 + t/t_0} + u \cdot sin(\theta) \tag{2.5}$$

Where:

c	is the resulting speed of sound	[m/s]
u	is the speed of wind	[m/s]
c_0	is the speed of sound at 0 °C	[m/s]
t	is the temperature	[°C]
t_0	is the temperature at 0 °C (273.15)	[K]
θ	is the angle of wind with respect to the wave propagation	[°]

2.4 Inhomogeneous atmospheric conditions

The aim of this section is to analyse the sound wave propagation in inhomogeneous atmospheric conditions. In an inhomogeneous atmosphere, the pressure and speed is a function of position. By this fact, the modelling of a sound wave is very complex and depend on various variables such as temperature and wind speed. The following sections give a short introduction to the effect of inhomogeneous atmospheric conditions.

2.4.1 Atmospheric refraction

When the speed of the wind, the temperature and humanity is assumed to be homogeneous in the sound field, the sound is travelling in a straight path. Often this is not the case, the wind speed increases logarithmically with the hight from the ground to the geostrophic wind [Yang, 2016] and the temperature and humanity are inhomogeneous. The geostrophic wind in founded from approximately 1 km above the ground [Association, 2003]. In such a situation the change of sound wave propagation is directly caused by the atmospheric temperature or wind. This often results in a curved path of the sound wave and is defined as atmospheric refraction. For small distances, the atmospheric refraction has a spars effect on the sound travelling path, because the speed of sound is much faster than the speed of the wind and the temperature. Generally distance up to 100 m is often assumed to have no significant refraction effect [de Oliveira, 2012]. For distances larger than 100 m the refraction is assumed to have a significant influence, especially when the sound source and the receiver are close to the ground.

Temperature The refraction occur because of the temperature change with respect to hight along the day. The sun heats the ground, the and the concert area is full of audience. Therefore, the eath and audience radiate warm air, which makes the temperature at a low hight warmer than the temperature at higher hight. As explained in section 2.3.1, the speed of sound depends on the temperature and therefore, the speed of sound in this situation decay with respect to hight and result in an upwards refraction. The following Figure 2.10 illustrate the phenomena where the temperature decay with respect to the hight.

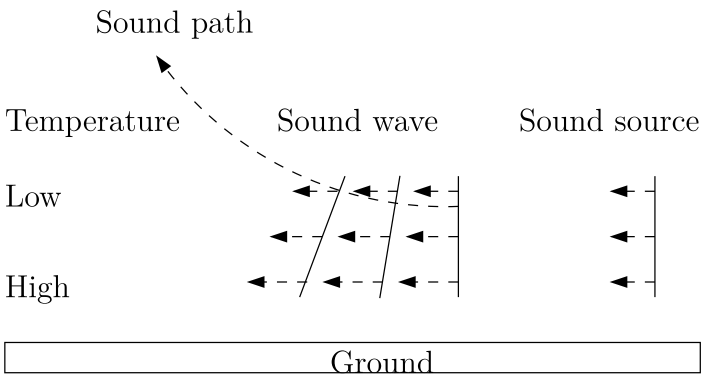

Figure 2.10: Wave refraction in inhomogeneous temperature

The sound refraction will be identically all around the source for a omnidirectional source with respect to temperature.

Wind With respect to the wind speed, a concert area is often a protected area with for example barrier, stage and building. This blockage slows down the wind speed close to the ground. Moreover, from nature itself, the wind speed is often logarithmically increased with respect to the hight. When the wave is propagation in the same direction as the wind, the atmospheric refraction refracts the sound wave downwards. When the wave propagates against the wind, the atmospheric refraction refracts the sound wave upwards. The following Figure 2.11 shows the phenomena when the wave propagates against the wind.

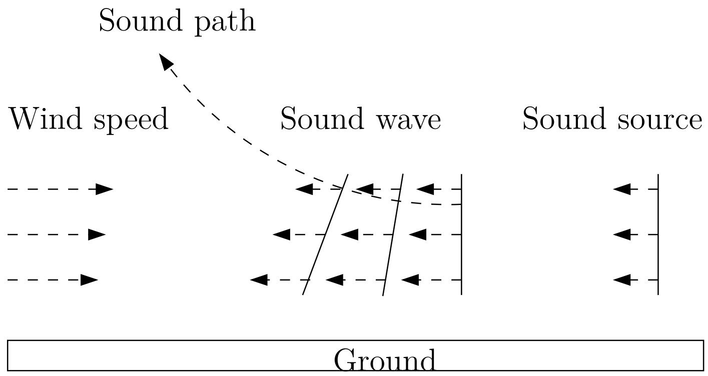

Figure 2.11: Wave refraction in inhomogeneous wind

Due to the wind refraction effect, the sound propagates faster at the ground under the described condition. The consequence is a change of wave direction. This upwards refraction creates a shadow zone in the audience area [Yang, 2016]. In this shadow zone, the SPL is very low and the audience intelligibility is dramatically decreased. The following Figure 2.12 shows the phenomena.

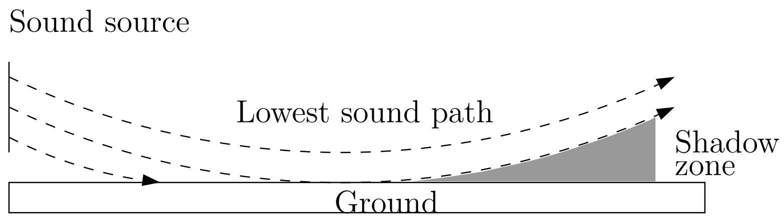

Figure 2.12: The figure illustrate the shadow zone ocourse from a upwards refraction. A line source speaker array contains of many couplet point sources. Every lowest sound path dashed line indicate the lower directional angle of one poins source in the line source array.

As shown in Figure 2.12 the refraction is upwards when the wind flows in the opposite direction as the wave propagation. Behind the line array source, the refraction is downwards and is therefore different than for temperature refraction.

Oblique- and crosswind The effect of oblique- and crosswind on acoustical wave propagation in inhomogeneous atmospheric conditions are rarly studied. The author was not able to find any relevant paper on the subject.

Turbulent Turbulence is a atmospheric condition where the wind does not flow continuesly from one direction, but fluctuates from all directions. Fluctuation often occur in scales of hour, minutes and second where the latter is defined as turbulence. The turbulence wind flow is a chaotic and stochastic process by the nature. It can occur because of change in landscape for example bulding stage and blockage, but can also be a process of flow speed increase in the wind, which make the wind to refract on itself. Turbulence occur often near the ground because the ground surface slow down the speed of wind by the resistance to the ground. This ground resistance also force the air to be turbulent.

2.5 Calibration of sound system

This section analyses the calibration method, which is used by a selection of some Danish sound company. By experience of the author, the hypothesis is that the sound system is calibrated in one point and the microphone is placed just in front of the FOH. The FOH is often a little tent, where the sound engineer controls the sound system. The tent is only open in the direction of the stage and reflection might occur from the tent ceiling to the calibration microphone.

2.6 Sound pressure level measurement doing the concert

Chapter 3

Summary of Problem Analysis

Three effect of atmospheric conditions have been observed on the analysis, pure attenuation, lowpass effect and refraction effect

Chapter 4

Problem statement

Based on the knowledge founded in chapter 2 and the concluction drawn from **??** a problem statement can be made. For the rest of the project the following will be the focus.

research the effect of oblique- and crosswind on wave propagation.

4.1 Deimitation

The following delemitation is made for the search for a solution of .

Part II

Test Design

Chapter 5

Design

Part III

Results

Chapter 6

Results

Chapter 7

Discussion and conclusion

7.1 Conclusion

Part IV

Appendix

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