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Forest Attenuation of Noise from Trams and Metros

A case study of the Oslo tramways and metros

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Preface

This master's thesis is the final work of the master's degree programme electronics at the university Norwegian University of Science and Technology (NTNU). The work is carried out during the spring semester of 2018, and is a part of the course TTT4900 within Acoustics, Signal Processing and Communication. Most of the work for this thesis has been conducted at the consulting company Brekke & Strand Akustikk office in Oslo.

The work concerns the attenuation of noise from Oslo tramways and metros as a function of distance in forest, and is based on measurements from Jarmyra in Bærum, close to Oslo. The measurements will hopefully be valid for other areas and cities as well. This project is proposed by Sigmund Olafsen, an employer at Brekke & Strand Akustikk. He has written a Ph.D. about indoor noise from urban rail bound transport, and this master of science is a continuation of his work.

This project will give a brief introduction to different outdoor parameters which contribute to the attenuation of noise as well as how an urban rail bound transport system behaves as a noise source. It is however assumed that the reader has a general knowledge within the fields of mathematics, physics and acoustics.

Oslo, 11.06.18

Daniel Stusvik Haug

Acknowledgment

After five years of education at NTNU which has led to this final master's thesis there are a lot of people I am very thankful for helping me. First of all, my supervisor Guillaume Dutilleux has helped me with the academic aspect of this work. Even though he has been in Trondheim whereas I have been in Oslo, he has supplied me with standards, relevant research documents and answered my questions. His knowledge has been very important as he often has a different perspective on the work.

The supervisor at Brekke & Strand's office, Sigmund Olafsen, is one of the most enthusiastic acousticians I have ever met. He always has good time for discussion and questioning, and he makes the work I do feel important. This has been very motivating for my work. His previously work regarding noise from rail bound traffic has helped me to form this task.

Thanks to both supervisors for comments and corrections on my thesis.

As most of the work has been conducted at Brekke & Strand's office in Oslo, the employers there have been open for questions and they have been curious about my work. The professional attitude among the employers has inspired me to work hard with my thesis. Thanks to Teresa Fernández Espejo for introducing me for the measurement equipment and related software. I am very thankful for liters of coffee and lunch Brekke & Strand has provided me every day as well as all the equipment for my work and finding new solutions if some equipment is out of service or occupied.

Many thanks to the sound instrumentation company Norsonic which gave me the opportunity to work with acoustics during multiple summers. Without them I would probably not have studied acoustics.

Thanks to my fellow students at NTNU and especially Øystein Meland which has been working with a simultaneous master's thesis next to me at Brekke & Strand's office. His help during the practical measurements has been valuable.

I would also like to thank my friends and family. Thanks to my brother, Andreas, for correcting the language in this thesis. My parents, Jan and Gunn, have been there for me all the time. Last but not least, my girlfriend Karoline has supported me in my daily life, motivated me if I have been feeling down, and has helped me planning when I have been very busy. She has also been important to distinguish between work and vacation which have made me work more efficiently.

The photographs and figures in this thesis are made by myself if nothing else is stated. Any errors in this report is my own responsibility.

D.S.H.

Abstract

The influence of vegetation and trees on sound propagation has been investigated by comparing measurements of metro and tram noise pass-by in an open field with a forest. The measurements are based on the metros and trams that run in Oslo, and the test site is located at Jarmyra in Bærum close to Oslo. All the measurements are done during the winter and early spring which means that the ground mostly is snow-covered and that the measurements are performed without vegetation in form of leaves. The forest consists of a mixture of spruce and birch with an average stem diameter in the range from 0.5 to 40 cm and an average height of 3 to 15 m. The average density of the forest ranges from 0.7 to 1.4 stems per square meter.

Inbound and outbound traffic which run on two separate tracks with a separation distance of four meters has been measured by the use of three microphone positions 1.3 m above the rail head placed normal to the tracks. The separation distance between the microphones is 10 m, and the microphone closest to the tracks is placed at a distance of six meters. This gives six different measurements distances at 6, 10, 16, 20, 26 and 30 m from the closest tracks. All the measurements are performed in the near field of the noise source.

When the frequency spectrum based on the parameter maximum sound pressure level with time weighting fast is compared between the microphone positions located 6 and 26 m from the center line of the outbound traffic track, there is an excess forest attenuation of 0.6 and 1.6 dB for the tram and metro measurements, respectively. This result yields for the entire audible frequency range spanning from 20 Hz to 20 kHz.

The results suggest that the frequency range below 1 kHz is mostly affected by interference effects and that the attenuation between open field and forest measurements start to differ from 1-2 kHz. By the consideration of the frequency range 1 to 20 kHz and sound propagation through 20 m of forest, the excess forest attenuation is 0.5 and 2.3 dB for trams and metros, respectively. With a 90 % confidence interval taken into account, the tram measurements have an excess forest attenuation between 0.1 to 0.9 dB whereas the metro measurements have an excess forest attenuation between 2.1 and 2.5 dB.

As these measurements are based on a sound propagation through 20 m of forest, the excess forest attenuation in the frequency range from 1 to 20 kHz can be approximated as 0.12 dB/m for metro noise. The excess forest attenuation for tram noise is negligible for this range.

Sammendrag

Effekten av vegetasjon og skog på lydutbredelse har blitt studert ved å sammenligne målinger av trikke- og T-banepasseringer i et åpent landskap med skog. Målingene er basert på trikken og T-banen som kjører i Oslo og målingene er gjennomført i Jarmyra i Bærum, like ved Oslo. Alle målingene er gjort ved vintertid og tidlig vår noe som vil si at bakken stort sett har vært dekket av snø og at målingene er gjennomført uten løv på trærne. Skogen som er brukt til målingene består av en blanding av gran og bjørk med en gjennomsnittlig stammediameter på 0,5 til 40 cm og gjennomsnittlig høyde på 3 til 15 meter. Den gjennomsnittlige tettheten til skogen varierer fra 0,7 til 1,4 stammer per kvadratmeter.

Inngående og utgående trafikk som går på to separate skinner med en avstand på fire meter fra hverandre har blitt målt med tre mikrofonposisjoner plassert 1,3 meter over toppen av skinnene og er rettet normalt mot togskinnene. Separasjonsavstanden mellom hver mikrofon er 10 meter, og nærmeste mikrofon er seks meter fra nærmeste skinne som dermed vil gi seks måleavstander på 6, 10, 16, 20, 26 og 30 meter. Alle målinger er utført i nærfeltet til støykilden.

Når frekvensspekteret basert på parameteren maksimalt lydtrykksnivå med en rask (fast) tidsvekting er brukt for å sammenligne mikrofonposisjonene plassert 6 og 26 meter unna linjesenteret for utgående trafikk er det målt en ekstra skogdemping på 0,6 og 1,6 dB for henholdsvis trikke- og T-banemålinger. Disse resultatene gjelder for hele det hørbare frekvensspekteret fra 20 Hz til 20 kHz.

Resultatene viser at frekvenser under 1 kHz stort sett er påvirket av interferenseffekter og at dempingen mellom åpent landskap og skog har et markert skille fra rundt 1-2 kHz. Den ekstra skogdempingen er 0,5 og 2,3 dB for henholdsvis trikker og T-baner når målingene er basert på frekvensspekteret 1 til 20 kHz. Med et 90 % konfidensintervall vil trikken oppnå en ekstra skogdemping mellom 0,1 og 0,9 dB, mens T-banen har en ekstra skogdemping mellom 2,1 og 2,5 dB.

Ettersom disse målingene er basert på lydutbredelse gjennom 20 meter med skog, kan den ekstra skogdempingen i frekvensområdet 1 til 20 kHz tilnærmes som 0,12 dB/m for T-banestøy. Den ekstra skogdempingen for trikkestøy er neglisjerbar for denne måleavstanden.

Contents

Chapter 1

Introduction

In this introduction chapter the background, objective, approach and limitations of the task will be presented. The outline of the report will be described in the end of this chapter.

1.1 Background

Trams and metros are a common sight in big cities around the world, and they are important to get people around in urban places because of the low power consumption compared to cars driven by fuel. They require less space than cars and when the metros started to run in Oslo in 1966, it was hoped that they could be a good alternative to the cars [21]. Even though there are a lot of cars that drive inside Oslo today, the infrastructure and transport in and out of the city would probably be even more chaotic without the rail bound transport system.

People in cities naturally live close to each other, and the need of public transport stations close to the citizens means that the transport has to run close to houses where people live. As a result of this, many people complain about noise and vibrations from trams and metros. When these transport systems run in the city center with buildings made of concrete on each side of the metros and trains, this will amplify the noise, but if there is vegetation such as grass, plants and forest nearby, this will probably attenuate the emitted noise.

When metros in Oslo not drive underground, they drive on a ballast track. The trams drive on ballast tracks as well as city and green tracks. If a rail bound system runs through a green area which consists of trees, plants and hedges, the noise from the transport systems will naturally be damped by its surroundings. When it is tried to predict noise reduction from vegetation in outdoor noise propagation, height and width can be modeled for a tree-barrier, but it is harder to take the leaf density or diffraction effects from trees into account. The influence of vegetation can be hard to model both geometrically and analytically, and it is often low compared to other attenuation factors. [45]

There is not any known research which regards how much the tram and metro noise is attenuated as a function of distance in a forest. If this work shows that the noise attenuation is greater than expected, maybe more trees around rail bound traffic will be planted, or new rails through forests will be made. Research about the noise imission from urban rail bound traffic in Oslo already exists, such as “Indoor noise from urban railbound transport” by Olafsen [38] and “Lydfelt i smale bygater med trikketrafikk” by Sivertsen [43] as well as an ongoing master’s thesis about the characterization of the noise sources of trams and metros by Øystein Meland.

It is important to investigate the behavior of forest when it comes to sound propagation because it could be an alternative way to protect quiet areas, as stated in Directive 2002/49/EC [15]. This investigation will be valuable to predict sound levels inside and around forests accurately for noise mapping. This work will also be important for Sporveien, the company responsible for most of the public transport in Oslo. They receive a lot of complaints related to the noise imission from metros and trams which they have to deal with [9, 10, 33].

There is a lot of research regarding noise attenuation by vegetation, but in this literature the noise sources are either loudspeakers or road traffic noise. The interest of the acoustics in forests started already in 1946 when Eyring investigated the Panamanian rain forest [17]. The literature from before 1980s was only experimental, but later several attempts to define formulas for sound propagation through a forest were done. This is not an easy task since the density of the trees is varying from place to place. A recent paper from 2007 [44] uses tree trunk scattering into the Green’s function parabolic equation as well as the atmospheric refraction and ground effect through a pine forest.

The work in this thesis will focus on the specific Norwegian vegetation and climate seasons. Since the recordings will take place during winter and spring, there is a great possibility of snow conditions, both on the ground and in tree branches. This work will also be unique since it will investigate noise attenuation by forest from both trams and metros.

1.2 Objective

The problem description of this Master’s thesis is:

Measure the influence of forest and vegetation on noise from Oslo tramways and metros as a function of distance in the near field

1.3 Approach

The task will be solved by doing measurements at Jarmyra in Oslo, the only place in Oslo where both trams and metros are running on the same tracks. This place is perfect since it has an open field which consists of grass and a forest next to the rails. Three different microphone positions will be used in a close, medium and far distance in the near field from the rails. Multiple measurements of the tram and metro pass-by will be done to obtain a statistically significant result, both in open field and forest.

The sound attenuation as a function of distance in the forest and open field will be compared. To eliminate the effect of ground absorption, a measurement of the ground impedance is necessary. The measurement method for ground impedance will be done in accordance with the American standard ANSI S1.18. It is also important to take the density of trees and leaves into consideration.

Only the near field of the trams and metros are studied during this work simply because the noise emission from trams and metros is a near field problem. The metros (when not driving underground) and trams drive inside urban areas with houses close to the tracks.

1.4 Limitations

It could be interesting to measure the rail corrugation in this area, but as these measurements only can be made at night with security personal from Sporveien and a senior engineer from Brekke & Strand present, this is not achievable. The acoustic ground impedance close to the rails will therefore not be possible to measure either.

1.5 Outline

Rest of this master's thesis is organized in the following chapters:

Chapter 2 and 3 represent the theory part of this thesis and will identify and give a theoretical background which is needed to understand the results in this report. In chapter 2 a brief description of the rail bound transport system and how it behaves as a noise source is given. Chapter 3 gives all the necessary background to understand how the sound is propagating outdoors and all the parameters which contribute to its attenuation.

Chapter 4 describes the experimental setup and methodology. All the necessary equipment to do this work is included in this chapter.

Chapter 5 gives the results obtained during this work. All the results are analyzed and discussed in this chapter, and will sum up to a conclusion given in Chapter 6.

The Appendices are presented next. Appendix A gives the raw data obtained from the measurements as well as an report from the ground impedance measurement at each measurement day, and Appendix B gives the MATLAB code used to analyze and interpret the results. Appendix C gives some screenshots and properties from the software ArtemiS used to collect the data. Some relevant theory is given in Appendix D and E. A Glossary of Symbols and Acronyms are given next, followed by the Bibliography.

Chapter 2

Urban Rail Bound Transport

The noise emitted from trams and metros is going to be investigated, so first some basic theory about the rail bound transport system is described. An overview of the different parameters which contribute to the noise emission from rail bound transport systems will be given.

In Oslo city, there is one type of metro (MX3000) and this vehicle will be described in section 2.2. There are two types of trams that run in Oslo; the models SL79 and SL95. Because SL95 is the only tram that passes Jarmyra, only this tram will be described in section 2.3.

2.1 Metros and Trams as Noise Sources

The trams and metros travel in city streets or separate tracks. Since these vehicles travel at low speed compared to cars and mainline railways, they are usually a short range sound and vibration-problem. Often the length of the trams and metros are much larger than the distance to a receiver, which means that the measurements are done in the near field of the source. Hence it is not possible to assume a point or finite line source for trams and metros [38].

Road traffic noise is different from rail bound noise because of the amount of vehicles are much higher. The weight of a car is much lower, so vibration problems are usually not a problem for cars and the frequency noise spectrum is different. Therefore data from road traffic noise can not be translated to rail bound traffic noise.

2.1.1 Sound Radiation from Wheels and Rail

The vibrations from the wheels and rail lead to sound radiation, and the main contributors to sound emission from rail bound transport are made from structural vibrations and unsteady aerodynamic flow (subsection 2.1.2). The structural vibrations of a solid will make the air around the object vibrate and therefore produce sound. [46]

When a structure, e.g. rail, becomes small compared to the wavelength at a specific frequency in one or two dimensions, bending waves might occur. This type of wave will then be dominant and the particle velocity will be normal to the direction of propagation. This implies that an efficient coupling between the medium and air is obtained since the acoustic wave is equal to the bending wave. This specific frequency is known as the critical frequency of the medium. [48]

The sound pressure level (SPL) will vary as a rail bound transport system passes when the receiver positions are at the track side. The trams and metros can be seen as a series of sources moving at specific velocity in one direction, or multiple monopole sources (which originate from the bogies) with a specific separating distance.

The interaction between wheels and rails will make the system vibrate and radiate noise. Hence it is then important that the rail roughness is low and that the rail corrugation is minimized, so that the interaction between rails and wheels is as smooth as possible.

According to CNOSSOS-EU (Noise Assessment Methods in Europe) which is a common methodological framework for strategic noise mapping under the Environmental Noise Directive (2002/49/EC), railway traffic noise has the noise sources originating from the rolling, traction, aerodynamic, impact (from junctions, switches and crossings) and squeal noise. The height of the rolling noise source is assumed to be 0.5 m above the upper part of the tracks. [28]

2.1.2 Aerodynamic Noise

Aerodynamic noise is a high speed phenomenon. When the air flow is disturbed or is too high it becomes very noisy, so it is important to keep the airflow as smooth and slow as possible to minimize the noise [39]. The maximum possible speed for trams and metros used in Oslo is 80 km/h [42, 51], so the rolling noise will dominate opposite as for mainline railways where the aerodynamic noise dominates at higher velocities.

Noise generated from engines, cooling systems and compressors will be a bigger problem as the speed is low.

2.2 Metros

The metro type MX3000 replaced the older T2000-series between 2006 and 2009. One set consists of three carriages, and the most common is the use of two sets, which means six carriages. The length of one set is about 54.1 m, and the maximum width is about 3.2 m. The total weight of a set without passengers is 94 tons. [49]

The metro is powered by 750 volt DC, and this electricity comes from a third rail. This rail is an additional rail which runs parallel to the existing tracks which carries an electric current delivered to the metros. [47]

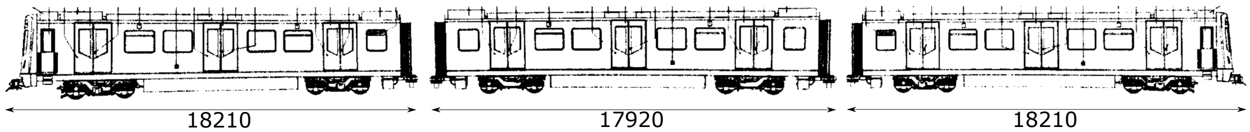


Figure 2.1: Technical drawing of the three MX3000 carriages with lengths given in millimeters [21].

2.3 Trams

The tram type SL95 was introduced in Oslo in 1995 and 32 trams of this type were produced between 1996 and 2004. The length of this tram is about 32.1 meter, and its width is 2.6 meter. The weight is 64 tons without passengers and the height of SL95 is approximately 3.6 meter. [51] SL95 is called the "thunder tram" because of the high noise emission and that it is approximately twice the weight of the older tram SL79 [3].

The Oslo tramway is electrified by an overhead wire connected to the tram's pantograph. In the same way as for the metros, the trams are driven by 750 volt DC. [47]

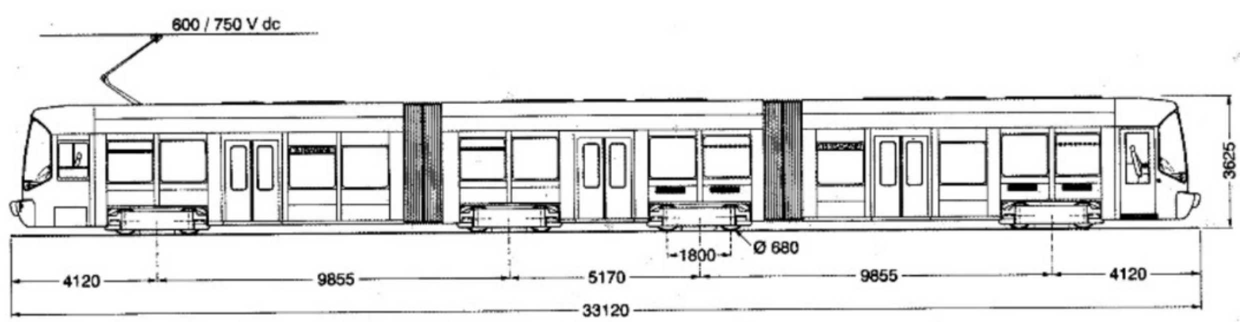


Figure 2.2: Technical drawing of SL95 with lengths given in millimeters [4].

Chapter 3

Outdoor Sound Propagation

In this chapter typical properties related to outdoor sound propagation will be described. This will include different aspects which influence the sound propagation such as scattering, diffraction, reflection and ground absorption.

3.1 Wave Interaction

If there is an object in the path of a sound wave, the relative size of the wavelength will decide how the sound wave interacts.

$$k = \frac{2\pi}{\lambda} \tag{3.1}$$

If the obstacle is hard, the energy of the sound wave will not be significantly reduced by the absorption of the object. The largest dimension of the object of the sound path is denoted by a given in meters (m), the product of the wave number k (equation 3.1) measured as radians per unit distance (m^{-1}) and a can be used to predict how the object will affect the sound wave. In equation 3.1 [29], λ is the wavelength in meters defined as $\lambda = c/f$ where c (m/s) and f (Hz) is the speed and frequency of the sound, respectively.

Diffraction may occur when $ka \leq 1$, which means that the sound wave travels around the object without getting disturbed by its presence. When $1 < ka < 5$, the scattering phenomenon takes place. Scattering implies that the sound wave will be partly reflected in all directions, but in a complicated pattern. If $ka > 5$ the sound wave will get reflected in one or more directions. By the use of geometry, the sound waves can therefore easily be modeled and predicted. All these phenomenons are under the assumption that there is no absorption from the object. [12]

3.2 Near Field of Sound Source

In the sound source's far field, the sound pressure decreases regularly as a function of distance. In the near field, the sound pressure level may vary in a complex manner dependent of the type of source. [48] The distance to the acoustic center of the sound source influences the directivity in the near field, and the limit between the far field and near field is a function of the wavelength and the emitting area's size.

The near field can be defined as the region close to a source where the acoustic particle velocity and the sound pressure are not in phase [5, 11, 22]. An approximation for a finite line source is that the reduction of the SPL is 3 dB for each doubling of distance up to a receiver distance of L/π, where L is the length of the source. After this limit, the reduction is normally 6 dB per doubling of distance. [18]

3.3 Air Attenuation

Geometrical spreading of the acoustical energy due to distance will lead to sound attenuation. By the approximation of a line monopole source or simply a monopole source in free field conditions, the sound pressure level will decrease by 3 or 6 dB for each doubling of the receiver distance, respectively. [46]

There are several additional attenuation mechanisms such as thermal losses, viscous and different relaxations effects. The combinations of these effects are known as atmospheric or air attenuation. The strength of the sound wave is reduced because the air attenuation effects will convert the sound energy into heat or internal energy of the air. [30] The excess attenuation due to air absorption varies from 0.5 to 0.7 dB per 100 m when the calculations are based on railway noise and the use of standard reference spectra [37].

The air absorption is dependent of the frequency and increases with increasing frequency [29].

3.4 Attenuation Through Forest

A forest can be described as a given amount of scatterers inside an area. When a sound wave enters a forest, multiple scattering will occur. By the use of a standing wave tube the acoustic absorption of six different tree species was measured by Reethof [40]. These results revealed that the absorption of the tree bark is about 5 % between the frequencies 400 and 1600 Hz. Even if the acoustic absorption is not very high for trees, the multiple scattering will lead to longer travel distance for the sound waves which leads to attenuation of the sound due to air absorption and multiple absorption when hitting a tree bark.

From the already existing literature, it can be found that there is some excess attenuation in forests caused by the scattering and absorption of trunks, leaves and branches [45]. The excess attenuation is mostly caused by trunk and limbs, and the attenuation caused by leaves is not a significant absorber. Leaves matter at higher frequencies [8].

ISO9613-2 [25] which describes attenuation of sound propagation outdoors takes the attenuation caused by dense foliage into account. It states that there is an excess attenuation of 1-3 dB in the frequency range 250 to 8000 Hz at distances 10-20 m between source and receiver.

$$\alpha_{wood} = 0.01\left(\frac{f}{1Hz}\right)^{1/3} \tag{3.2}$$

One way to express a general excess attenuation through various woods is given in equation 3.2 [23]. This attenuation α_{wood} is given in dB/m and is a function of frequency f (Hz). This formula says that the excess attenuation through forests is 10 dB per 100 m at 1 kHz. This formula is based on an average of data compiled for all types of American forests.

There are also researchers that have measured an excess attenuation of 3 dB per 100 m for bare trees, and on the other side there is measured 18-27 dB per 100 m for heavy Canadian forests. [30]

3.4.1 Predictions by the Nord2000 Model

Nord2000 is an advanced prediction software for outdoor noise. It models the sound pressure level at an observation point from the sound power source which corrects for geometric divergence, atmospheric absorption, ground effect and scattering effect. Attenuation caused by trees and other obstacles is included in the scattering effects. If a forest is modeled, the parameters density and average diameter of tree trunks are taken into account. The coherence effect of the sound waves will be lost as scattering occurs, implying that ground and scattering effects must be combined at each frequency. [45]

The Nord2000 model only predicts a significant effect of the trees when the frequency is above a specific frequency (1-2 kHz) and the distance between source and receiver is at least 40 m. A comparison between experimental results and the Nord2000 shows that it predicts the reduction of the ground effect due to interference in acceptable agreement, but at high frequencies, the agreement is not that good. These measurements are based on a number of measurements carried out in different forests with different tree density and stem diameter where pink noise has been used as excitation signal. The experimental results show however that the predictions are slightly better with the effect of trees taken into account than without the effect of trees. [45]

3.5 Ground Effects

Ground effects, sound scattering and meteorological effects are the most important physical parameters related to the sound propagation in a forest.

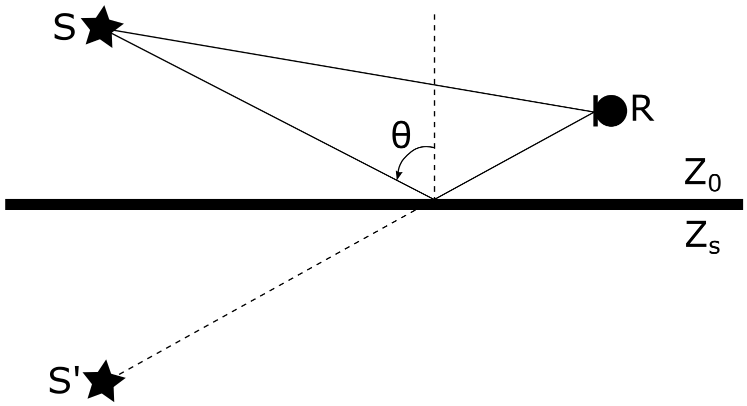


Figure 3.1: Direct and reflected sound source represented as S and the mirror source S', respectively. The sound sources are illustrated as stars and the receiver R is illustrated as a microphone symbol. The ground is assumed to be homogeneous.

A sound source S with the power P located above the ground with an absorption coefficient α_{gr} will give both direct and reflected sound to a receiver point (Figure 3.1). The reflection coefficient Q will vary with frequency, and the reflected sound will behave as it comes from a mirror sound source with the sound pressure PQ. [41]

$$R_r - R_d = n\lambda \tag{3.3}$$

$$R_r - R_d = (n - 0.5)\lambda \tag{3.4}$$

The direct and reflected sound will lead interference effects at the receiver location, dependent of how the phase of the sound waves are added together. If the reflected wave is 180 degrees out of phase compared to the direct wave with the same frequency, destructive interference occurs (equation 3.4). Constructive interference will occur if the sound waves are in phase, see equation 3.3. This will result in multiple peaks and dips in the net frequency response and is known as the comb-filter effect. [7, 20]

In equation 3.3 and 3.4, R_d and R_r is the direct and reflected distance path of the sound wave, respectively, and n is a positive integer. This phenomenon will be directly influenced by the ground's characteristics, such as the impedance which will be described in section 3.5.1.

The forest floor is often a superposition of many layers where the layers are in the same state as the forest itself, where the top floor is a organic deposit and the next layer consists of minerals.

The organic layer can be subdivided into two layers consisting of dead plants such as foliage and humus which is a result of decomposition. [13]

3.5.1 Specific Acoustic Impedance

The specific acoustic impedance of a sound wave can be represented as the equivalent to mechanical impedance.

$$Z_s = \frac{p}{u} \tag{3.5}$$

The specific acoustic impedance Z_s (equation 3.5 [29]) with the unit Pa · s/m where p (Pa) and u (m/s) is the complex pressure and particle velocity, respectively. Therefore the specific acoustic impedance is a complex quantity where the real part is the specific acoustic resistance and the imaginary part is the specific acoustic reactance.

$$Z_{norm} = \frac{Z_s}{\rho c} \tag{3.6}$$

The normalized specific acoustic impedance ratio is the ratio between the specific acoustic impedance of a ground surface and the characteristic impedance of air where the atmospheric conditions are specified [2]. This formula is given in equation 3.6, where ρ and c is the mass density and speed of sound for air, respectively. This equation is valid under the assumption that the sound wave is plane.

$$\rho c = \frac{428.0}{\sqrt{T/273.15} \cdot \left(1 + 1.95 \cdot 10^{-5} \cdot RH\right)} \tag{3.7}$$

The specific acoustic characteristic impedance ρc of air is given in equation 3.7 [2], where T is the temperature in Kelvin (K), RH is the relative humidity with the unit percent (%). This equation is defined at sea level where the atmospheric pressure is 101.325 kPa, and has an accuracy of better than ± 0.2 %.

The speed of sound differs through different media with dissimilar acoustic impedance, but it also changes as a function of temperature.

$$c = 20.06 \cdot \sqrt{T} \tag{3.8}$$

The speed of sound c in air with the unit m/s is given in equation 3.8 [16, 34], where T is the temperature in degrees Kelvin (K).

3.5.2 Reflection and Absorption Coefficient

The absorption coefficient is dependent of the reflection coefficient which is dependent of the acoustic impedance.

$$Q = \frac{Z_s cos\theta - Z_0}{Z_s cos\theta + Z_0} \tag{3.9}$$

For sound incidence in air, the reflection coefficient can be written as given in equation 3.9, see Figure 3.1. Z_0 is the specific acoustic impedance (described in section 3.5.1) of air, Z_s is the specific acoustic impedance of the reflecting medium and θ is the sound wave's angle of incidence. For normal sound wave incidence, $\theta = 0°$, which means that $cos\theta$ equals 1. [6, 19]

$$\alpha(\theta) = 1 - |Q|^2 \tag{3.10}$$

The absorption coefficient of the medium can then be found by the use of equation 3.10. [6, 19]

3.5.3 Ground Impedance Measurement

The American standard ANSI/ASA S1.18-2010 [2] describes the procedure for determining the acoustic impedance of ground surfaces. The method used in this standard is based on interference measurements between direct and ground-reflected sound.

$$H(f) = \frac{p_u(f)}{p_l(f)} \tag{3.11}$$

$$p(f) = \frac{1}{R_d} e^{ikR_d} + Q(f,\beta)\frac{1}{R_r} e^{ikR_r} \tag{3.12}$$

In equation 3.11 [2], $H(f)$ is the transfer function and $p(f)$ is the complex sound pressure where u and l denote the upper and lower microphone, respectively. This pressure is defined in equation 3.12 where R_d and R_r is the distance in meters (m) from the source to the receiver for the direct and reflected sound, respectively. The wave number k is defined in equation 3.1, Q is the reflection coefficient and β is the specific acoustic surface admittance given as a function of frequency. β is the reciprocal of the specific acoustic impedance with the unit (m/s)/Pa, where the real part is the conductance and the imaginary part is the susceptance.

Equation 3.12 can also be used to describe the simplest case of sound propagation with a first order reflection (see Figure 3.1), where R_d is the direct path from the sound source S to the receiver R, and R_r is the reflected sound path with the distance from the image source S' to the receiver R. In this equation, it is assumed a point source which emits spherical waves in an isotropic manner and that there is a homogeneous atmosphere over a flat uniform ground. [45]

Chapter 4

Methodology

This chapter describes the methodology and how the measurements are performed. All the measurements are made at Jarmyra, in Bærum, close to Oslo. As described in chapter 3, there are multiple parameters that contribute to attenuation in a forest. Therefore field measurements are needed to study the difference in attenuation between this specific forest and open field.

In section 4.1 the methodology for the measurement of the sound propagation as a function of distance will be described, both when the sound propagates through an open field and in a forest. In section 4.2 the measurement procedure for measuring the ground impedance in accordance with the American standard ANSI S1.18 will be described.

4.1 Sound Propagation as a Function of Distance

To distinguish if the noise attenuation from the trams and metros is caused by the forest and not just air and ground absorption, measurements in an open field are compared with measurements in a vegetated area.

4.1.1 Setup

Three microphone positions are necessary to get a clear view of how the sound propagates as a function of distance, such that it is possible to see if there is a stronger sound attenuation the first meters or farther away. Since the rails have a safety area with a fence next to them, it is not possible to get any closer than about six meters from the center line of the closest rails which represent the outbound traffic. The distance between the outbound and inbound rails is found to be four meters by the study of a satellite map [35] as well as the use of a laser meter.

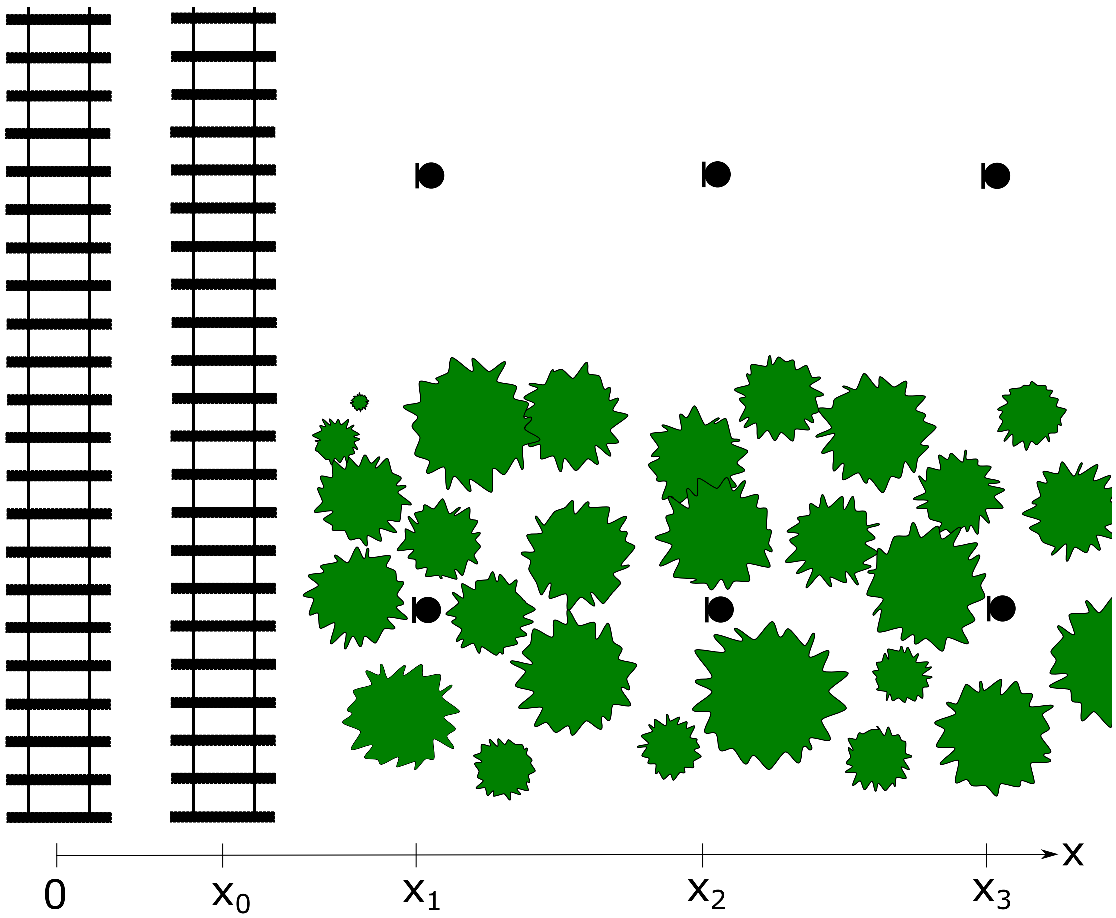


Figure 4.1: Illustration of the experimental setup seen from above which shows the bottom area which is covered with vegetation and the upper part which shows the open field conditions.

The two other microphones are placed at distances of 10 and 20 m from the microphone closest to the rails. This implies that the measurement distances will be 6, 16 and 26 m and 10, 20 and 30 m for the outbound and inbound traffic, respectively (see Figure 4.1). This also means that there will be a total of six different measurement positions for each tram and metro pass-by, but since the speed parameter will vary between inbound and outbound traffic all the measurement distances have to be analyzed with caution if they are directly compared.

In Figure 4.1, the inbound tracks are located to the left ($x = 0$) and outbound tracks closest to the microphones ($x = x_0$). In rest of this thesis, outbound traffic will be referred as the tracks closest to the microphones and inbound traffic as the tracks farthest from the microphones. The distance between the center line of the tracks is 4 m. During the measurements the variables are $x_1 = 10$ m, $x_2 = 20$ m and $x_3 = 30$ m, which represents the position to the microphones with the rail farthest away from the microphones as reference (where $x = 0$).

The specific distances between tracks and microphones are selected because of practical reasons. The closest microphone position is limited due to the fence protecting the tracks, and an equal separating distance between the microphones of 10 m is used. The depth of the forest is also a limitation as it only ranges about 25 m from the fence.

Since most of the metros and trams in Oslo use two tracks next to each other with traffic in each direction, noise from both inbound and outbound traffic will be recorded to study if there is any difference. Noise from both tracks affect people living nearby metro and tram traffic. The conclusion will however be based on the pass-by measurements of the outbound traffic only as outbound traffic is closest to the forest. In this way the influence of other parameters than the forest is limited.

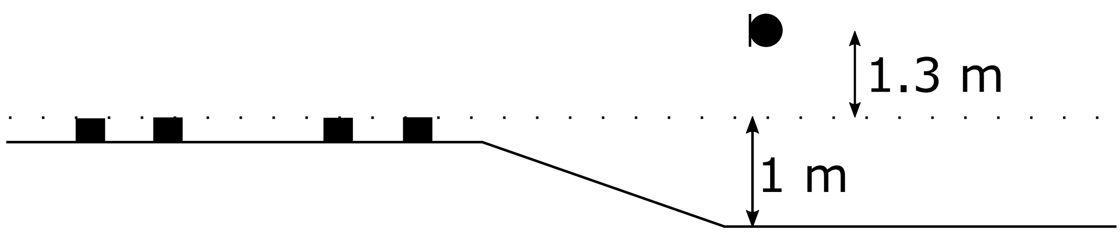


Figure 4.2: Illustration of the experimental setup seen from the side. The closest microphone position and height is illustrated to the right, and the railway tracks are illustrated to the left.

The height of the microphones is chosen to get as free sight between the tracks and receivers as possible, with snowy conditions taken into consideration. The microphones are however not placed too high as it could be less denser forest or no vegetation at all at this height. The height of the nearest microphone and the terrain around the tracks are illustrated in Figure 4.2, and the two other microphones are placed at the same height as the closest microphone. The leftmost tracks are the inbound tracks, and the tracks to the right represent the outbound traffic.

The distance from the ground to the top of the rails (dotted line) is 1 m and the distance from the top of the rails to the microphone is 1.3 m. This gives a total height of 2.3 m above the surrounding ground as the tracks are a bit elevated compared to the surrounding ground.

4.1.2 Procedure

For each pass-by of a metro or tram, a recording is started by the use of SQuadriga II, a sound recording device. The average speed of the train is found by using a stopwatch to measure the time it takes for the front and the back of the vehicle to pass a reference point. This method is considered to be accurate enough as the speed parameter is not the most important parameter during the measurements. The identification number of the trams and metros is noted in case of abnormal behavior of a specific vehicle.

After the measurements are performed, they are analyzed by the use of the software designed for measurements done with the SQuadriga II, called ArtemiS suite. Every recording is cropped to a signal segment which only contains the vehicle pass-by based on the study of the time signal, so the effect of the background and unwanted noise is minimized. ArtemiS suite gives the maximum SPL for every microphone position, both with and without spectral weighting. These levels are analyzed in MATLAB to find the average values, other calculations and for all the plots. The MATLAB script is found in Appendix B, and screenshots and properties used in ArtemiS are given in Appendix C.

The frequency spectrum and the maximum sound pressure level of the different measurement distances are analyzed. The analysis compares how the frequency and sound pressure level changes as a function of distance for the open field condition and when there is vegetation and trees between the rails and the receivers. The frequency range of interest is the audible range from 20 Hz to 20 kHz in 1/3-octave bands. The measured parameters are $L_{p,Fmax}$ and $L_{p,AFmax}$ with a time duration equal the individual pass-by time and a fast time constant. Details about the time- and frequency-weighting are found in Appendix D.

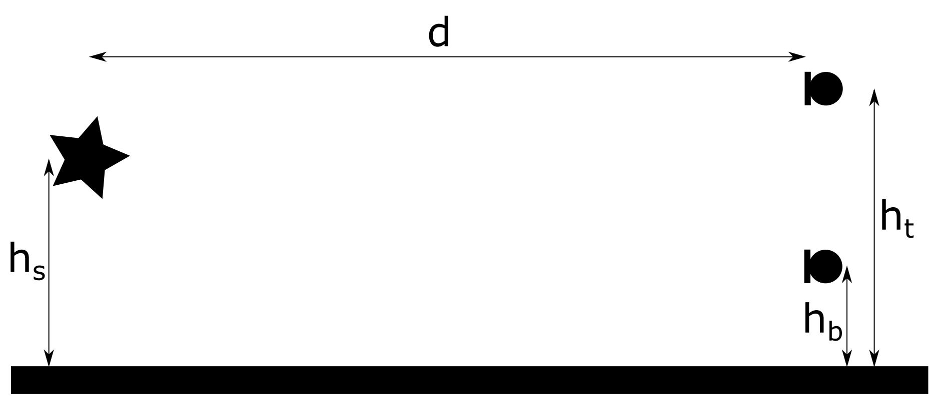


Figure 4.3: Illustration of the geometrical definitions seen from the side. The sound source is illustrated as a star and the microphones are shown on the right hand side of the image. The source height is defined as h_s and the bottom and top microphone is defined as h_b and h_t, respectively. The distance between the source and receivers is denoted as d.

4.2 Ground Impedance

The two different geometries which require one sound source and two microphones are given in Table 4.1 and Figure 4.3. The sound source emits a continuous pink noise signal with a frequency content between 200 and 5000 Hz to cover the frequency range from 250 to 4000 Hz, created with the software AUDACITY. Also here the SQuadriga II is used for the measurements. The ambient sound pressure at the test site is measured to ensure that the sound source is generating a sound pressure level that is at least 10 dB higher than the background noise in each 1/3 octave bands from 250 to 4000 Hz.

Since the acoustic impedance of the ground will vary with location, four independent mea-

Table 4.1: Recommended geometries in accordance with ANSI S1.18. [2]

	Geometry A	**Geometry B**
Source height (h_s)	0.325 m	0.20 m
Upper microphone height (h_t)	0.46 m	0.20 m
Lower microphone height (h_b)	0.23 m	0.05 m
Horizontal separation (d)	1.75 m	1.0 m

surements are made for each geometry in accordance with the standard [2]. The sound source and receiver are moved and rotated around the ground area to be tested. By the use of equation 3.11, the total complex sound pressure ratio $H(f)$ is calculated for each geometry and test location. A report is generated for each day impedance measurements are performed which includes a description and photograph of the test area, documentation of the instrumentation, meteorological data, the real and imaginary parts of the normalized specific acoustic impedance ratio and other observations.

4.2.1 Normalized Specific Acoustic Impedance Calculations

The normalized specific acoustic impedance calculation is based on the transfer function $H(f)$, and a MATLAB script is used for this computation. The equations in section 3.5.3 are the basis for this impedance calculation, and the script is developed at National Research Council of Canada and revised at the Open University, UK. This script assumes e^{-iwt} time convention, and the input text file is required to have three columns consisting of frequency, real and imaginary part of the transfer function. The other parameters that the script requires are the geometry and the speed of the sound during the measurement.

The program will give a plot of the real and imaginary parts of the impedance as well as generating a text file with the impedance values. A message will also be given if convergence is not achieved after 20 iterations at any frequency value.

4.2.2 Requirements

The microphones should ideally have nominally identical pressure sensitivity, frequency response and phase response. This will require extensive calibrations, and it is important to take the complex sound pressure ratio method into account by averaging the pressures obtained before and after switching the positions of the microphones.

If the wind velocity is above 5 m/s measured at 2 m above the ground, this method is not valid. No measurements are done if there is any form of precipitation. The sound source in this experiment is omnidirectional within 1 dB for a ± 45 ° sector both in horizontal and vertical plane. For rough grounds where the height varies more than half of the shortest wavelength of interest, this method is not applicable. With an upper frequency limit of 4 kHz, this means that the maximum variation of the ground is about 5 cm. It should not be any reflecting objects within 10 times the separation distance d.

4.3 Equipment

The equipment used for the sound propagation and ground impedance measurements are given in table 4.2 below. Details are given about what type of equipment, manufacturer, serial number (if it is given) and the number of equipment. Only the most important items are included in the list, and equipment such as cables, microphone stands and measurement tape are omitted. The calibrator (Nor1251) is fulfilling IEC 60942-2003 Class 1, and it was calibrated 24.01.17. The output level of the calibrator is 114±0.2 dB at 1 kHz [36].

Table 4.2: List of equipment

Type	**Manufacturer**	**Model**	**Serial No.**	**No.**
Mobile recording system	HEAD Acoustics	SQuadriga II	33221268	1
Free-field 1/2” microphone	GRAS	46AE	259983	3
Microphone preamplifier	GRAS	46AE	260054	3
Free-field 1/2” microphone	Norsonic	1206	31055	1
Microphone preamplifier	Norsonic	1225	79581	1
Microphone amplifier	Norsonic	Type 336	20578	1
Windscreen	GRAS	AM0069	-	3
Calibrator	Norsonic	Nor1251	33028	1
Portable loudspeaker	Music Angel	JH-MD04E3	800169593	1
Laptop	Lenovo	320S	MP1BS8GW	1
Software	MathWorks	MATLAB 2017b	-	1
Software	HEAD Acoustics	ArtemiS suite	-	1
Software	Audacity Team	Audacity 2.2.1	-	1

Chapter 5

Measurement Results

In this chapter all the obtained results will be presented. The results will answer the objective of this thesis which regards how much the noise from Oslo tramways and metros becomes attenuated when there is a forest between the sound source and receiver.

First a description of the measurement area will be given in section 5.1.1 followed by section 5.1.2 which will focus on the attenuation as a function of distance, where the trams and metros are analyzed individually. In section 5.1.6 the frequency content will be analyzed to see how the different frequencies are attenuated. A statistical analysis is included in section 5.1.5 to study how consistent the measured level at each microphone position is.

In section 5.2 the ground impedance results are analyzed. These results will be discussed together with the sound propagation analysis to eliminate the ground reflection and absorption as a parameter contributing to the attenuation. This will lead to section 5.3 where the attenuation caused by the vegetation and forest only is studied, based on the upper frequency range.

Last part of this chapter will include the possible sources of error in section 5.4 and discuss the results and the significance of the findings in section 5.5. In this section the results are summarized leading to the conclusion in the next chapter.

5.1 Sound Propagation Analysis

All the calculations in this section are based on multiple measurements done various days during the months from January to April. Every single measurement from each measurement day is tabulated in Appendix A with information about vehicle type, what identification number it has, average velocity and the maximum SPL at the different microphone positions; both unweighted and A-weighted.

Figure 5.1: Measurement area 13.02.18 with open field conditions and ground covered with snow. The tracks are just below the upper part of the fence. An acoustic camera is shown to the right.

5.1.1 Description of Measurement Area

Every single forest is unique. Hence it is important to describe what kind of forest that is used during the measurements. All measurements are performed at Jarmyra, and even if there are lot of trees and vegetation there, it is hard to find a spot with continuous and dense forest that covers the measurement distance of interest.

More information about the specific conditions on the measurement day such as snow depth is given in Appendix A.

(a) Microphone closest to the tracks (position 1).

(b) Vegetation in front of microphone position 2.

(c) Trees in front of microphone position 3.

Figure 5.2: Microphone positions in forest area.

A field with a kind of barriers made of trees is chosen as it is one of the denser places in the forest. Figure 5.2 shows the different microphone positions and how the vegetation is in this area. Microphone closest to the tracks (Figure 5.2a) in the forest area consist of small shrubs of birch. There is no shrubs between microphone position 1 and the tracks. The tree density is about 1.4 trees/m^2 when an area of 10 m x 10 m (100 m^2) between the first and second microphone position is considered.

The birch stem diameter ranges from 0.5 to 4 cm with an average height of 3 m which is close to microphone position 1. The vegetation in front of microphone position 2 (Figure 5.2b) is like a barrier on a straight line which consists of spruce and birch. Here the average stem diameter is bigger in the range from 1 to 40 cm, but there is a greater space without any trees within a radius of one meter from this microphone position. The average height of this vegetation is about 10 m.

Microphone position 3 (Figure 5.2c) is placed behind a forest which consists of birch and spruce like the vegetation in front of microphone position 2, but the stem size is in general even greater here in the range from 1 to 40 cm. The average height of the forest is about 15 m. When a 100 m^2 area between microphone position 2 and 3 is considered, the density is about 0.7 stems per square meter. Just in front of the microphone position the vegetation is denser (10 stems/m^2), but on the sides, there are some open spots.

The open field measurements are done about 100 m away from the forest area (see Figure 5.1). As the image shows, there are a few small shrubs consisting of birch, but there are no obstacles in front of the microphones.

As the ground conditions vary with snow depth during the different measurements, all the heights are based on the relative height from the top of the tracks which is constant instead of the height from the surrounding ground. This means that the height from the surrounding ground to the top of the tracks which is equal to 1 m is based on an average value with and without snowy conditions.

5.1.2 Level Attenuation

All the metro and tram pass-by measurements are aggregated into a mean value separated for the open field and forest measurements. The parameter used for the measurements is the maximum sound pressure level with a fast time constant and with both A-weighting and no spectral weighting.

The level attenuation analysis is based on the average of a total of 78 and 96 measurements for open field and forest conditions, respectively. 111 of the measurements were performed with snowy conditions (January and February), and 63 of the measurements were done when there were almost no snow in April. The results are based on measurements from both inbound and outbound trams and metros representing six different measurement distances in the range from 6 to 30 m from the center line of the tracks to the receivers.

In the following sections the inbound and outbound pass-by measurements are included in the same plots, but they are also studied individually. A regression model is made for the level attenuation to take all the measurement distances into account, and make the overall level attenuation more robust. Details about the regression model can be found in the MATLAB code in Appendix B.

5.1.3 Level Attenuation of Trams

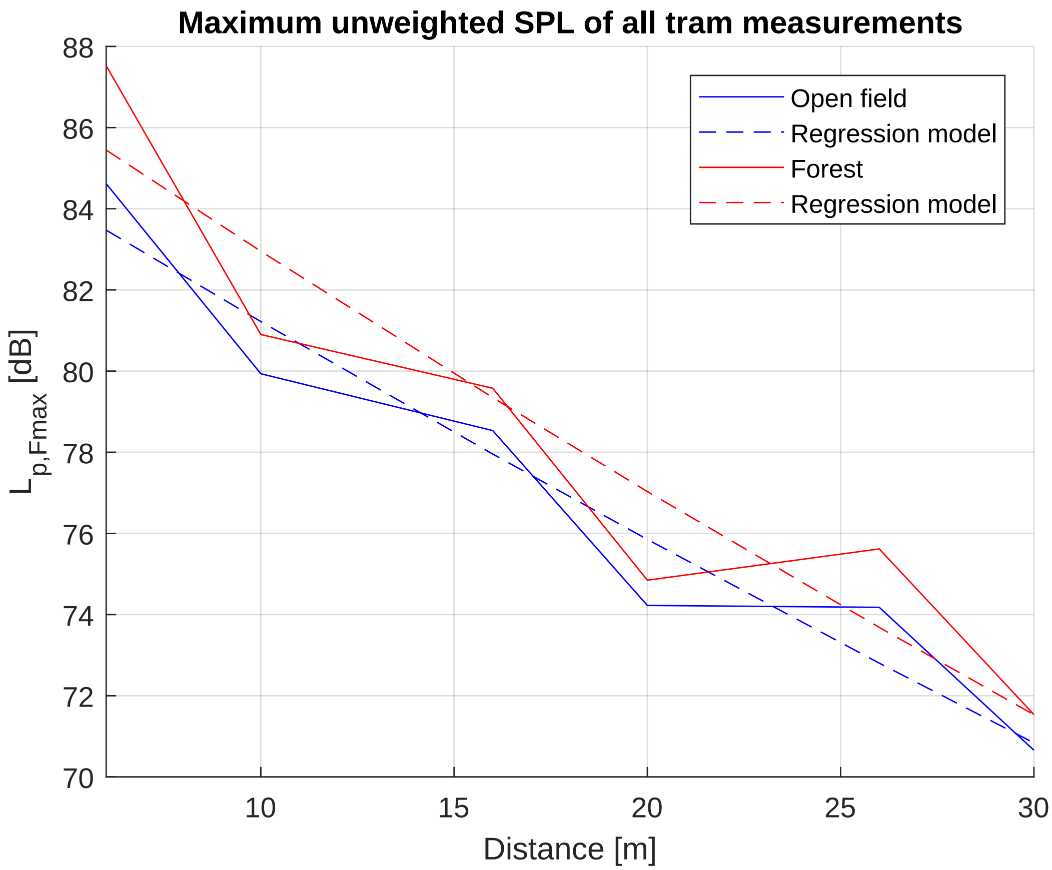


Figure 5.3: Level attenuation of trams with open field and forest measurements. No weighting filter is used.

Figure 5.3 shows how the noise from trams are propagating as a function of distance from the center line from the track farthest away from the microphone positions. The microphone positions are 6, 10, 16, 20, 26 and 30 m away, see also Figure 4.1 for experimental setup. The tram measurement curve for open field conditions decreases monotonically and has a decrease of about 6-7 dB per doubling of distance. The forest measurement curve has much of the same behavior, but with a higher slightly higher level at every position and especially at the distance of 26 m.

The measured initial level for the open field conditions is 84.6 dB in Figure 5.3 and it ends with the level of 70.7 dB, giving a total decrease of 13.9 dB. For the forest conditions, the measured level at the closest microphone position is 87.5 dB and 71.5 dB at the microphone at 30 m distance. This implies a total level decrease of 16.0 dB from 6 to 30 m. For this distance range, this means that there is an excess forest attenuation of 2.1 dB.

For the regression models, the total level attenuation is 14.0 dB for the forest conditions and

12.7 dB for the open field conditions. This suggests an excess forest attenuation of 1.3 dB.

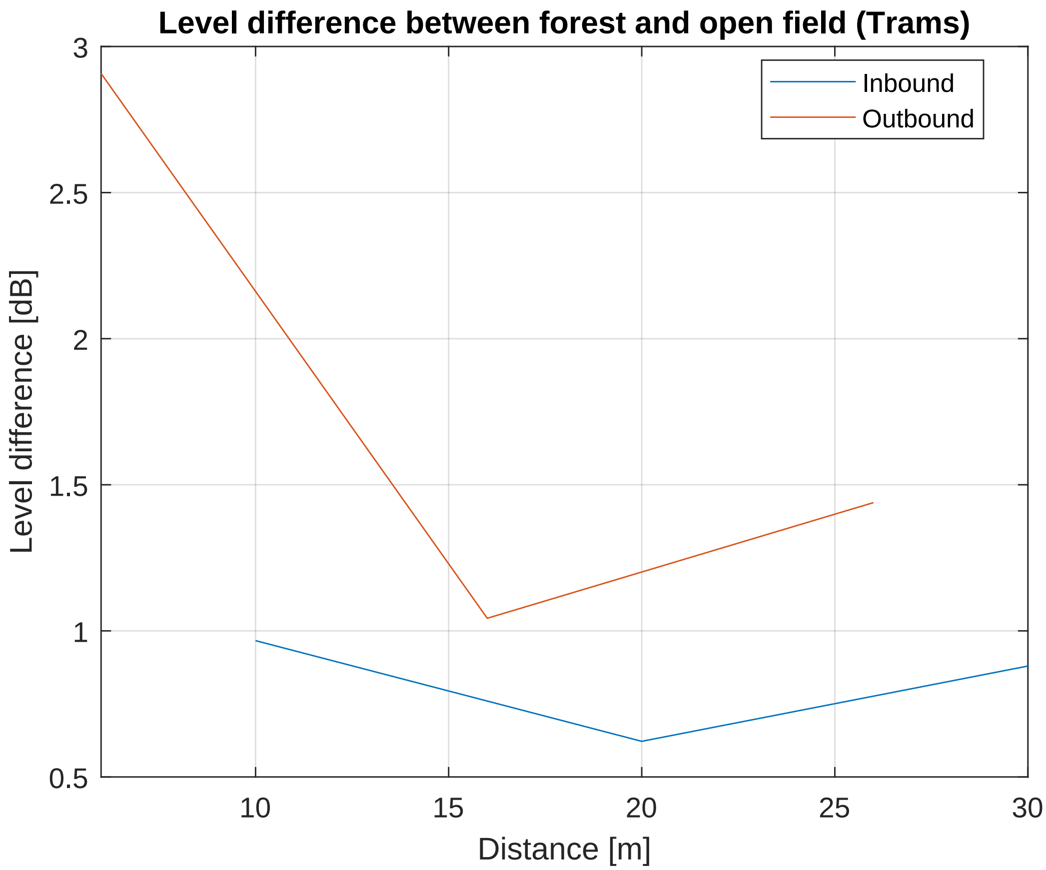


Figure 5.4: Level difference between forest and open field measurements when the open field measurements are used as reference. The results are based on all the inbound and outbound tram measurements.

The level difference between forest and open field tram measurements for inbound and outbound traffic is given in Figure 5.4. There is a significant difference between the inbound and outbound level difference measurements. This is confirmed by the uneven pattern for the tram measurements in Figure 5.3 where all the peaks represent the outbound traffic. The inbound level difference ranges from about 1.0 dB to 0.6 dB whereas the outbound tram level difference ranges from 2.9 to 1.4 dB.

For the outbound level difference, the attenuation is greatest at the closest microphone position (6 m), which is natural since the SPL is in general higher for the forest measurements. For the inbound measurements the level difference is also greatest at the closest microphone position (10 m). Both for inbound and outbound measurements the level difference increases from microphone position 2 to 3, which is expected as the sound travels longer and through more vegetation.

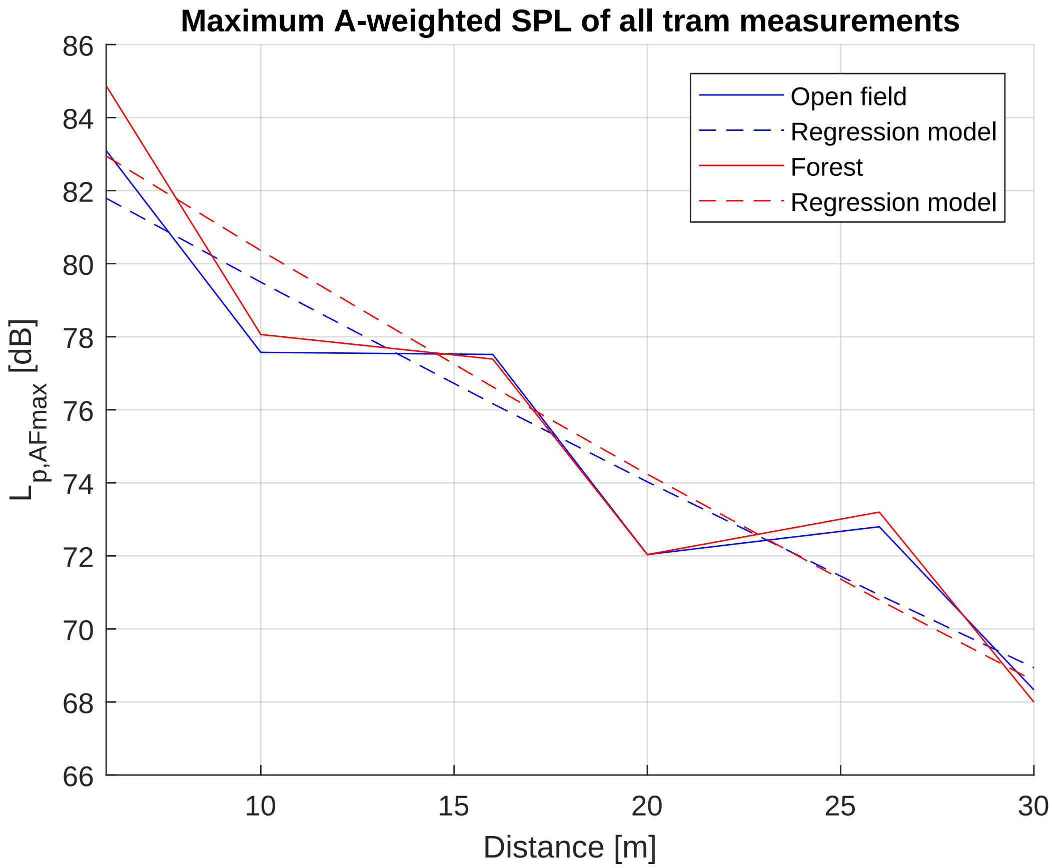


Figure 5.5: Level attenuation of trams with field and forest measurements. A-weighting filter is used.

In Figure 5.5, the maximum A-weighted SPL for trams are shown. The forest and open field measurements are almost equal, except from a higher initial level and lower which ends level for the forest measurements. Both curves have a saw tooth shape which means that the SPL is higher at all the outbound measurements which represent the distances of 6, 16 and 26 m. The values at the distances 6 and 30 m are 84.9 dB and 69.0 dB for the forest measurements. For the open field measurements the values are 83.1 and 68.3 dB. This implies that there is a total attenuation of 15.9 dB for forest conditions and 14.8 dB for open field conditions which means a 1.1 dB excess forest attenuation.

When the regression models are studied, the total level difference for the forest measurements is 14.4 dB, whereas it is 12.9 dB for the open field measurements. This suggests an excess forest attenuation of 1.5 dB.

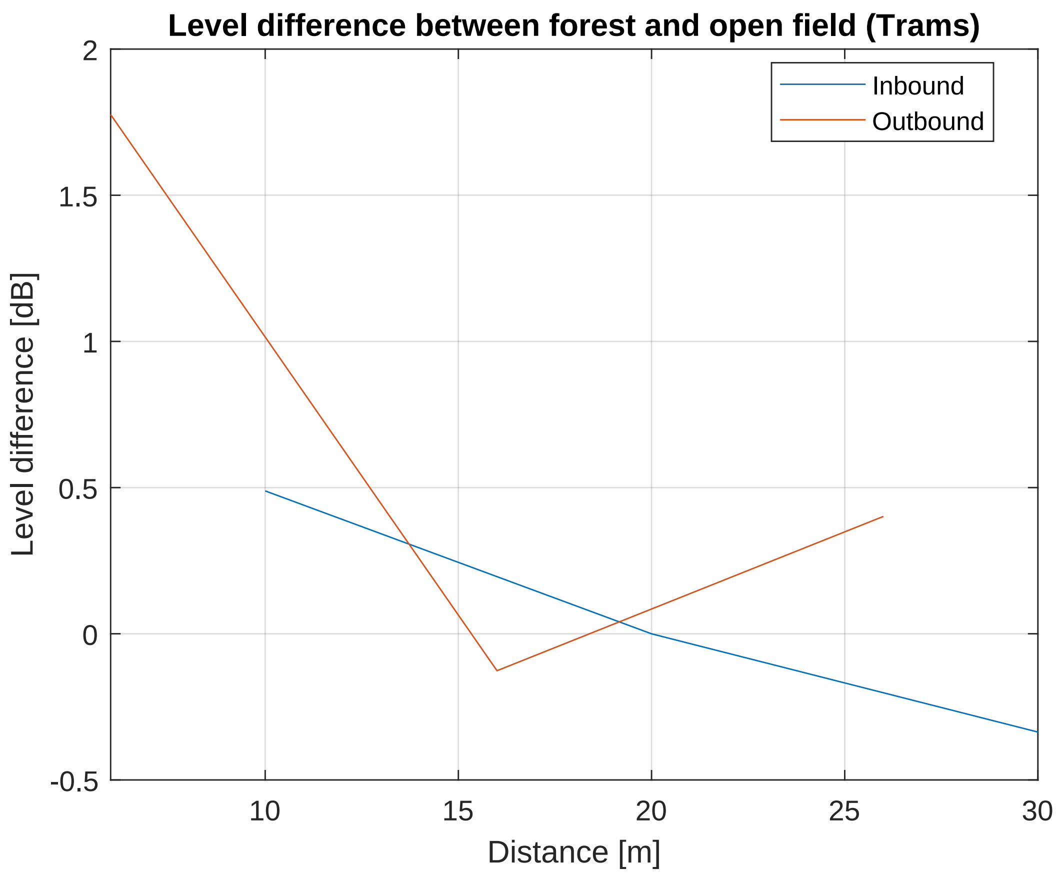


Figure 5.6: A-weighted level difference between forest and open field measurements when the open field measurements are used as reference. The results are based on all the inbound and outbound tram measurements.

The behavior in Figure 5.6 shows a lower excess forest attenuation compared to the unweighted measurements in Figure 5.4. The inbound level difference is getting smaller with increasing distance, whereas the outbound level difference is negative at the distance of 16 meters and close to 0.5 dB at 26 m. The difference between open field and forest conditions for A-weighted tram measurements is overall not very big.

Even if the A-weighted level difference in Figure 5.6 looks like the unweighted level difference in Figure 5.4, the A-weighted levels reveal that there is less difference between forest and open field conditions when trams are the noise source.

5.1.4 Level Attenuation of Metros

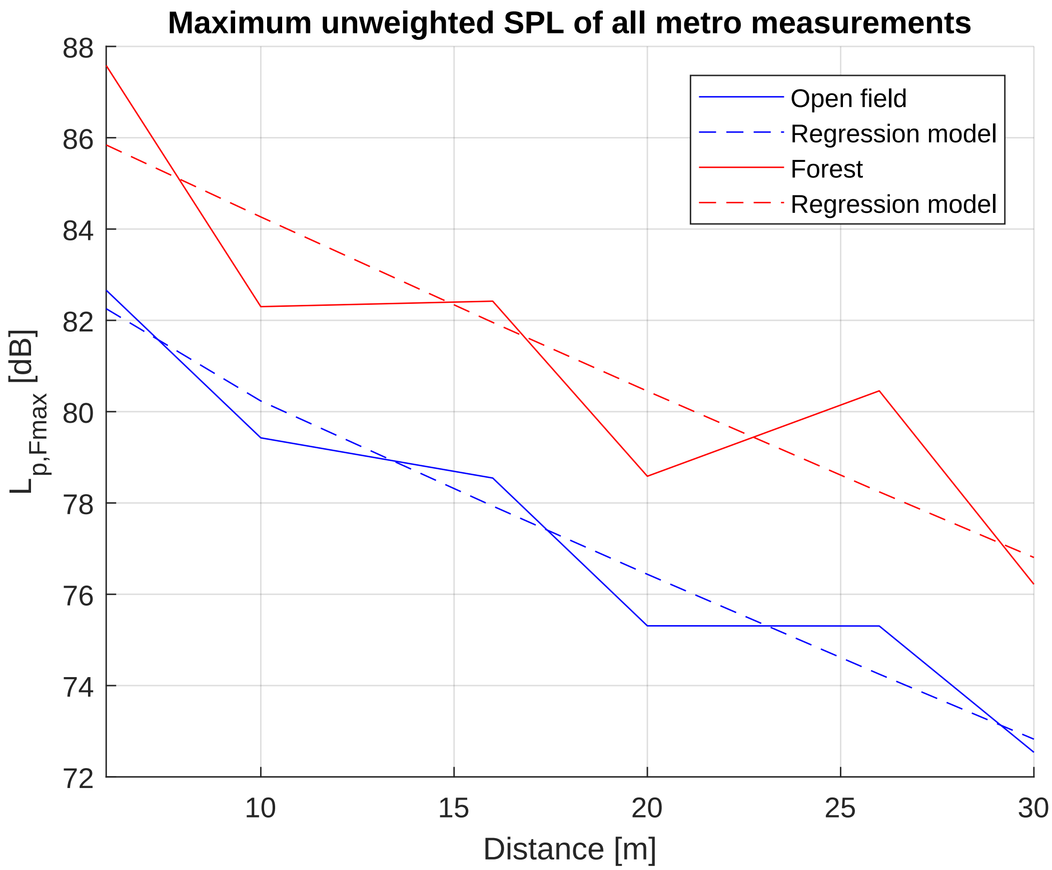


Figure 5.7: Level attenuation of metros with open field and forest conditions. No weighting filter is used.

The metro noise level curves for both the open field and forest measurements are very uneven where it seems like all the measurements from the inbound measurements (at the distances 10, 20 and 30 m) are 2-3 dB lower than expected. The reason for this could be because of something between the tracks disturbing the direct sound path.

The total metro noise level decrease from 6 to 30 m for open field conditions is about 10.1 dB; from 82.6 to 72.5 dB. For the forest measurement, the decrease is approximately 11.4 dB; from 87.6 dB to 76.2 dB. This implies that there is a 1.3 dB excess attenuation at 30 meter distance when there is a forest between source and receiver for metro noise.

The regression model for the forest measurements is almost 4 dB higher than the regression model for the open field measurements, where the total level decrease for the forest conditions only is 8.7 dB. For the open field conditions the total level decrease is 9.5 dB. This means that there is an negative attenuation for the forest conditions of 0.8 dB when the calculations are based on the unweighted SPL of all metro measurements.

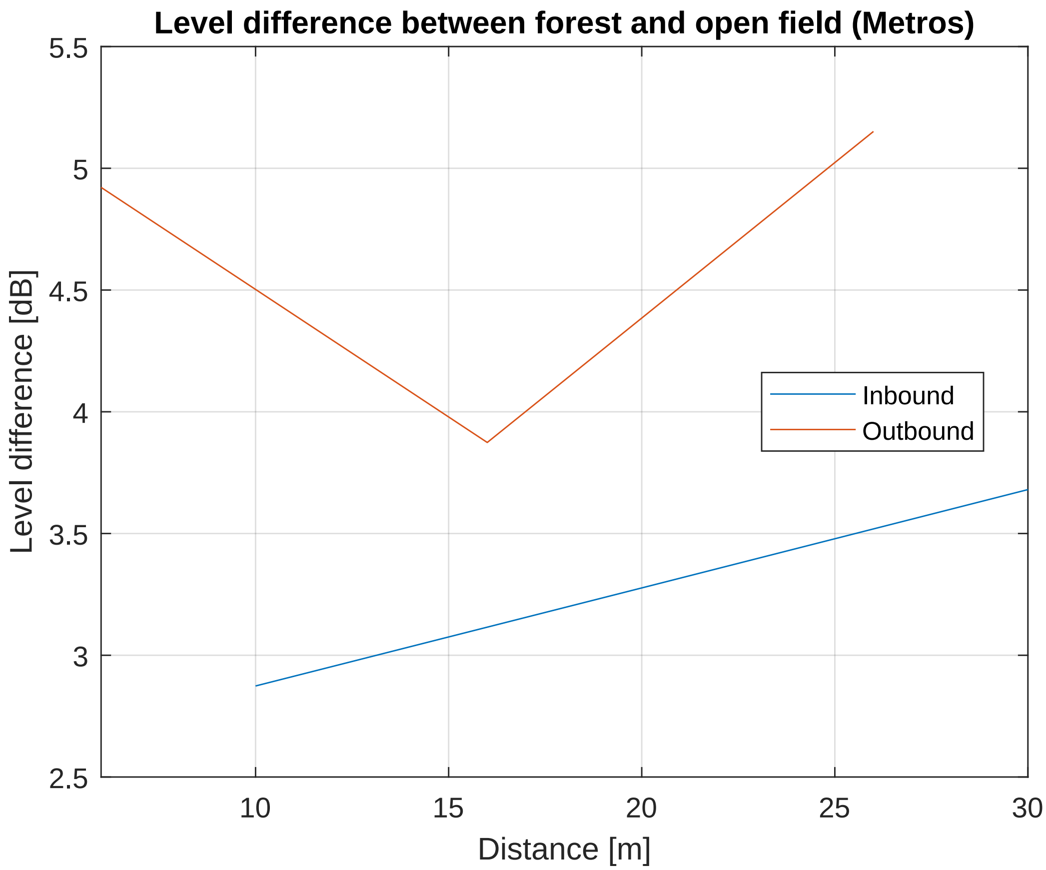


Figure 5.8: Level difference between forest and open field measurements when the open field measurements are used as reference. The results are based on all the inbound and outbound metro measurements.

In Figure 5.8 the difference between the level attenuation for forest and open field are compared. The plot shows that the level difference for unweighted metro measurements in general is high, ranging from about 3 to 5 dB when forest measurements are compared to open field measurements. The outbound measurements have a greater difference, in the same way as for the tram measurements. The inbound measurements have a linearly increase as a function of distance, whereas the outbound measurements only increases from 16 to 26 m, though with a steeper slope.

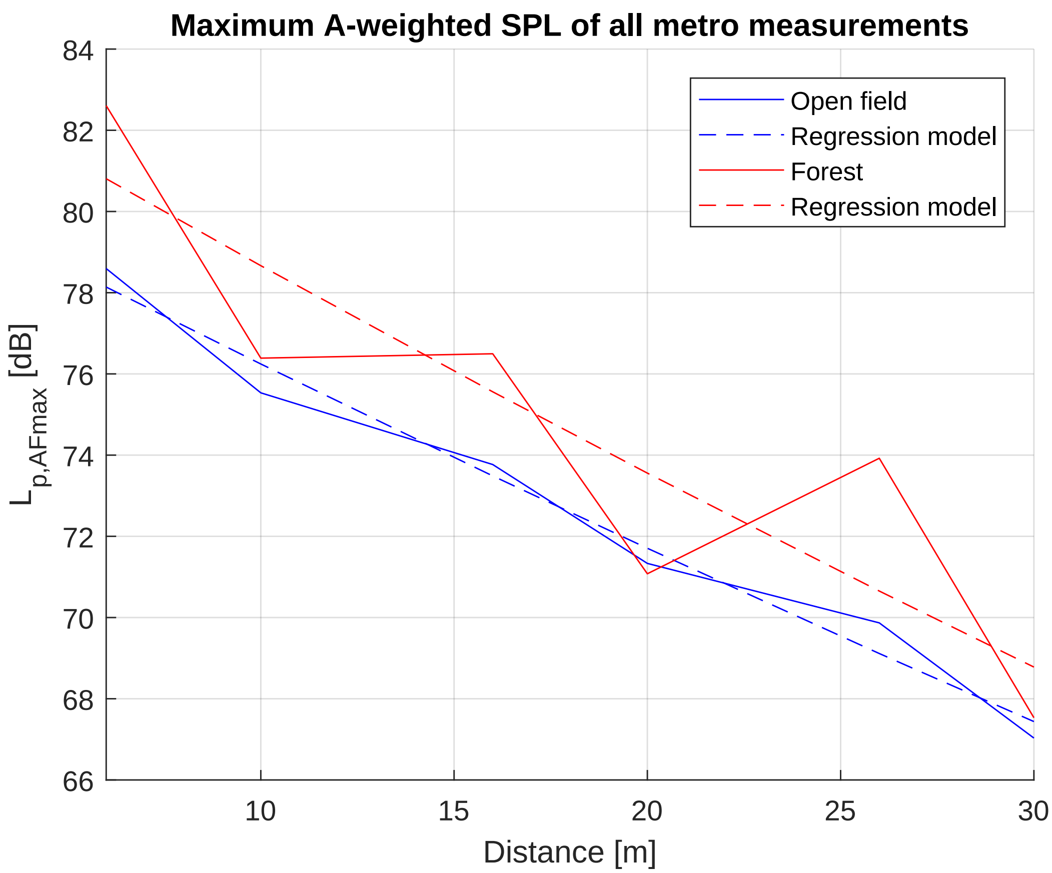


Figure 5.9: Level attenuation of metros with open field and forest conditions. A-weighting filter is used.

The A-weighted maximum sound pressure levels is compared for forest and open field measurements. In Figure 5.9 the sound level attenuation as a function of distance is shown, and the curves for the open field and forest measurements are quite different. The open field measurements decrease monotonically and look smoother, whereas the forest measurement curve has a higher level at the distances which represent outbound traffic.

The total A-weighted attenuation from 6 to 30 m is 11.6 and 15.1 dB for open field and forest measurements, respectively, giving an excess forest attenuation of 3.5 dB.

For the regression models, the total level decrease for the forest conditions is 12.0 dB and for the open field conditions the total level decrease is 10.6 dB. This suggests an excess forest attenuation of 1.4 dB.

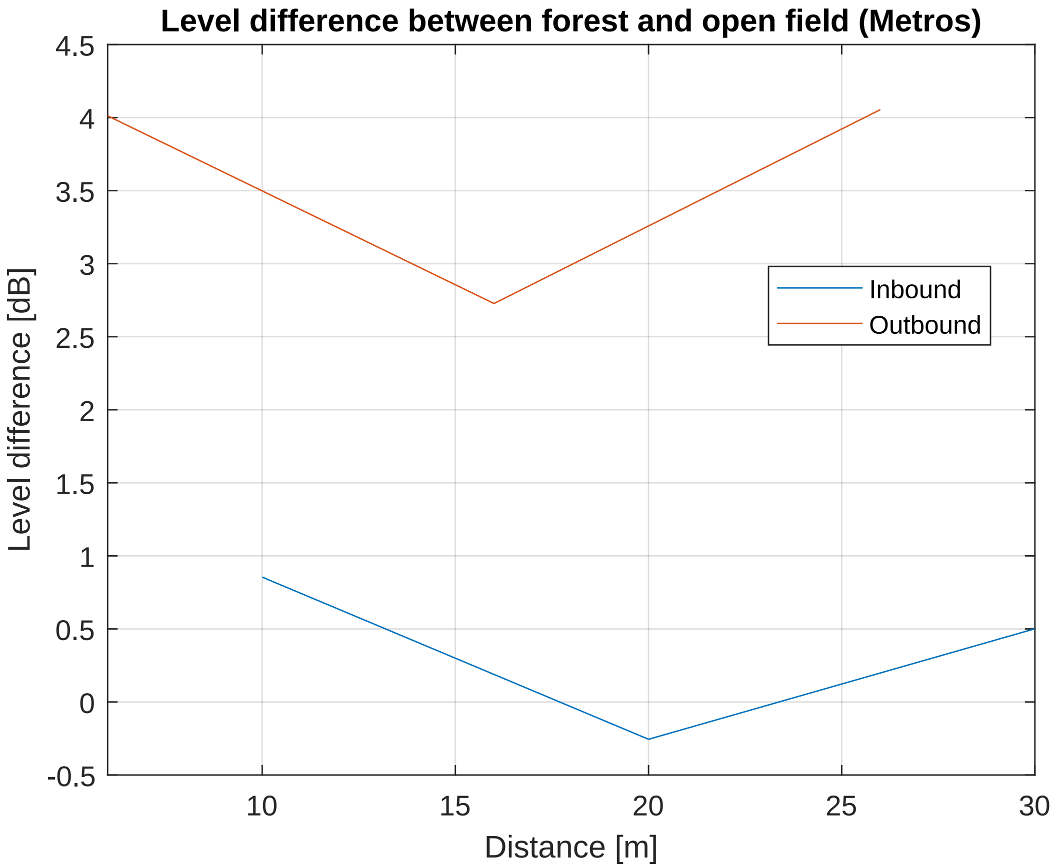


Figure 5.10: A-weighted level difference between forest and open field measurements when the open field measurements are used as reference. The results are based on all the inbound and outbound metro measurements.

The level difference plots between the inbound and outbound metro measurements are shown in Figure 5.10 when A-weighting is used. As for all the other level difference plots, the outbound level difference is greater than the inbound. The level difference is smaller for both the inbound and outbound measurements compared to the unweighted level difference (Figure 5.8).

The inbound and outbound curves almost have the same shape, with a greater level difference at the closest (6 and 10 m) and farthest microphone position (26 and 30 m). The inbound measurements show that the attenuation almost is the same for forest and open field conditions ranging from about -0.2 to 0.8 dB.

The results from these sections based on the overall level attenuation both from inbound and outbound measurements give that the excess forest attenuation is greater when the initial level (at 6 m) is directly subtracted by the ending level (at 30 m) compared to the total level attenuation based on the regression models. All the measurements suggest that there is an excess forest attenuation, except from the calculations based on the regression models of the unweighted metro measurements.

5.1.5 Statistical Analysis

This section will investigate the statistical significance of the results. The box plots in this section are divided into separate inbound and outbound plots as there is a significant difference between these two traffic directions. More details about box plots are found in Appendix E.

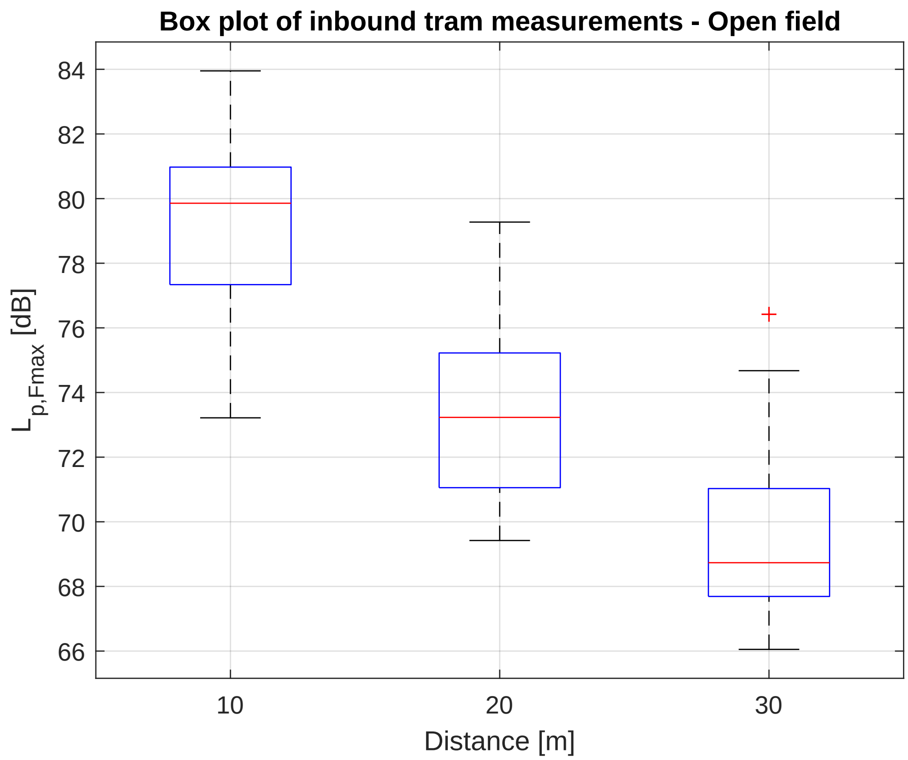


Figure 5.11: Box plot of inbound tram measurement in open field conditions.

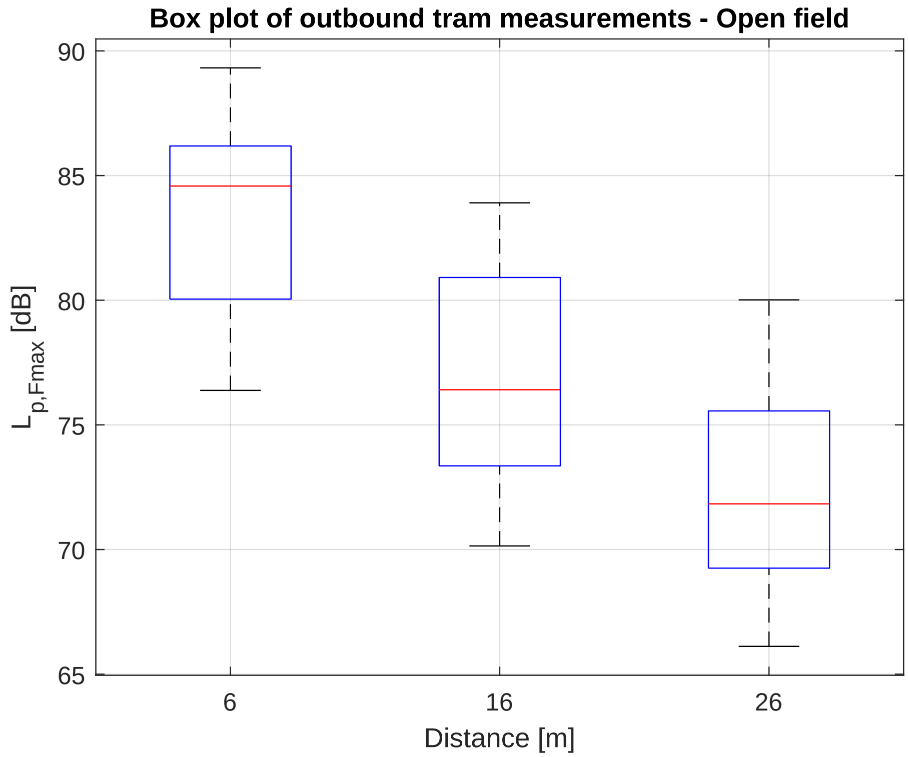


Figure 5.12: Box plot of outbound tram measurement in open field conditions.

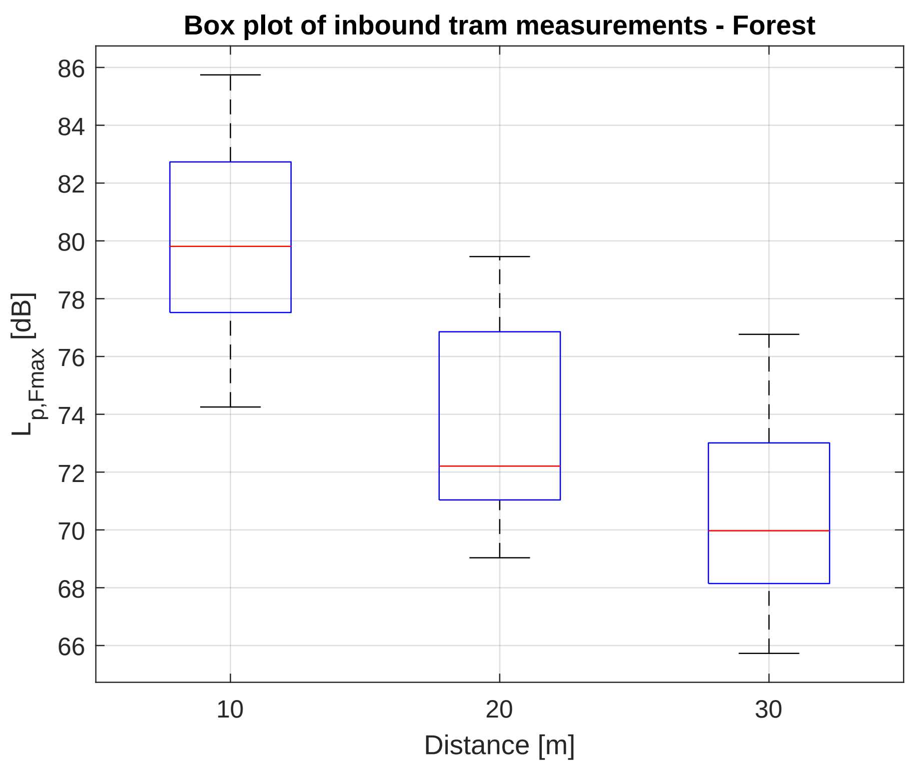


Figure 5.13: Box plot of inbound tram measurements with vegetation.

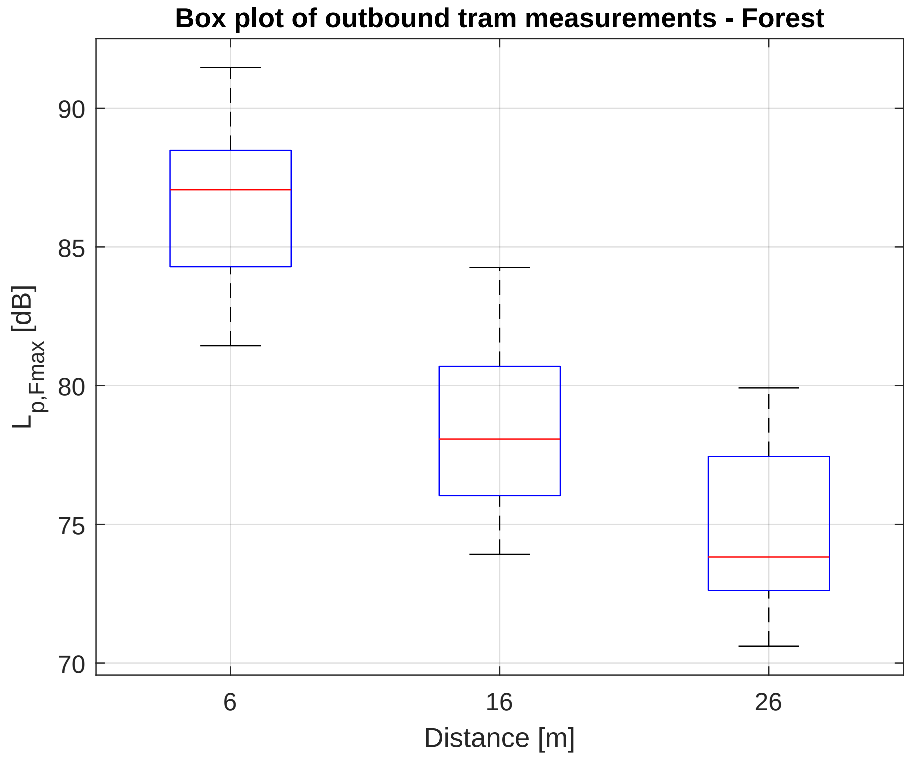


Figure 5.14: Box plot of outbound tram measurements with vegetation.

The box plots of the tram measurements are given with open field conditions in Figure 5.11 and 5.12, and with forest conditions in Figure 5.13 and 5.14. All the plots look very similar with a difference of 7-8 dB between the median measured at the first and second microphone position. The median value between the second and third microphone position is in the order from 2 to 4 dB. For all the inbound measurement, the distance is doubled from the first to second microphone position, and the results show that the attenuation is a bit larger than what it is for an ideal monopole source.

The difference between the 25th and 75th percentile (blue boxes) is in the range from about 2 to 6 dB for all the tram measurements, and the whiskers are in the range from 9 to 15 dB. There is only one outlier at the distance of 30 m for the inbound tram measurements with open field conditions, but the outlier is not that far away from the upper limit of the whisker. All the measurements show a natural sound level decrease as a function of distance when the inbound and outbound measurements are studied separately.

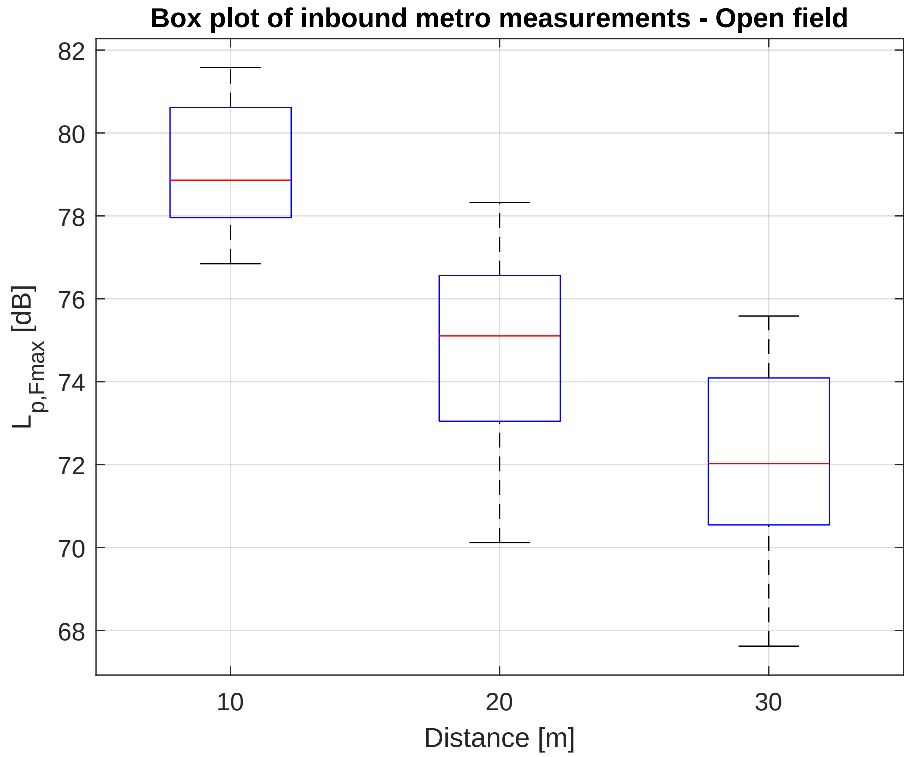


Figure 5.15: Box plot of inbound metro measurement in open field conditions.

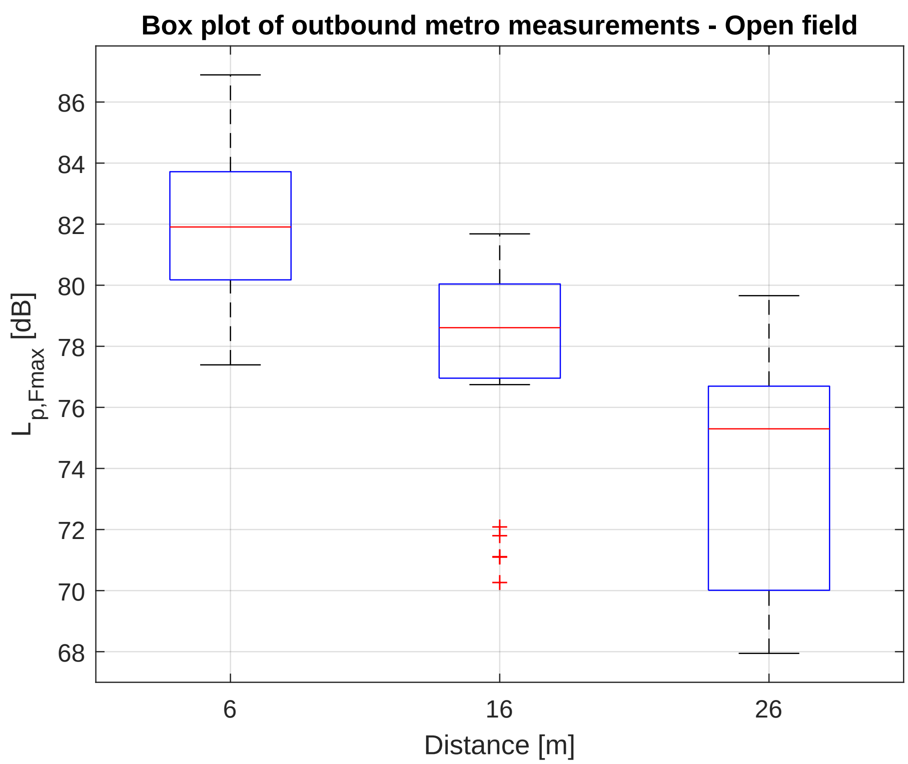


Figure 5.16: Box plot of outbound metro measurement in open field conditions.

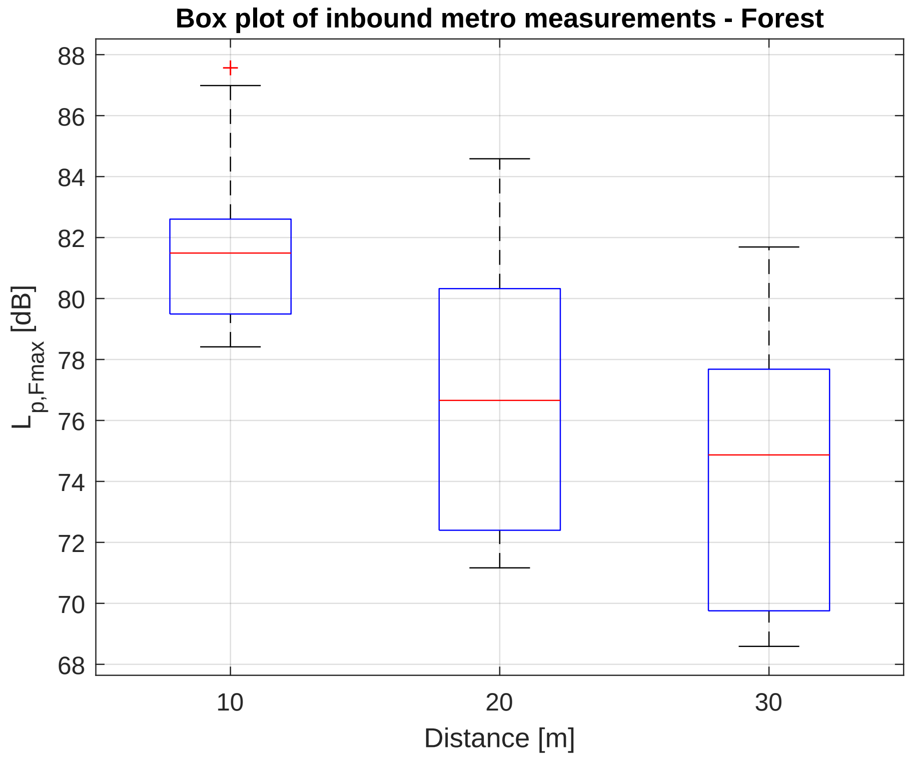


Figure 5.17: Box plot of inbound metro measurements with vegetation.

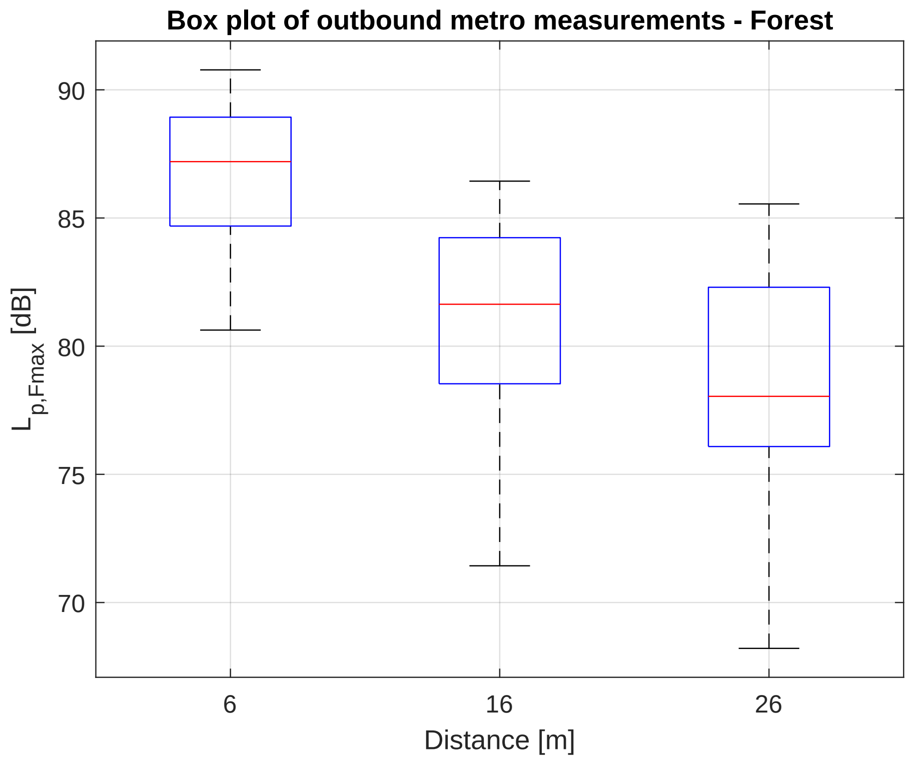


Figure 5.18: Box plot of outbound metro measurements with vegetation.

The box plots of the metro measurements are given with open field conditions in Figure 5.15 and 5.16, and with forest conditions in Figure 5.17 and 5.18. The plots show that the variance is smallest at the first microphone position for all the metro measurements. Here the difference between the 25th and 75th percentile is in the range from 3 to 4 dB. The variance is smallest at microphone position 1 because there are less parameters contributing to the variability in SPL. At the second and third microphone position the ground and forest effects might influence the SPL in a more significant way.

The variance is greatest for the inbound metro measurements with forest conditions at microphone positions two and three. There are four outliers at the distance of 16 m for the outbound metro measurement with open field conditions, whereas the whiskers are only ranging about 5 dB. The reason of the outliers at this distance is that the sample size is a bit smaller here as one microphone did not work during the measurement session performed 13.02, and that the SPL measurements performed 28.02 in general were lower. The reason of this is probably because it was most snow at this measurement day.

The findings from this statistical analysis are that the median of the sound level decreases monotonically as a function of distance for both the tram and metro measurements when inbound and outbound traffic is studied separately. There is however a higher variance at the plots representing the metro measurements with forest conditions, where some of the whiskers are in the range of 17 dB.

5.1.6 Frequency Attenuation

In this section the frequency spectrum of the tram and metro measurements for the different distances are analyzed to study the different behavior and to distinguish if the attenuation is caused by the vegetation or the ground.

All the maximum SPL frequency measurements with open field and forest conditions are presented in the figures below. The different colors represent the distance from the center line of the track to receivers i.e. the different microphone positions. In all the figures, the open field measurements are in the upper plot and the forest measurements are in the lower plot. The frequency plots are based on an average of all the measurements.

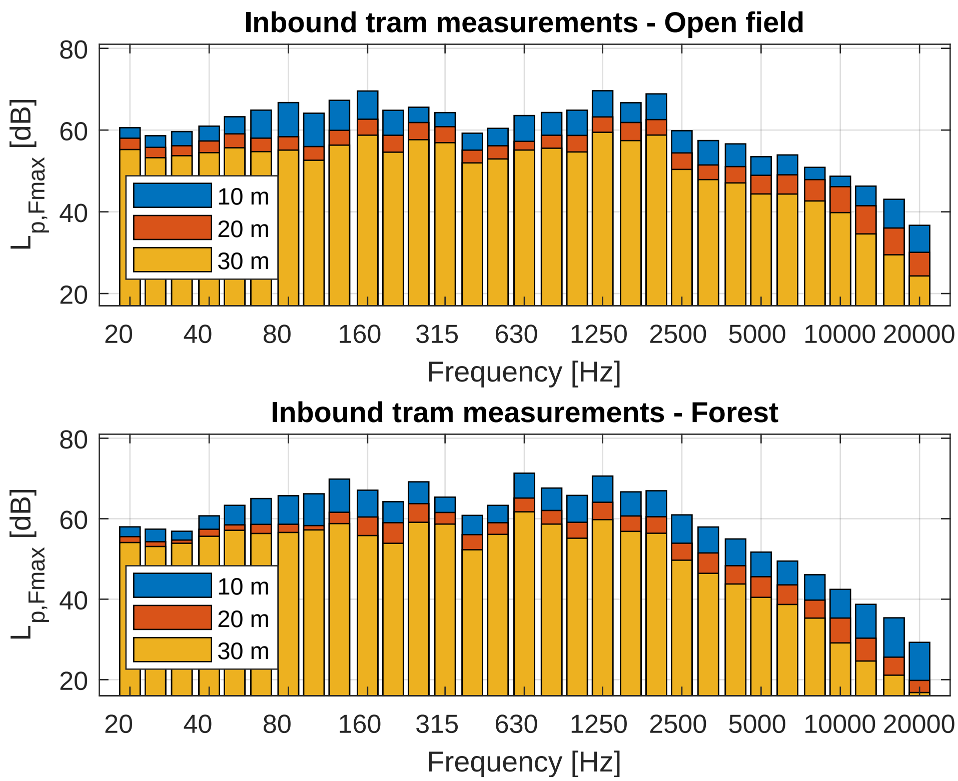


Figure 5.19: Inbound frequency spectra for tram measurements.

The bar graphs for open field and forest conditions in Figure 5.19 have pretty much of the same shape. The peaks around 1250-2000 Hz are visible in upper and lower subplot as well as the decreasing level with increasing frequency above 2000 Hz. The most significant difference between the plots are that the red bars are greater for the open field conditions in the frequency range from about 2500 Hz. It therefore seems like most of the higher frequency content is attenuated already at the second microphone position (red bar) for the forest conditions.

For the lower frequency range below 125 Hz, the attenuation from the middle microphone position (red bar) to the farthest microphone position (orange bar) is very small when forest conditions are studied. In the higher frequency range on the other hand, the difference is greater.

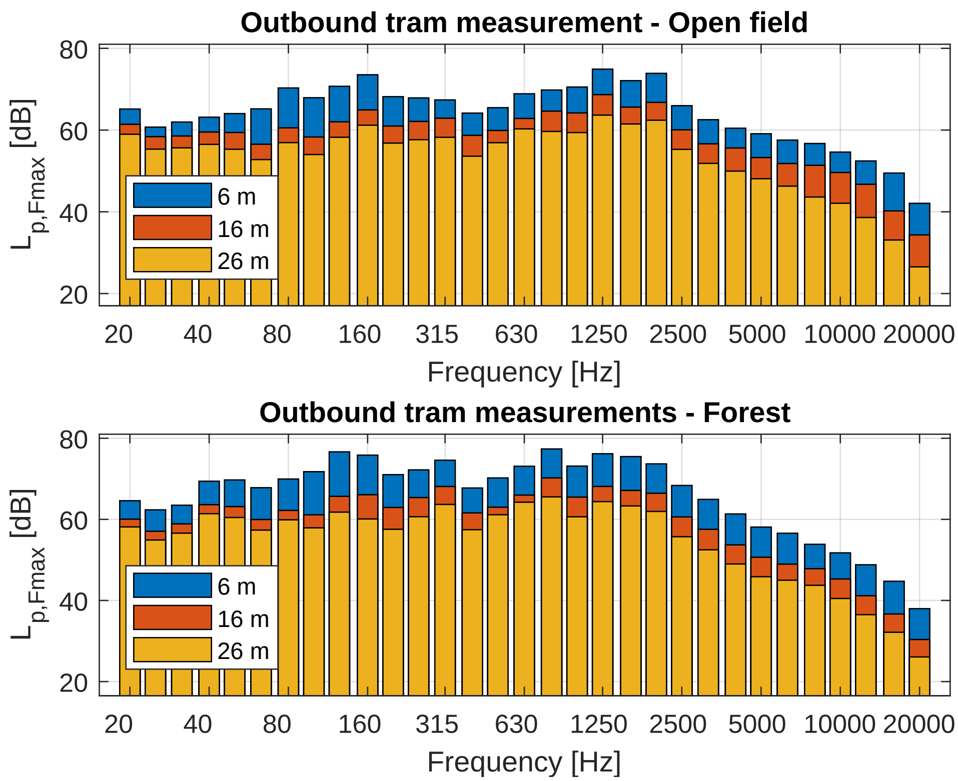


Figure 5.20: Outbound frequency spectra for tram measurements.

The frequency spectra in Figure 5.20 represent the outbound tram traffic which have much of the same shape as the frequency spectra which represent inbound trams in Figure 5.19. For the outbound traffic, the difference between the blue bars and the red and orange bars are however much greater. Since the receiver distances are shorter for the outbound traffic, the overall level is higher.

The peaks around 1250-2000 Hz are also visible for the outbound traffic plots. The difference from 6 to 26 m for the open field measurements is a bit greater from 10 kHz compared to the forest measurements.

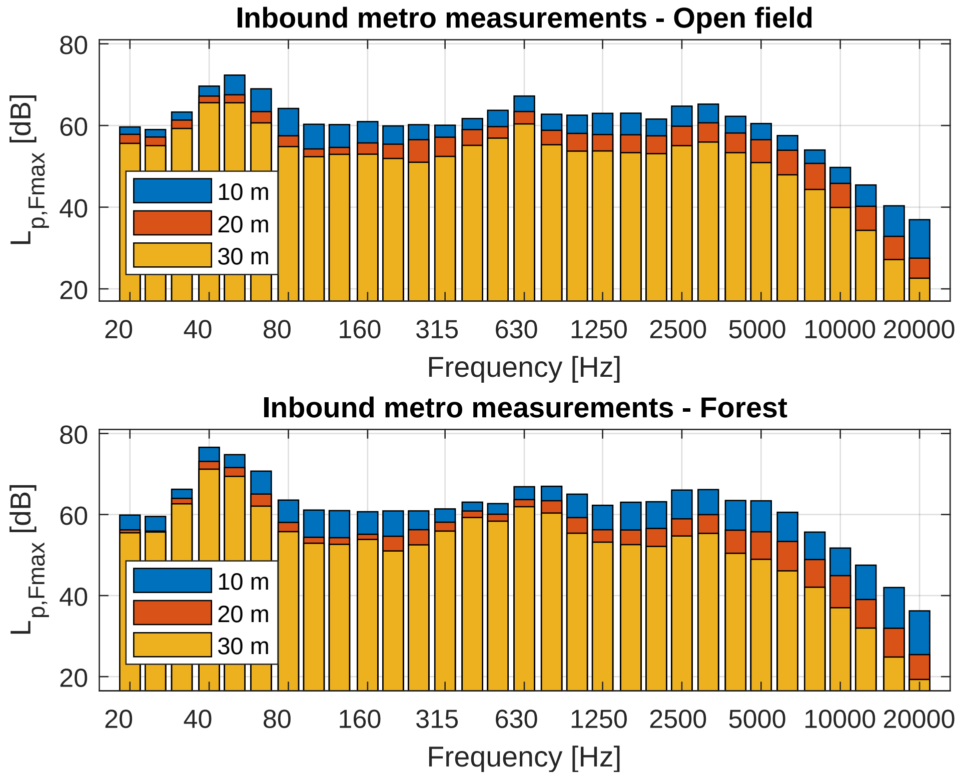


Figure 5.21: Inbound frequency spectra for metro measurements.

For the inbound metro measurements in Figure 5.21 there is a significant peak around 30-80 Hz and around 630 Hz. Above 630 Hz, the measured level approximately decreases with increasing frequency except from a higher level at the 2500 and 3150 Hz frequency bands. The SPL at the different distances is almost the same for the open field and forest measurements for frequencies below about 1 kHz. Above this frequency the SPL has a much greater difference between the closest microphone (blue bars) and farthest microphone (orange bars) position.

Compared to the inbound tram measurements, the metro measurements have a slightly higher level for the higher frequency content as well as the higher low frequency content around 30-80 Hz.

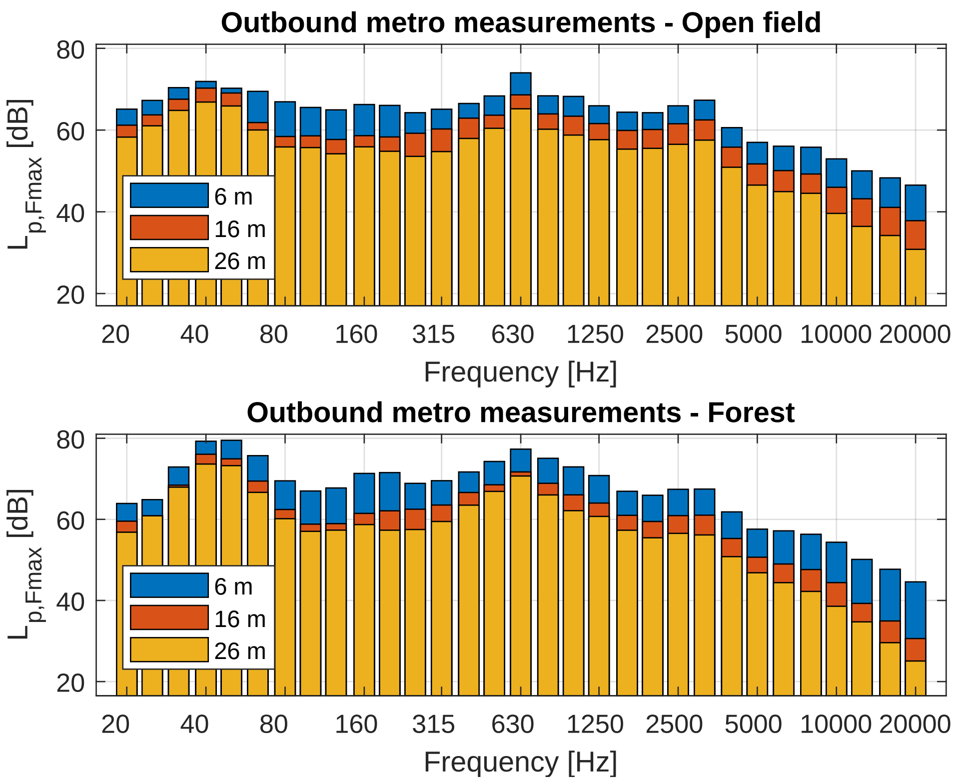


Figure 5.22: Outbound frequency spectra for metro measurements.

The frequency spectra for the outbound metro measurements in Figure 5.22 are also dominated by some low frequent noise in the area 30 to 80 Hz as well as a higher value at the frequency band of 630 Hz. After this peak value, the SPL decreases with increasing frequency except from the higher levels at the bands 2500 and 3150 Hz like for the inbound measurements. For the frequency content above 1 kHz, the SPL is much lower at the microphone position located at 26 m distance for the forest measurements compared to the open field measurements. The figure also shows that most of the noise in the forest conditions is attenuated already at 16 m where the red bars are closer to the orange bars.

Almost all the tram and metro measurements suggest that there is a greater level difference for outbound than inbound measurements. This is confirmed under Section 5.1.3 and 5.1.4. From the frequency plots above it can be seen that the high frequency content is some decibels lower for the inbound traffic compared to the outbound traffic.

It is hard to distinguish the difference between the vegetation and open field bar graphs above, so in the next paragraphs the level difference between the nearest and farthest microphone positions will be given as a function of frequency. Only unweighted plots are given above, and the next results will show which frequency bands that get most attenuated, independent of weighting filters.

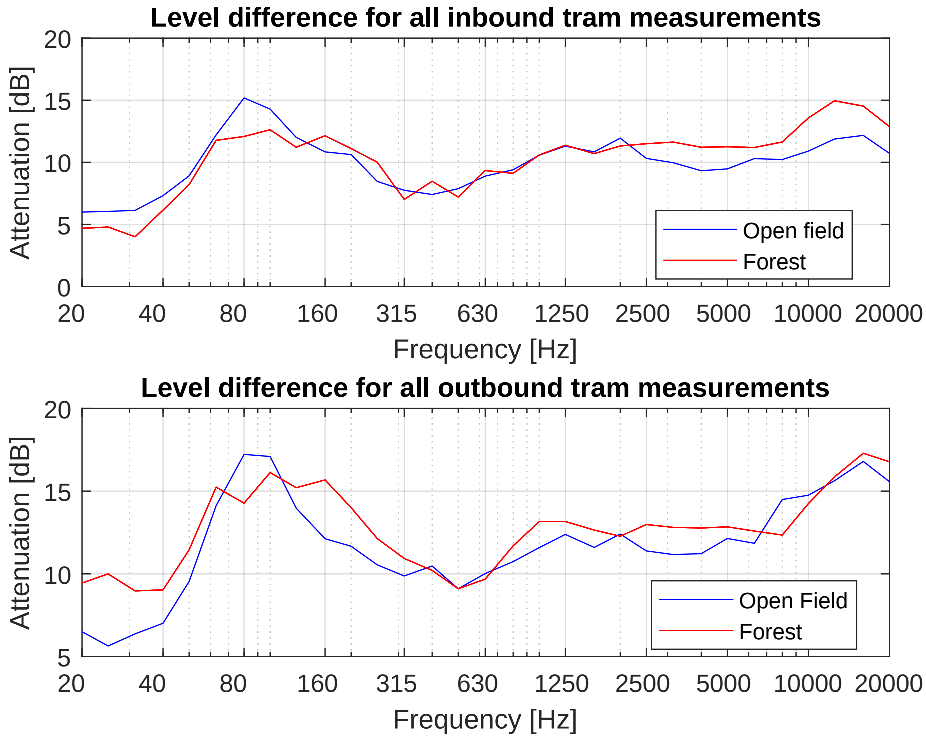


Figure 5.23: Tram noise attenuation when the nearest and farthest microphone positions are compared. Inbound trams are shown in upper plot and outbound trams in lower plot.

The results in Figure 5.23 are based on the maximum sound pressure level difference between the closest and farthest microphone position. Each individual tram pass-by level difference is found for the frequency range 20 Hz to 20 kHz and thereby averaged. The inbound and outbound level difference spectra have the same shape with a peak value around 80 Hz for the open field measurements and a dip in the frequency range from 20 to 50 Hz and 315 to 630 Hz. For the highest frequency content the level difference is higher for the open field conditions.

For the forest conditions the level difference curve follows the open field measurements with a dip in the range from 20 to 50 Hz and 315 to 630 Hz, but the peak is more stretched out from 63 to 200 Hz. The inbound measurements show that the attenuation is almost the same for open field and forest conditions except from a slightly lower forest level difference below 200 Hz, but 2-3 dB higher from approximately 2 kHz. For the outbound tram measurements the overall forest attenuation curve is a bit higher than the open field attenuation curve.

In the frequency range above 1 kHz, the outbound forest and open field level difference curves are almost equal to the inbound curves, but for the outbound open field attenuation curve, the attenuation is much higher from approximately 6.3 kHz.

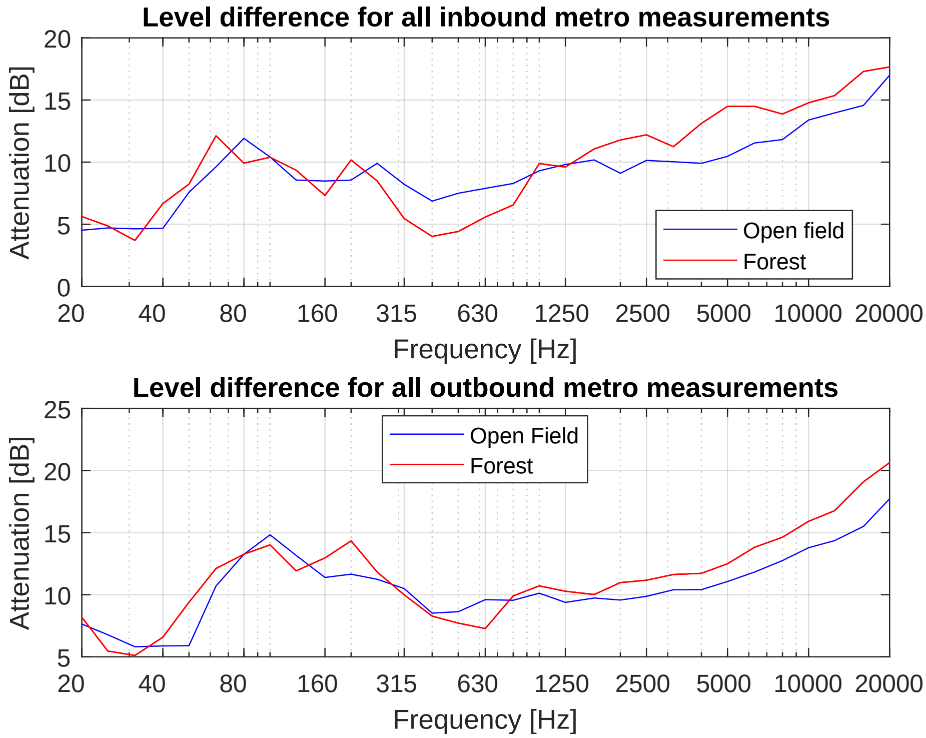


Figure 5.24: Metro noise level difference between nearest and farthest microphone position. Inbound metros in upper plot and outbound metros in lower plot.

For the metro measurements in Figure 5.24 there is a peak in the level difference at 80 and 100 Hz for the open field inbound and outbound traffic, respectively. The attenuation is smallest from 20 to 50 Hz for forest and open field conditions, and whereas the forest conditions have a dip in the area 315 to 630 Hz, the attenuation for the open field conditions is pretty flat after the peak around 80-100 Hz. The forest attenuation has a peak at 63 Hz for the inbound traffic, and two peaks at 100 and 200 Hz for the outbound measurements.

As for the tram measurements in Figure 5.23, the forest and open field attenuation curves have much of the same behavior, but from about 1 kHz, it is visible that the attenuation is consequently greater for the forest measurements. For the outbound measurements, the curves increase in a smooth manner and show a clear excess forest attenuation which increases with increasing frequency. The difference is in the order from 1 to 4 dB.

Table 5.1: Level attenuation based on the frequency analysis.

	Tram attenuation [dB]		
Parameter	**Forest**	**Open field**	**Excess attenuation**
Inbound	11.0 (10.6-11.3)	10.5 (10.1-10.9)	**0.5** (−0.3-1.2)
Outbound	13.4 (13.1-13.6)	12.8 (12.5-13.0)	**0.6** (0.1-1.1)

	Metro attenuation [dB]		
Parameter	**Forest**	**Open field**	**Excess attenuation**
Inbound	11.7 (11.5-11.9)	10.5 (10.1-10.8)	**1.2** (0.7-1.8)
Outbound	13.2 (13.0-13.4)	11.6 (11.4-11.9)	**1.6** (1.1-2.0)

The average attenuation for open field and forest conditions is compared in Table 5.1. The expanded uncertainty is based on a Student's t-distribution for a 90 % confidence interval [27]. As the upper and lower intervals are asymmetric around the average level because of decibel levels, they are included in a parenthesis after the average value. The sample sizes for the open field measurements are 19 and 21 inbound and outbound tram measurements, and 28 and 29 inbound and outbound metro measurements, respectively. The sample sizes when there are forest conditions are 20 each for outbound and inbound tram measurements, and 30 and 25 for inbound and outbound metro measurements, respectively.

The attenuation is based on the entire frequency range from 20 Hz to 20 kHz, and the results in Table 5.1 show that the difference between the forest and open field attenuation is almost equal for the inbound and outbound tram traffic. For the tram measurements there is an excess forest attenuation of 0.5-0.6 dB. For the metro measurements there is an excess attenuation of 1.2 and 1.6 dB for inbound and outbound measurements, respectively. If the expanded uncertainty is taken into account, the excess forest attenuation is at worst negative for inbound tram measurements. If the upper limit of the 90 % confidence interval of forest is compared to the lower limit for open field conditions, the excess forest attenuation is at best 1.1-1.2 dB for the tram measurements. For the metro measurements, the excess forest attenuation is at worst 0.7 dB and at best 2.0 dB.

Even if the results in Table 5.1 say that there is an excess attenuation for forest conditions based on the average attenuation levels, these calculations are based on the entire frequency range. It is needed to study multiple factors as ground and interference effects to conclude if the forest measurements really are caused by forest and vegetation. The ground and interference effects will be studied in section 5.2 and a deeper look at the higher frequency content is performed in section 5.3.

According to equation 3.2 with a frequency of $f = 2$ kHz, the expected absorption coefficient for woods is $\alpha_{woods,2000} \approx 0.13$ dB/m. If this is multiplied with the distance of 20 m, the total expected excess attenuation is approximately 2.5 dB. For the metro measurements, this answer is in great accordance with the excess attenuation in Figure 5.24, whereas for the tram measurements there is approximately no attenuation difference between forest and open field measurements.

If $f = 5$ kHz, the theoretically absorption coefficient for forest is $\alpha_{woods,5000} \approx 0.17$ dB/m. This implies a total attenuation of about 3.4 dB for a distance of 20 m. An average of the inbound and outbound metro measurements for the excess forest attenuation gives an approximately level of 3.0 dB, whereas the attenuation for the tram measurements is in the area of only 1 dB. It seems like the formula (equation 3.2) overestimates the excess forest attenuation when it is compared to the tram measurements, but it is not that far from reality for the metro measurements.

5.2 Ground Impedance Measurements

In this section, the results from the ground impedance measurements are presented. For each measurement, a small report is generated and is found in Appendix A. In the Appendix the measured ground impedances are tabulated. The results from the ground impedance measurements will be used to calculate the ground absorption to discuss the results obtained from the specific day to eliminate other factors than the attenuation caused by the trees and vegetation.

The absorption coefficient is found by the use of equation 3.10, where the reflection coefficient is found by the measured specific acoustic impedance of the ground (Z_s) and air (Z_0) given by equation 3.9.

5.2.1 Ground Absorption

In this section the absorption coefficient from the open field and forest ground will be presented in two individually plots. The determination of the ground impedance by the use of ANSI S1.18 only covers the frequency range from 250 to 4000 Hz. The results from the frequency analysis (section 5.1.6) show that there is a peak attenuation in the range from 50 to 200 Hz, but the standard will not be able to confirm if this attenuation is caused by the ground.

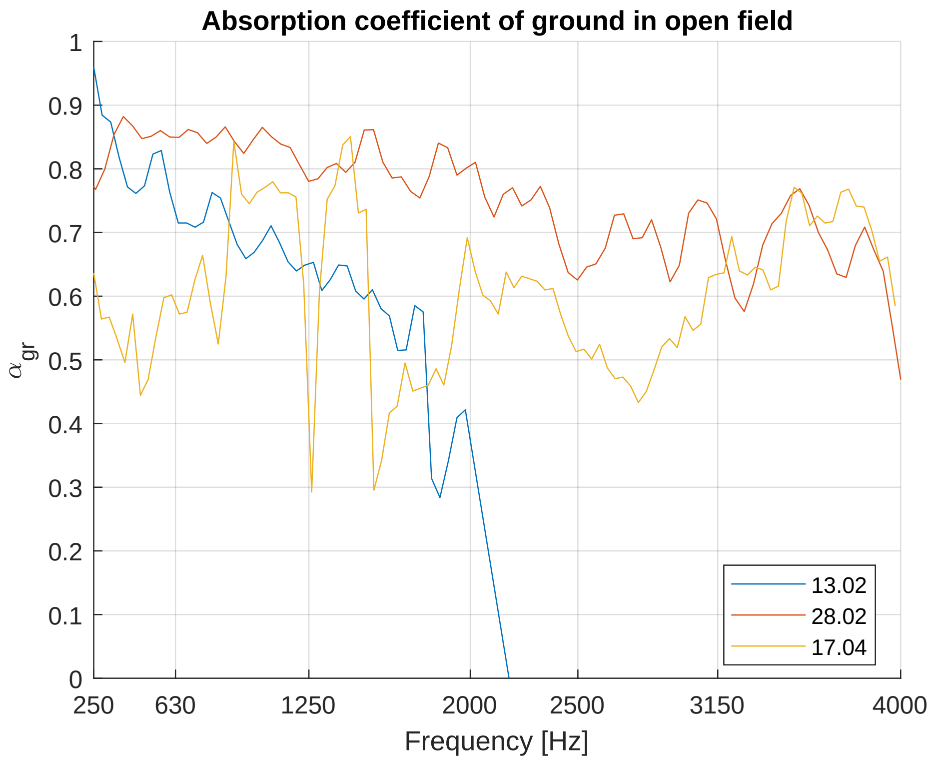


Figure 5.25: Measured absorption coefficient of ground with open field conditions.

The calculated ground absorption coefficient based on the impedance measurements in open field conditions is presented in Figure 5.25. The measurements performed 13.02 (blue curve) and 28.02 (red curve) is done with a ground covered with snow (more details in Appendix A). For these measurement days, it can be shown from the plot that the absorption is very high (above 0.7) below approximately 1 kHz. The ground absorption 28.02 is high over the entire range between 0.5 and 0.9. Both are decreasing with frequency, and the measurement from 13.02 is not converging after 2 kHz.

The absorption coefficient measured 17.04 (yellow curve) has a more uneven shape. The ground absorption this day has some dips around 250-630, 1250, 1550 and 2800 Hz. The two highest peaks are located at about 900 and 1440 Hz, and the absorption coefficient is ranging from 0.3 to 0.85 between the dips and peaks.

The measurement curve from 13.02 is performed by the use of geometry A, whereas the measurements performed 28.02 and 17.04 are measured with geometry B. The ground absorption curves in Figure 5.25 are based on the ground impedance measurement at the specific day that did converge over the entire frequency range in the MATLAB script.

The MATLAB script takes the real and imaginary part of the transfer function as input parameter. The generation of the transfer function is done both with a built-in function in the analyzing software ArtemiS and by the use of equation 3.11 in MATLAB (see Appendix B). This is done to eliminate possible sources of error, and see if one method made the MATLAB script converge over the entire frequency range.

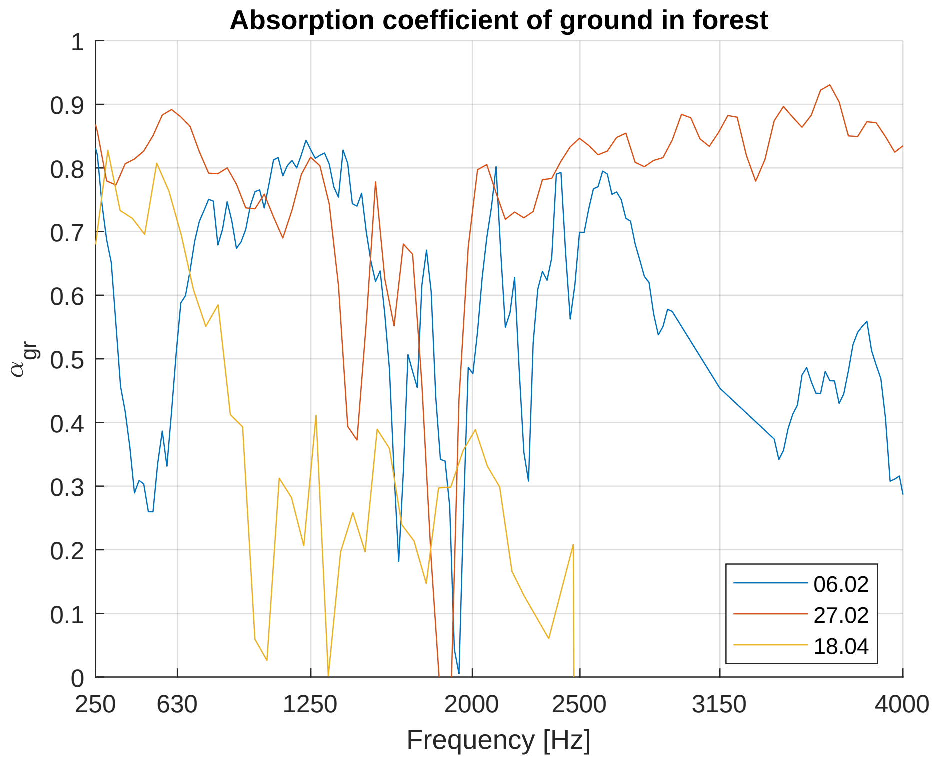


Figure 5.26: Measured absorption coefficient of ground with forest conditions.

For the ground absorption with forest conditions in Figure 5.26 there are more variations in the different curves. The measurements performed 06.02 (blue curve) and 27.02 (red curve) are done with snowy conditions, and the measurement performed 18.04 (yellow curve) is done with a combination of a thin layer of snow and ice. For the measurements performed with snowy conditions, there is some of the same behavior with a dip just below 2 kHz. The absorption coefficient performed 06.02 has a much lower value between 250 and 630 Hz and above 2.6 kHz compared the the absorption coefficient performed 27.02.

The absorption coefficient measured 18.04 (yellow curve) starts with an absorption of almost 0.9 at 250 Hz and decreases fast toward 0.1-0.4. At approximately 2.5 kHz, the absorption coefficient is not converging. The measurements performed 18.04 and 27.02 are based on geometry B and the measurement performed 06.02 is done with geometry A.

From the measured absorption coefficients, there is no clear correlation between the different curves, but the measurements performed 27.02 and 28.02 is pretty equal, except from the dip in the absorption coefficient measured 27.02. It is expected that snow would absorb sound like a porous absorber, and this is not visible in the measured results except from the absorption coefficient measured 06.02 if the high value at 250 Hz is omitted. The frequency range from 250 to 4000 Hz is a relatively small part of the frequency range from 20 Hz to 20 kHz used during the tram and metro measurements.

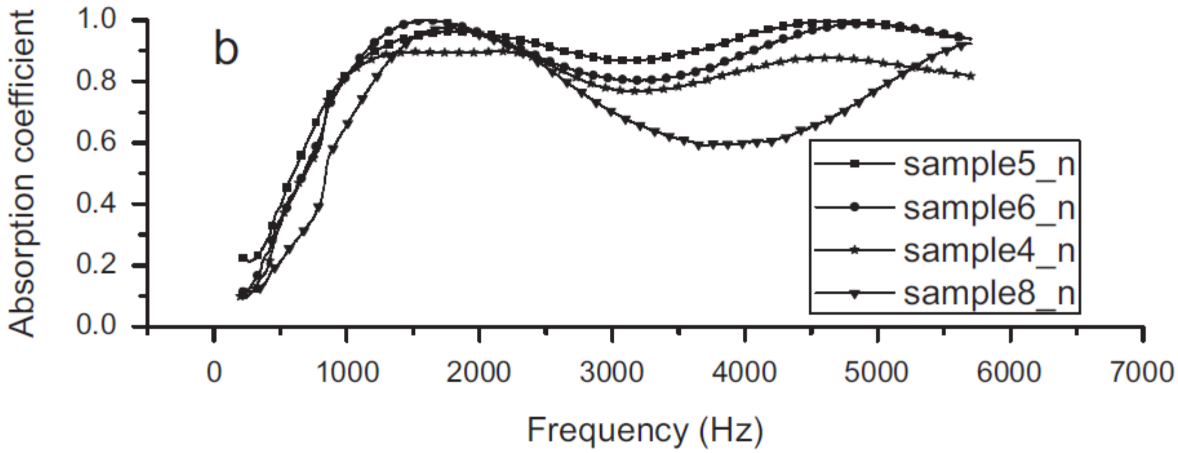


Figure 5.27: Absorption coefficients of snow measured by [14]. Sample 5 has a porosity of 0.89, sample 6 has a porosity of 0.73, sample 4 has a porosity of 0.63 and sample 8 has a porosity of 0.52. Sample 5 and 6 is based on a snow thickness of 40 cm, and sample 4 and 8 is based on a snow thickness of 30 cm.

The literature shows that snow itself with different porosity has a peak absorption above 1 kHz [14, 32], and above this frequency the absorption coefficient is in general high, but below 1 kHz the absorption decreases with decreasing frequency. An example of the absorption coefficient of snow measured by an impedance tube is given in Figure 5.27 [14], and does not look like the measured result in Figure 5.25 and 5.26.

The most interesting level difference found in the frequency analysis is outside the frequency range from 250 to 4000 Hz, so other possibilities have to be used to investigate if the attenuation is caused by vegetation or ground. Since all measurements have a peak level difference around 80 Hz, this frequency has to be studied. This frequency corresponds to a wavelength of 4.1 m when the average air temperature is 0 °C which gives a speed of sound of approximately 331 m/s.

If the ground is assumed to be infinitely large, the wave number $k = 2\pi/\lambda = 1.5$ m^{-1} when $f = 80$ Hz and a is the size of the ground i.e. $a \to \infty$. This means that $ka > 5$, which according to the theory will give reflections in one or more directions. The biggest size of any stem in the forest is 40 cm, and with $a = 0.4$ m, this corresponds to $ka = 0.6$ when $f = 80$ Hz, which implies that diffraction is obtained. Therefore the visible level difference around 80 Hz is most probably due to the ground effects, and not the forest.

The behavior of the higher frequencies is studied to investigate their reaction with vegetation and forest. From the metro measurements, it seems like the frequency 1-2 kHz is the critical frequency where every frequency above this has a higher attenuation for the forest measurements.

For the frequency of 2 kHz, the wave number is $k = 39.3\ \mathrm{m}^{-1}$. This means that obstacles with a size $a > 0.12$ m will obtain reflections, $a > 0.03$ cm gives scattering and smaller obstacles will be diffracted at the frequency of 2 kHz. It is therefore a great possibility that the forest will reflect and possibly absorb some of the frequency content above 2 kHz.

The effects of atmospheric absorption is negligible because very short sound propagation distances are analyzed, and the atmospheric conditions are almost equal for all the open field and forest measurements. The open field and forest measurements are assumed to be directly comparable.

5.2.2 Interference Simulations

The possibility of interference effects caused by the interaction between the direct and reflected sound wave from the ground has to be investigated. The direct sound path from the closest track to the closest microphone can be found by the use of Pythagoras: $R_d = \sqrt{6.0^2 + 0.8^2}$. Here the noise source from the trains is assumed to be 0.5 m above the top of the tracks which is 1 m above the surrounding ground. The microphone position is 2.3 m above ground. In the same way, by the use of an image source, the reflected distance path will be $R_r = \sqrt{3.8^2 + 6.0^2}$.

By the use of equation 3.3 with $R_d = 6.05$ m and $R_r = 7.10$ m, the first complete constructive interference will occur at the frequency 312 Hz when the speed of sound is 331 m/s, by the assumption of an average temperature of 0 °C. This fits well with the measured results, which might mean that the dip in all the frequency attenuation plots (Figure 5.23 and 5.24) around 200-500 Hz is caused by constructive interference at the closest microphone position.

To investigate which frequency representing destructive interference, equation 3.4 is used with the same parameters as above. This will give the first destructive interference at the frequency 156 Hz. This is also in accordance with the frequency attenuation plots. The ground is not even, and the calculations are only taking the first reflection into account in an idealized way, but the theoretically calculations seem to fit with the measured results.

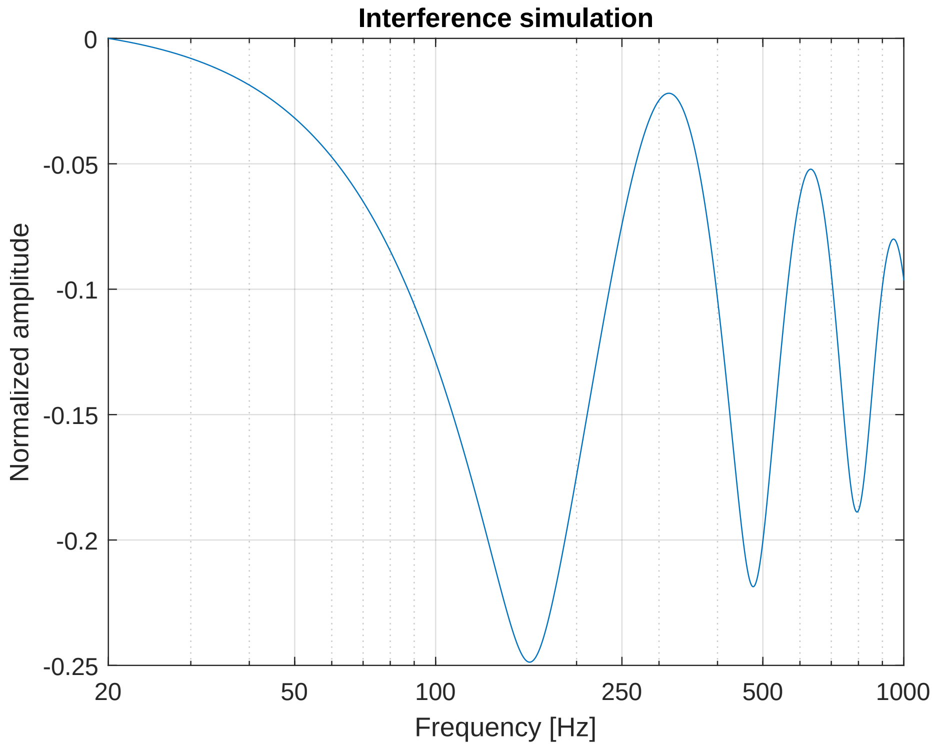


Figure 5.28: Simple simulation of the interference effects on the closest microphone position 2.3 m above ground when the noise source is 1.5 m above ground with a separation distance of 6 m.

The interference effects on the closest microphone position as a function of frequency is given in Figure 5.28. Equation 3.12 is used for the simulation, and the reflection coefficient is based on the snow absorption coefficient given by experimental measurements given by Datt et al. [14] (sample 5 in Figure 5.27). The interference simulation shows the calculated interference peaks and dips as well as a constructive peak around 20 Hz, which is in great correspondence with the frequency attenuation plots (Figure 5.23 and 5.24).

The interference simulations in Figure 5.28 is almost an inverse copy of the level difference for tram and metro frequency attenuation measurements in Figure 5.23 and 5.24, but the interference effects are not that visible in the measured results for frequencies above 500 Hz. This is natural as higher frequencies will have shorter wavelength and thus multiple reflections will occur as well as getting more easily absorbed which makes the interference effect less visible.

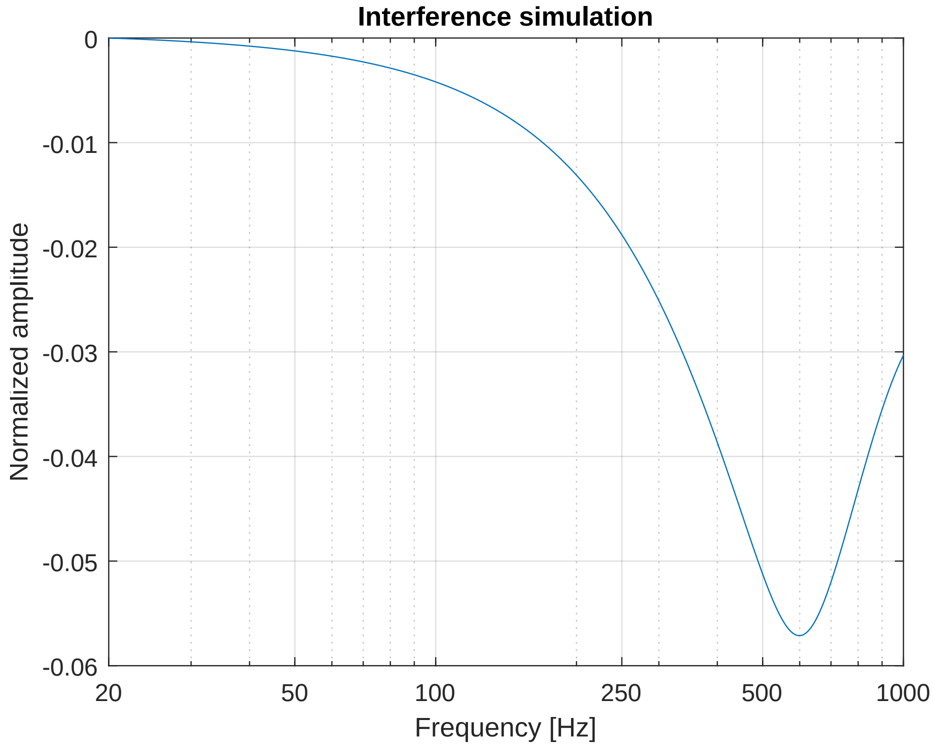


Figure 5.29: Simple simulation of the interference effects on the farthest microphone position 2.3 m above ground when the noise source is 1.5 m above ground with a separation distance of 26 m.

Since most of the analysis in this chapter is based on a difference between the nearest and farthest microphone position, an interference simulation is also needed for the farthest microphone position. This is given in Figure 5.29 where the separation distance between the center line of the outbound tracks and the microphone position farthest away is 26 m. This give the values $R_d = 26.01$ m and $R_r = 26.28$ m. As the difference between the direct and reflected sound wave is very small, the longest wavelengths will not be affected significantly. The distance from the noise source is also longer, so the normalized amplitude is smaller at this microphone position compared to the closest microphone position.

The interference simulation in Figure 5.29 shows that the sound pressure is lower in the frequency range from approximately 400 to 800 Hz. This is in accordance with the Figures 5.23 and 5.24 where the attenuation is smaller in this frequency range where a destructive interference effect at microphone position 3 seems to occur.

The calculations and simulations above are based on outbound traffic only. This is done as a simplification because the tracks are about 1 m above the surrounding ground where the microphones are placed, and since the outbound tracks are closest to the surrounding ground the influence of the ground height where the tracks are will be minimized. Frequencies above 1 kHz are omitted from the interference simulations as it is assumed that most of the frequency content above 1 kHz is absorbed by the ground and not contributing that much to the interference effects.

5.3 Attenuation Caused by Vegetation

The findings from the frequency analysis and the ground effects suggest that the attenuation below approximately 1-2 kHz is caused by other factors than the forest. This is because of the interference effects shown in section 5.2 and the relatively small size of the vegetation which will easier reflect and absorb the higher frequency content. Therefore this section will focus on the excess attenuation of the forest compared to open field from 1 to 20 kHz.

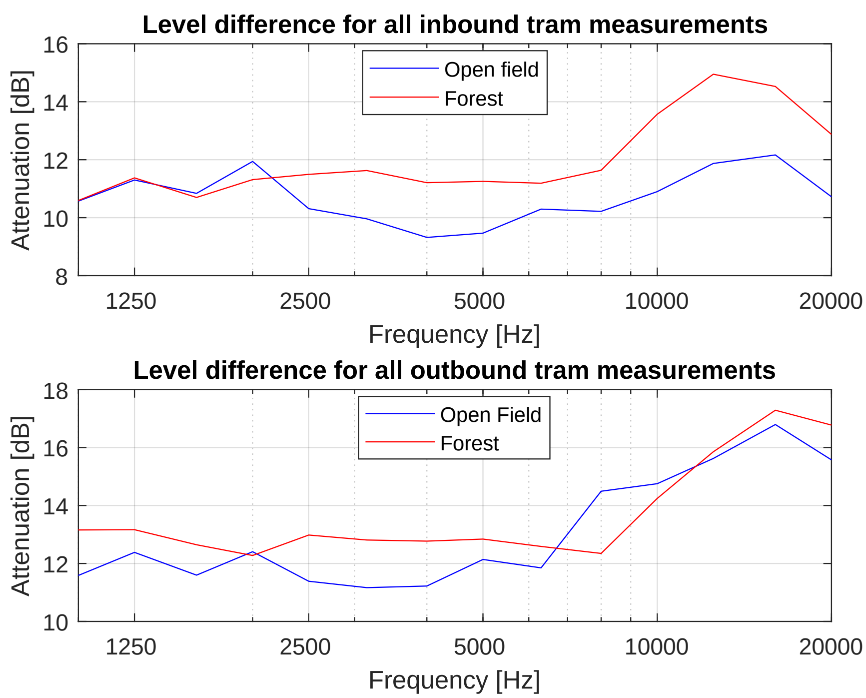


Figure 5.30: Tram noise level difference between nearest and farthest microphone position which ranges from 1 to 20 kHz. Inbound and outbound trams in upper and lower subplot, respectively.

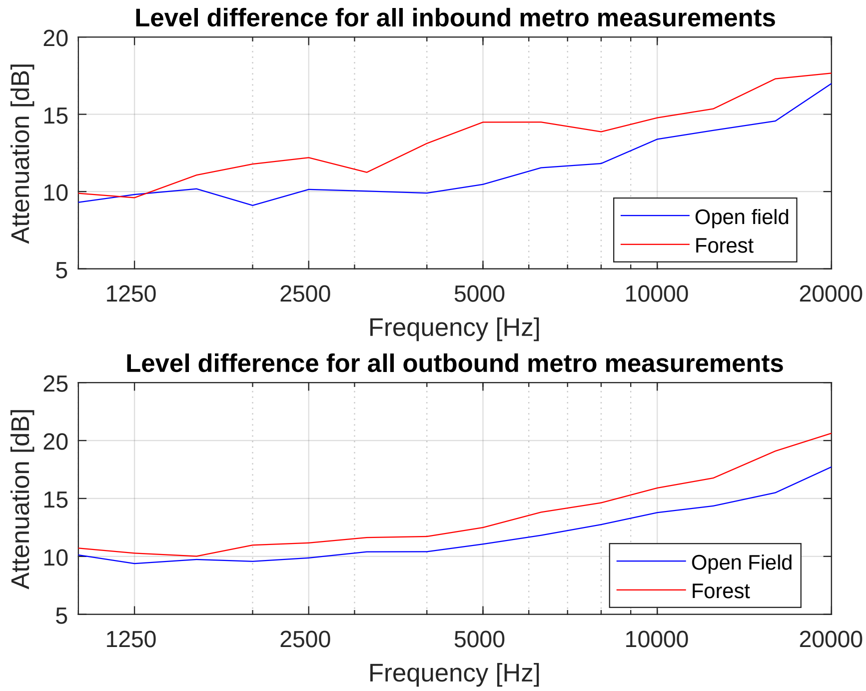


Figure 5.31: Metro noise level difference between nearest and farthest microphone position which ranges from 1 to 20 kHz. Inbound and outbound metros in upper and lower subplot, respectively.

The plots given in Figure 5.30 and 5.31 are excerpts from plots in Figure 5.23 and 5.24 which focus on the frequency range from 1 to 20 kHz. All these plots seem to have a higher level difference for the forest measurements compared to the open field measurements, except from some parts of the the outbound tram measurements. Note that the y-axis range is different for the two figures.

For the tram measurements in Figure 5.30, the inbound and outbound forest attenuation curves have the same shape, but the outbound curve has 2-3 dB higher attenuation. The forest attenuation is flat from 1 to 8 kHz, but increases fast from 8 to 12.5-16 kHz. The open field attenuation curve has the same shape for inbound and outbound traffic as well, but with a much higher attenuation for the frequency content above approximately 6 kHz.

The metro attenuation in the frequency range form 1 to 20 kHz has a smoother frequency response than the tram attenuation frequency response. There is no significant peaks or dips in either of the subplots, but almost a monotonically increasing attenuation for both open field and forest measurements. The maximum difference between the open field and forest inbound metro measurements are almost 5 dB around 5 kHz, whereas the overall excess forest attenuation for the metro outbound measurements are higher and slightly increases with increasing frequency.

Table 5.2: Level difference for the frequency range from 1 to 20 kHz

	Tram attenuation (1-20 kHz) [dB]		
Parameter	**Forest**	**Open field**	**Excess attenuation**
Inbound	12.3 (12.0-12.5)	10.8 (10.3-11.2)	**1.5** (0.8-2.2)
Outbound	14.0 (13.8-14.2)	13.5 (13.3-13.7)	**0.5** (0.1-0.9)

	Metro attenuation (1-20 kHz) [dB]		
Parameter	**Forest**	**Open field**	**Excess attenuation**
Inbound	14.0 (13.9-14.1)	12.2 (12.0-12.4)	**1.8** (1.5-2.1)
Outbound	15.0 (14.9-15.1)	12.7 (12.6-12.8)	**2.3** (2.1-2.5)

The average value for the level difference when the frequency ranges from 1 to 20 kHz is given in Table 5.2. The expanded uncertainty is included with the maximum upper and lower limit when a 90 % confidence interval is considered. These results are based on 21 tram and 29 metro measurements for open field conditions, and 20 tram and 25 metro measurements with forest conditions. There is an excess attenuation for all the forest measurements in this frequency range, even though the difference is very small for the outbound tram measurements.

The inbound tram attenuation is 1.5 dB with a lower limit of 0.8 dB and upper limit of 2.2 dB. The outbound tram attenuation is 1 dB lower, with an average value of 0.5 dB. At worst, the excess attenuation is only 0.1 dB, but at best it is 0.9 dB. Compared to Table 5.1 where the entire frequency range is taken into consideration, the average inbound excess forest attenuation is 1 dB higher whereas the outbound excess attenuation actually is 0.1 dB lower in this frequency range.

For the metro measurements, the inbound excess attenuation has an average level of 1.8 dB with expanded uncertainties ranging from 1.5 to 2.1 dB. The outbound excess metro attenuation is 2.3 dB and the expanded uncertainty only ranges 0.4 dB; from 2.1 to 2.5 dB. If the attenuation is compared with the attenuation based on the entire frequency range where the inbound and outbound excess forest attenuation is 1.2 and 1.6 dB, respectively, the excess forest attenuation based on 1-20 kHz is 0.4 and 0.7 dB higher.

All the results in this chapter show that there is a general difference between inbound and outbound traffic. As shown in section 5.1.3 and 5.1.4, the level difference between forest and open field is greater for outbound than inbound traffic. In the next paragraphs only the outbound traffic will be studied.

To eliminate factors related to different initial SPL at each pass-by, the level difference between the first and second microphone as well as the difference between the first and third microphone position will be presented next. To eliminate the effect of ground absorption and significant interference effects, also here the frequency range from 1 to 20 kHz will be studied.

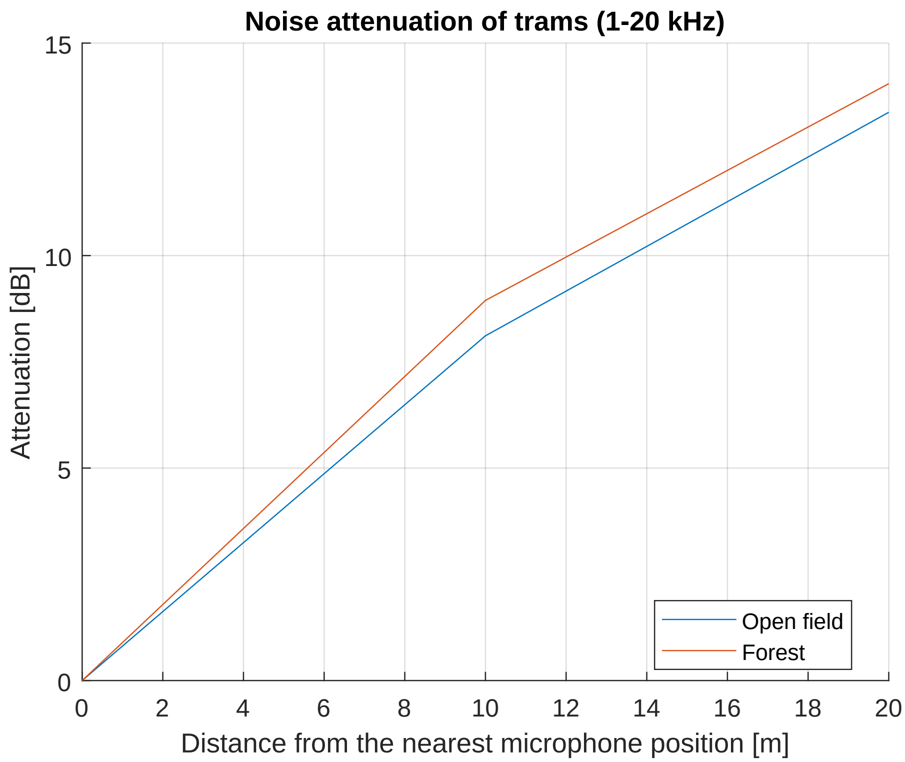


Figure 5.32: Level attenuation for outbound tram traffic as a function of distance.

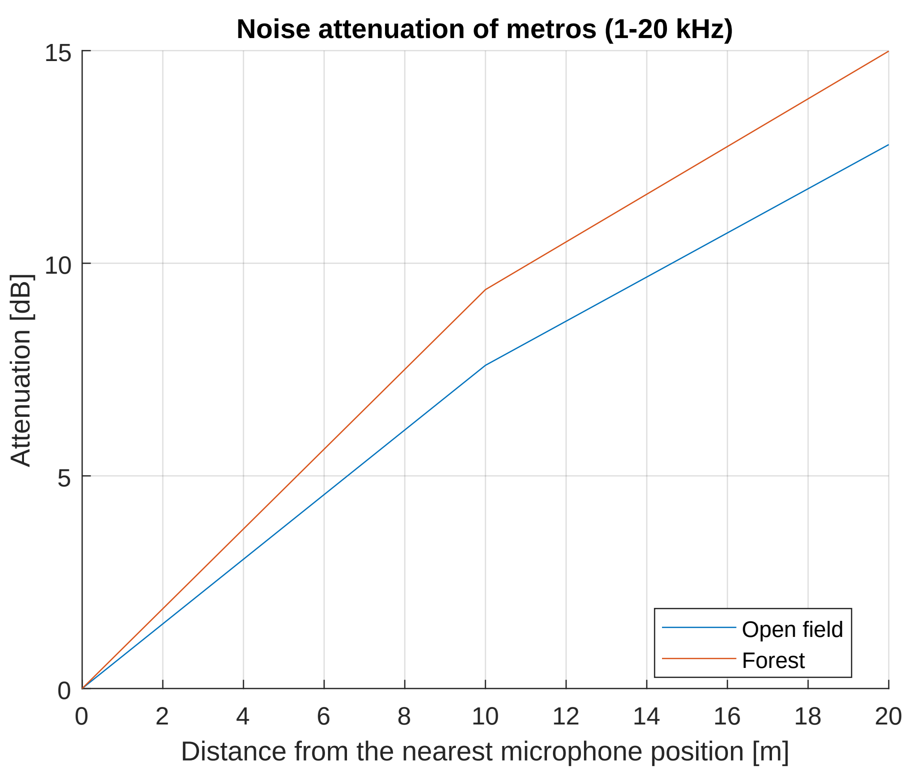


Figure 5.33: Level attenuation for outbound metro traffic as a function of distance.

The outbound measurements are given in Figure 5.32 and 5.33 representing tram and metro measurements, respectively. The results are based on 25 metro and 20 tram measurements for the forest measurements, and 23 metro and 16 tram measurements for the open field measurements.

Table 5.3: Level attenuation for the frequency range from 1 to 20 kHz

	Tram attenuation (1-20 kHz) [dB]		
Parameter	**Forest**	**Open field**	**Excess attenuation**
$L_{p,Fmax,x_1-x_2}$	8.9 (8.2-9.6)	8.1 (7.2-8.9)	**0.8** (−0.7-2.4)
$L_{p,Fmax,x_1-x_3}$	14.0 (13.8-14.2)	13.4 (13.1-13.6)	**0.6** (0.2-1.1)

	Metro attenuation (1-20 kHz) [dB]		
Parameter	**Forest**	**Open field**	**Excess attenuation**
$L_{p,Fmax,x_1-x_2}$	9.4 (9.2-9.6)	7.6 (7.2-8.0)	**1.8** (1.2-2.4)
$L_{p,Fmax,x_1-x_3}$	15.0 (14.9-15.1)	12.8 (12.6-12.9)	**2.2** (2.0-2.5)

Numerical values from the plots (Figure 5.32 and 5.33) including expanded uncertainty are given in Table 5.3. Note that the open field measurements performed 13th of February are omitted because only two microphone positions were used this day. That is the reason the results differ a bit from the outbound traffic results in Table 5.2. The average excess forest attenuation is decreasing 0.2 dB from microphone position 2 to 3 for the tram measurements from 0.8 to 0.6 dB. The expanded uncertainty is big for the tram measurements between microphone position 1 and 2 ($L_{p,Fmax,x_1-x_2}$) which means that the excess attenuation varies from -0.7 to 2.4 dB.

The excess forest metro attenuation increases with increasing distance in the order of 0.4 dB from 1.8 to 2.2 dB. When the expanded uncertainty is taken into account, the excess forest attenuation ranges from 1.2 to 2.4 dB for the level difference between microphone position 1 and 2 ($L_{p,Fmax,x_1-x_2}$). The level difference between microphone position 1 and 3 ($L_{p,Fmax,x_1-x_3}$) ranges from 2.0 to 2.5 dB.

5.4 Sources of Error

There are a lot of possible sources of error when performing such a big field measurement. The first challenge is to get close enough to the tracks, but as the tracks have a safety zone which is protected by a fence, it is not possible to get closer than about 6 m to the center line of the closest tracks. Then it is impossible to investigate the ground properties around the tracks and measure at closer distances. This also made it impossible to measure the exact distance from the center line of the tracks to the microphones.

Another problem is the background noise both from car traffic and wind noise. This is usually not a problem for the two closest microphones, but for the microphone farthest away. Even though a tram or metro pass-by makes a lot of noise, the background noise can in some cases dominate the microphone farthest away because the sound level already has decreased too much here. The different velocities of the trams and metros are also a factor here as higher velocity usually gives higher noise emission. This means that traffic with low speed potentially records more of the background noise than the tram and metro pass-by itself.

It is assumed that the velocity of the trams and metros are constant during pass-by. However, acceleration and braking occurred during some recordings. The trams are as well emitting noise from a compressor now and then, which naturally influences the results. This should however not influence the relative SPL between the microphone positions.

Calibration issues are a possible source of error. The microphones were calibrated both at the office and outside in the field, but the cold winter conditions possibly influence the sensitivity at the microphones after a couple of hours in -10 °C. At the measurements 30th of January, the middle microphone was 2 dB lower than its intended level and was corrected for in the post-processing. It should be mentioned that the measurements performed on the 27th and 28th of February were done with another microphone (Norsonic Nor1225) and a microphone amplifier (see equipment list in section 4.3) because one of the standard microphones (Gras 46AE) did not work. The characteristics of this specific microphone might have influenced the measurements.

A potential problem is if the microphones are placed too close to a tree leading to dominating constructive or destructive interference for specific frequencies. It was focused on placing the microphones at least 0.5 m away from a tree if possible, but this was of course hard in the forest condition measurements. The same problems yield for the open field measurements where there was a forest on both sides of the open field area.

The microphone positions were placed at the same distances from the tracks for both open field and forest measurements by the use of a measurement tape and laser meter. It was tried to get as equal distance as possible, but this was hard to obtain. It was harder to measure an accurate distance in the forest because of all the vegetation. These variations in distances could of course influence the attenuation results as the SPL is dependent of the distance.

All measurements of tram and metro pass-by are performed in the near field. The behavior in this field is complicated and may disturb or give unexpected results at certain receiver positions.

As the interference simulations are based on the acoustic properties of snow, and some of the measurements were performed without snow on the ground, this is a possible source of error for the interference effects simulations caused by the ground which is most dominating below 1 kHz.

Possible sources of error in the impedance measurements could be that there should be no obstacles causing reflections within $10d$ of the measurement site. This was impossible as footsteps made the surrounding ground uneven as well as other trees and vegetation close to the microphones caused reflections. The sound source used for this test could also be a problem, but this sound source was tested before the measurements to see that the frequency response was flat in the range from 250 to 4000 Hz as well as ensuring high enough signal-to-noise-ratio on the test site.

Another source of error related to the impedance measurements could be phase or gain mismatches among the microphones as the microphone positions not were switched which is recommended in ANSI S1.18. The reason of this is simply because switching the microphones would have changed the microphone positions as the microphone stands mostly was placed on the snow. It was therefore considered that this would have led to another source of error and maybe made the impedance measurements worse. It could be errors related to the calculation of the transfer function or impedance in the software ArtemiS or the MATLAB script as well.

5.5 Discussion

The final question is if all the measurements suggest that there is some excess attenuation when there is a forest between source and receiver in the near field, when the noise source is trams and metros. In this section all the obtained results will be discussed leading to a conclusion.

As each forest is unique, the forest conditions are important and a qualitative description of the forest area is needed. The forest used during all the measurements in this experiment is a typical Norwegian forest consisting of birch and spruce. The stem diameter is in the range from 0.5 to 40 cm. The average density is ranging from 0.7 to 1.4 trees/m^2, but at some locations between the source and receiver the density is as high as 10 stems/m^2. The average height of the forest is ranging from 3 to 15 m. The forest conditions are therefore uneven and not homogeneous.

All the measurements are performed during winter and early spring which means that there is less vegetation and leaves compared to what would have been in the summer. This would have influenced the vegetation of the birches.

For the level attenuation measurements when both inbound and outbound traffic are used for the calculations, the level attenuation is very uneven. As discussed earlier, the outbound SPL measurements are in general some decibels higher. The results from the analysis also show that the excess forest attenuation is higher for outbound compared to inbound traffic, except for the frequency range from 1 to 20 kHz tram measurements.

A reason for this is that there was some snow between the inbound and outbound tracks with a height of approximately 30 cm and width of approximately 60 cm. It might be that some of the higher frequency content is blocked already here, and this high frequency content could probably have been attenuated by the forest instead. Of course some of this frequency content will be blocked for the first microphone position so the relative SPL is unaffected, but this also means that the difference will be lower as well.

For all the measurements there is a peak in attenuation around 80 Hz as well as higher attenuation in the higher frequency range. The peak around 80 Hz followed by a dip from around 315 to 500 Hz seems to be caused by reflections by the ground leading to constructive interference around 80 Hz and destructive interference around 315 to 500 Hz at the first microphone position. It is assumed that the ground absorption is lower at lower frequencies leading to more visible interference effects for lower frequencies.

Simple calculations show that obstacles with a diameter size greater than 12 cm will cause reflections and possibly also a bit absorption in the bark when the frequency is greater than 2 kHz. As most of the trees have an average stem diameter of 10-15 cm there is a great possibility that frequencies around 1-2 kHz is directly attenuated by the forest. This calculation, the interference simulations and the study of the frequency spectra attenuation lead to the assumption that the excess attenuation is caused by frequencies above 1 kHz.

The difference in attenuation between trams and metros are also remarkable, as the excess forest attenuation for trams in the frequency range from 1 to 20 kHz is only 0.5 dB, and for metros the excess attenuation is 2.3 dB. A possible solution of this is that the trams have a pantograph which makes some noise when it is conducted to the power wire giving electricity to the tram. The dominating noise source is the wheel and track interaction, but measurements made by an acoustic camera shows that there is some high frequency noise emission from the roof below this pantograph and wire interaction. It is also a possibility that the noise source originates from a compressor on the roof. The picture made by the acoustic camera is found in Appendix A in the measurement data from 30.01.18, and shows a dominating noise source in the frequency range from 2.5 to 20 kHz originating from the pantograph.

In this way, the noise source is located above some of the vegetation as well as that the vegetation is less denser in this height. The height of the tram is about 3.6 m, which means that the tram roof has direct sound path to the second microphone position unaffected by the forest, but for the third microphone position the forest is higher. This is however not visible in the noise attenuation graph (Figure 5.32) for the frequency range 1-20 kHz for trams where the attenuation actually is higher at microphone position 2 than microphone position 3.

Another possibility of this difference between tram and metro excess forest attenuation can simply be because of the sample size. There were more metros passing the measurement area than trams which is why the sample size is a bit greater for metros compared to trams. The results would maybe have looked smoother and better if multiple measurements had been performed.

Since most of the results are found by the comparison of attenuation in frequency, the excess forest attenuation is in this case independent of frequency weighting. The statistical analysis which includes the confidence interval is based on the Student's t-distribution and assumes a normal distribution.

The measurements of the ground impedance was not as expected for snow (according to other literature it should have been lower absorption below 1 kHz). It was hard to calculate the ground impedance as the MATLAB script did not converge when it reached a certain frequency. It was tried to use the best of two worlds by calculating the transfer function by the use of both ArtemiS and MATLAB. It was discovered that the MATLAB script which calculated the ground impedance was very dependent of the input temperature as only one degrees change could make the impedance calculation converge over the entire frequency range.

Because of the unstable ground impedance calculations and thereby absorption coefficient, another ground absorption coefficient was used for the interference calculations. The covered frequency range of the ground impedance measurements is only from 250 to 4000 Hz which is too small to tell something interesting about the tram and metro measurements. Ideally, the calculated absorption coefficient from each measurement day should have been taken into the calculation for the frequency response of the tram and metro pass-by from the specific day. This would have removed the ground's influence of the results, but also here the impedance measurements only covered a small part of the frequency range and looked very strange, so they were omitted.

According to ISO 3095 [26], which describes the measurement of noise emitted by rail bound vehicles, the standard measurement quantity is the equivalent A-weighted SPL with a time duration equal to the pass-by. In this project, the maximum SPL with fast time constant is considered to be the best choice as the maximum sound pressure level is what people will find annoying. This quantity is also used since a maximum attenuation is what is of interest in this research, and the relative SPL between the microphones is what matter in this study. Measurements performed by Olafsen [38] confirm that the use of the parameter maximum SPL is not problematic for urban rail bound traffic.

The use of this quantity can of course have lead to some errors as it takes the maximum level during the measurement sessions. This could be maximum sound levels in a specific frequency band caused by for example wind, a barking dog, bird whistle or a plane which passes during the measurement. Both the time signals as well as each frequency spectrum are studied to avoid such errors.

The standard measurement distance from center line to receiver is 7.5 m according to ISO 3095 [26]. This standard does not describe multiple microphone positions as a function of distance normal to the tracks, but it could had been an idea to use a distance of 7.5 m from the track to the closest microphone position. But as two tracks (inbound and outbound) are measured it was considered to get as close as possible as well as it was almost impossible to measure accurate distances because of the snow and fence protecting the tracks. The relative distance between the microphones is the most important parameter anyway. Because of the practical limitation by the forest and no specification in any standard, the equal separation distance of 10 m was chosen.

When the newer measurements in April without snow conditions were performed, it was reconsidered to change the distances and height of the microphones. The same distances and height were chosen to make the comparison still directly comparable. It is not most important to measure accurate sound pressure levels, but the relative SPL at each receiver location. If the exact noise level should have been found, the ISO standard height and distances should have been chosen.

To focus more on the forest attenuation itself, an externally sound source could have been used. As the main objective is to study the sound attenuation from actual noise from trams and metros, real pass-by measurements only are performed. A possibility would be to use a loudspeaker with a recording of a metro or tram pass-by and play it in an isolated forest. Then a higher signal-to-noise ratio would have been obtained and made it easier to select a specific forest, but there are some practical limitations with this setup such as power output for the loudspeaker, power supply in the forest and to cover the entire frequency range in an authentic way with an external sound source.

As a further work, multiple forests should be investigated to get a better description of the mechanisms which contribute to this attenuation effect of the noise emission from trams and metros. Measurements during summer should be performed, when there is more leaves on the trees. As metros and trams dirve close to buildings and people, different types of dense trees and hedges could be tested as sound barriers inside cities when multiple parameters as reflections from asphalt and other buildings would complicate the problem even more.

The difference in attenuation between trams and metros should be investigated by using different heights of the forests to see if the pantograph is the main contributor to this difference. The findings could be included in a noise mapping software, and multiple measurements could have been performed to see how accurate the software simulations are.

There is already planned research on how the psychological noise effects from trams and metros affect humans. The experienced noise attenuation effect of vegetation and forests can be higher than the actual findings, which is given qualitative in this report. In 2020 there will be completely new trams running in Oslo [50], and the noise emission and spectrum will probably be different from today's SL79 and SL95. Therefore new measurements will be needed in the future, both with and without forest between source and receiver.

Chapter 6

Conclusion

The influence of vegetation and trees on sound propagation has been investigated by comparing measurements of metro and tram noise pass-by in an open field with a forest. The distance between sound source and receiver is in the near-field of the noise source ranging from 6 to 30 m, and three microphone positions are used with a separating distance of 10 m. For the measurements the parameter maximum sound pressure level with time weighting fast is used for the analysis, both unweighted and with A-weighting.

When all the measurements of the inbound and outbound traffic which run on two separate tracks are taken into consideration, the results suggest that there is an excess forest attenuation of 1.3 and 1.5 dB for unweighted and A-weighted tram measurements, respectively. For the metros, the excess forest attenuation is −0.8 and 1.4 dB for unweighted and A-weighted measurements, respectively. These results are based on a regression model based on the average of all the measurements.

Based on the outbound traffic only where the measurements at the distances 6 and 26 m from the center line of the track are compared, the experimental results suggest that there is an excess forest attenuation of 0.6 and 1.6 dB for tram and metro measurements, respectively. These results are based on a comparison between the entire frequency range from 20 Hz to 20 kHz with no frequency weighting. If a 90 % confidence interval is considered, the lower and upper limit is 0.1 and 1.1 dB for trams, and 1.1 and 2.0 dB for metros, respectively.

The vegetation at the forest measurement area is a mixture of spruce and birch with an average diameter size ranging from 0.5 to 40 cm, average height of 3-15 m and average stem density of 0.7-1.4 trees per square meter. Calculations, simulations and the frequency attenuation spectra show that there is a great possibility that the reflection, scattering and absorption from this vegetation are reducing the noise level in the frequency range above 1 kHz.

In the frequency range from 1 to 20 kHz, the excess forest attenuation for the outbound traffic is 0.5 and 2.3 dB for trams and metros, respectively. When the 90 % confidence interval is included, the lower and upper attenuation limit is 0.1 and 0.9 dB for trams and 2.1 and 2.5

dB for metros. This result is frequency independent as the frequency spectra measured at the distances 6 and 26 m are directly compared. These results are based on 21 tram and 29 metro measurements for open field conditions, and 20 tram and 25 metro measurements with forest conditions.

As these measurements are based on a sound propagation through 20 m of forest, the excess forest attenuation in the frequency range from 1 to 20 kHz can be approximated as 0.12 dB/m for metro noise. The excess forest attenuation for tram noise is negligible for this range.

The reason why tram noise is not attenuated as much as the metros, could be the additional noise source from the pantograph connected to the wire above the tram or a compressor on the roof. This noise source is probably not affected by the vegetation in the same way as for the noise source originating from the wheel and track interaction.

The results of these measurements suggest that there is an excess forest attenuation for metros when the distances 6 and 26 m from the center line of the track is compared. The excess forest attenuation for tram noise is almost not measurable, but the noise from metros will achieve a couple of decibels attenuation at this measurement distance. As most of the urban rail bound transport systems drive close to houses and people, this excess attenuation contributes to a better noise control. A forest between the urban rail bound transport and residences will therefore work as a very small sound barrier for the higher frequency content above 1 kHz, at least for metro noise.

Appendix A

Measurement Data

All the obtained raw data contain information about identification of tram and metro, average velocity, in- or outbound traffic and maximum unweighted and A-weighted SPL at each of the three microphone positions. A logarithmic average is included for the sound pressure levels as well as the average velocity. A small report made in accordance with ANSI S1.18 is made for the ground impedance measurements for each measurement day.

A.1 Measurements 30.01.18

A.1.1 Ground Impedance

Instrumentation

The equipment used for the ground impedance measurement is listed in Table 4.2. A sampling frequency of 44.1 kHz and bit rate of 16 are used for the SQuadriga II. The weather information is partly based on information from the temperature sensor from the car used to the measurement site as well as information from weather broadcast [1] from Bygdøy observation station, 4.4 km away from Jarmyra.

Figure A.1: Test area 30.01.18 with snowy conditions. This image shows geometry A of ANSI S1.18 used.

Unfortunately, the two microphones are not calibrated with the same value this day. The calibrator is given with the value of 114 dB at 1 kHz, and upper microphone has this value, but lower microphone has the value 111.9 dB. With a difference of 2.1 dB, the results are not valid. An image of the test area is given in Figure A.1.

Meteorological Data

The temperature started at -7 °C when the SPL attenuation measurements started about 09:00, and ended with -4 °C around 13:00 when the impedance measurements are done. The wind velocity is about 0-1 m/s, the relative humidity is about 93 % and the atmospheric pressure is 1011 mb. It is cloudy this day and no precipitation. At the test area, the ground is covered with about 2-3 cm relatively fresh snow above 10 cm older and harder snow (see Figure A.1).

Impedance Values

The impedance values did not give any interesting information due to the big difference in the calibrated level, so they are not valid for this measurement session.

Other Observations

Since the ground is made of snow, it is impossible to have a totally flat area around the test area which ANSI S1.18 recommends.

A.1.2 Sound Pressure Level

Table A.1: Tram Measurements - Open Field

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
156	16.3	In	77.0	70.6	66.6		71.0	64.9	60.0
153	24.0	In	78.2	71.9	68.1		72.7	64.6	60.8
163	17.1	In	81.0	73.5	68.7		70.3	63.6	59.3
171	22.2	In	78.6	71.7	67.2		71.5	65.0	60.2
168	19.7	In	81.0	73.0	68.8		73.5	66.1	62.0
146	26.9	In	73.2	69.8	67.6		69.0	66.3	65.2
Average	**21.0**		**78.8**	**71.9**	**67.9**		**71.6**	**65.2**	**61.8**
153	35.1	Out	80.1	73.3	69.1		76.9	68.1	64.5
163	26.5	Out	80.8	73.4	69.7		72.0	65.4	61.3
193	29.4	Out	79.8	74.0	70.7		74.1	66.5	62.9
168	25.4	Out	82.8	73.5	69.3		78.2	70.3	65.7
146	21.8	Out	76.4	70.1	66.1		68.2	62.9	60.2
156	26.9	Out	77.4	70.7	68.5		71.8	64.3	61.0
153	30.0	Out	79.4	73.1	69.0		75.0	68.0	63.4
Average	**27.9**		**80.0**	**72.8**	**69.1**		**74.8**	**67.1**	**63.1**

Table A.2: Metro Measurements - Open Field

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
39-62	56.2	In	78.0	74.9	72.1		72.7	68.3	65.0
10-25	48.7	In	77.3	73.6	71.0		71.9	67.4	64.2
68-93	50.5	In	77.3	73.0	70.7		71.0	66.3	64.0
108-58	56.3	In	79.1	75.3	72.4		73.9	69.5	66.2
102-106	52.5	In	78.2	73.7	71.0		73.0	67.8	64.9
113-72	48.5	In	76.8	72.6	70.4		71.6	66.4	63.7
60-50	56.7	In	77.8	74.2	71.2		72.5	67.1	64.5
14-51	52.6	In	78.5	74.8	71.8		73.9	69.9	66.6
Average	**52.3**		**79.2**	**75.0**	**72.2**		**73.4**	**68.4**	**65.1**
93-68	53.1	Out	84.4	80.2	77.1		78.2	71.5	67.5
58-108	63.7	Out	86.2	81.1	78.8		80.7	74.2	70.6
106-102	56.4	Out	84.5	80.3	77.0		78.8	72.6	68.5
72-113	49.5	Out	84.4	79.5	76.6		79.3	72.3	67.6
50-60	65.3	Out	85.8	81.3	78.9		79.4	73.4	69.3
51-14	65.6	Out	86.9	81.7	79.7		82.1	75.1	72.3
93-57	44.9	Out	83.5	78.4	75.1		76.0	69.7	65.9
10-25	51.2	Out	85.5	81.1	78.3		79.7	73.0	69.9
Average	**56.2**		**85.3**	**80.6**	**77.9**		**79.6**	**73.0**	**69.4**

A.1.3 Acoustic Image of Tram Pantograph

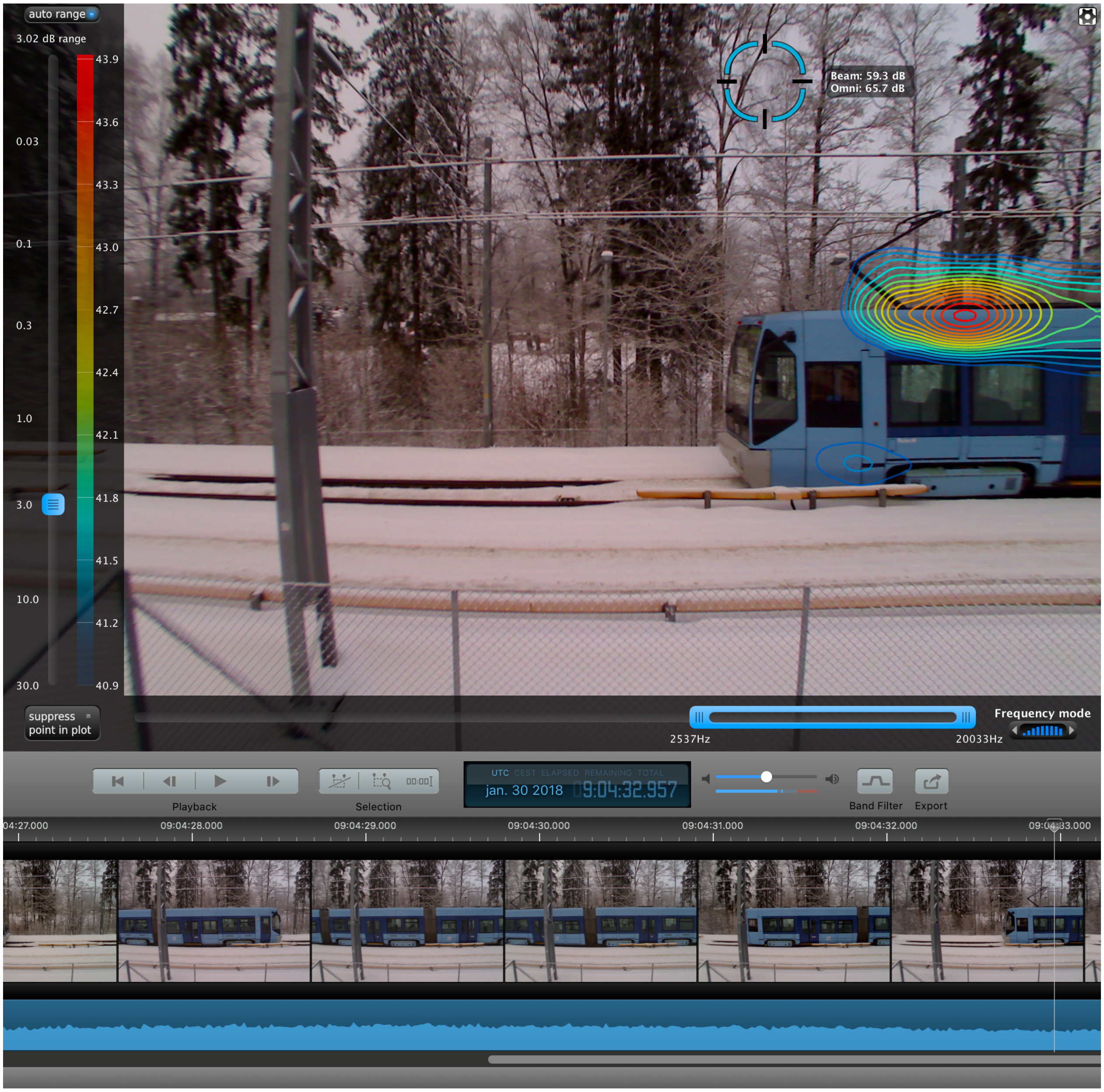


Figure A.2: A tram pass-by measured by an acoustic camera. The frequency range is given from 2.5 to 20 kHz and the image shows a dominating noise source from the roof below the pantograph of the tram. The warm colors (red) represent higher SPL whereas the colder colors (blue) represent lower SPL. The image is taken by Øystein Meland.

A.2 Measurements 06.02.18

A.2.1 Ground Impedance

Instrumentation

The equipment used for the ground impedance measurement is listed in Table 4.2. A sampling frequency of 44.1 kHz and bit rate of 16 are used for the SQuadriga II. The weather information is partly based on information from the temperature sensor from the car used to the measurement site as well as information from weather broadcast [1] from Bygdøy observation station, 4.4 km away from Jarmyra.

Figure A.3: Test area 06.02.18 with snowy conditions and geometry B setup.

The calibrator is given with the value of 114 dB at 1 kHz, and the upper and lower microphone has a value of 114.1 and 114.2 dB, respectively. An image of the test area is given in Figure A.3. Four independent measurements are done by slightly moving the microphones and sound source, both for geometry A and B. The positions could not be moved very much because of the footsteps in the snow as well as the ground is very uneven (a difference of more than 5 cm). The upper and lower microphone positions are not switched.

Meteorological Data

The temperature started at -6 °C when the SPL measurements started about 09:00, and ended with -3 °C around 12:00 when the impedance measurements are done. The wind velocity is about 0-1 m/s, the relative humidity is in average 75 % and ambient pressure is 1019 mb. It is cloudy this day, no precipitation, but a bit foggy. At the test area, the ground is hard and snow-covered (see Figure A.3). The depth of the snow is about 25 cm at the test site.

Impedance Values

Table A.3: Acoustic Impedance

	Normalized Acoustic Impedance ($Z_s/\rho c$)	
Frequency (Hz)	**Real**	**Imaginary**
250	1.108	-0.031
315	1.086	-0.159
400	0.977	-0.268
500	0.845	-0.275
630	0.745	-0.067
800	0.919	-0.166
1000	0.988	-0.010
1250	1.185	-0.216
1600	1.441	-0.877
2000	0.297	-0.602
2500	0.506	-0.210
3150	0.575	-0.705
4000	0.091	-0.866

Other Observations

Since the ground is made of snow, it is impossible to have a totally flat area around the test area which ANSI S1.18 recommends.

A.2.2 Sound Pressure Level

Table A.4: Tram Measurements - With Vegetation

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
142	35.7	In	77.6	70.8	68.0		75.4	67.9	65.1
149	26.9	In	74.3	69.1	65.7		67.3	61.3	58.3
168	41.8	In	82.5	75.0	71.8		78.8	71.6	69.1
147	48.3	In	76.0	69.1	66.8		73.5	65.2	62.7
169	40.1	In	75.2	69.0	66.8		70.4	63.6	62.1
143	36.5	In	77.5	72.0	68.5		74.6	68.6	64.2
142	33.2	In	78.4	71.1	68.3		76.8	67.9	64.4
Average	**37.5**		**78.2**	**71.4**	**68.4**		**75.1**	**67.7**	**64.8**
142	44.8	Out	83.4	76.6	72.7		81.7	74.4	69.6
149	32.7	Out	84.1	74.6	70.6		82.5	70.5	66.2
168	41.8	Out	87.1	77.1	73.6		82.2	73.4	70.4
147	43.4	Out	83.3	75.5	72.9		81.0	73.1	70.7
169	41.1	Out	85.2	78.4	75.8		81.5	75.3	71.8
143	48.3	Out	86.6	78.2	74.1		85.9	77.1	72.4
142	34.7	Out	81.4	73.9	71.0		77.4	69.9	66.5
Average	**41.0**		**84.8**	**76.6**	**73.3**		**82.3**	**74.0**	**70.2**

Table A.5: Metro Measurements - With Vegetation

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
90-18	49.3	In	87.0	81.7	78.6		72.5	66.7	63.8
19-30	50.5	In	80.3	76.0	74.7		72.8	67.4	64.6
82-41	50.9	In	79.5	75.2	73.5		73.5	67.8	64.7
99-84	51.4	In	82.9	76.6	74.8		75.0	69.1	65.7
65-100	53.5	In	82.4	76.5	75.5		73.1	67.9	65.5
17-31	47.6	In	80.0	75.0	73.3		73.4	66.7	64.0
110-96	49.3	In	78.6	74.4	72.3		72.6	67.7	65.1
44-42	51.2	In	82.4	76.7	74.9		73.5	68.2	65.3
90-18	50.7	In	87.6	80.9	78.8		73.5	68.4	65.1
Average	**50.5**		**83.4**	**77.8**	**75.7**		**73.4**	**67.8**	**64.9**
84-99	47.7	Out	84.9	78.3	76.4		77.9	70.5	67.8
100-65	42.6	Out	85.9	80.0	76.4		77.7	72.0	68.9
08-09	48.2	Out	84.0	78.9	76.7		77.5	70.9	69.4
31-17	45.5	Out	83.7	78.2	76.1		76.1	70.2	67.5
96-110	48.5	Out	83.4	77.2	75.8		76.6	71.2	69.5
42-44	54.7	Out	86.2	79.7	78.0		80.4	73.2	70.4
18-90	57.7	Out	90.6	84.0	81.1		81.0	74.5	71.9
41-82	47.8	Out	83.6	77.7	75.8		77.0	71.6	69.8
Average	**49.1**		**86.0**	**79.8**	**77.4**		**78.4**	**72.0**	**69.6**

A.3 Measurements 13.02.18

A.3.1 Ground Impedance

Instrumentation

The equipment used for the ground impedance measurement is listed in Table 4.2. A sampling frequency of 44.1 kHz and bit rate of 16 are used for the SQuadriga II. The weather information is partly based on information from the temperature sensor from the car used to the measurement site as well as information from weather broadcast [1] from Bygdøy observation station, 4.4 km away from Jarmyra.

Figure A.4: Test area 13.02.18 with snowy conditions.

The calibrator is given with the value of 114 dB at 1 kHz, and the upper and lower microphone has a value of 114.1 and 114.2 dB, respectively. An image of the test area is given in Figure A.4. Four independent measurements are done by moving the microphones and sound source, both for geometry A and B. The positions could not be moved very much because of the footsteps in the snow. The upper and lower microphone positions are not switched.

Meteorological Data

The temperature started at -9 °C when the SPL measurements started about 10:00, and ended with -2 °C around 13:00 when the impedance measurements are done. The wind velocity is about 0-1 m/s and the relative humidity is in average 80 %. It is sunny this day with an ambient pressure of 1008 mb and no precipitation. At the test area, the ground is hard and snow-covered (see Figure A.4). The depth of the snow is about 40 cm, and is medium soft.

Impedance Values

Table A.6: Acoustic Impedance

	Normalized Acoustic Impedance ($Z_s/\rho c$)	
Frequency (Hz)	**Real**	**Imaginary**
250	0.748	0.223
315	0.927	0.737
400	0.735	0.900
500	0.834	0.837
630	1.059	1.318
800	1.383	1.283
1000	2.017	1.771
1250	3.162	1.583
1600	4.562	-1.048
2000	2.126	-3.289
2500	-1.050	-2.454
3150	-1.055	-0.990
4000	-1.139	-1.102

Other Observations

Since the ground is made of snow, it is impossible to have a totally flat area around the test area which ANSI S1.18 recommends.

A.3.2 Sound Pressure Level

Table A.7: Tram Measurements - Open Field[1]

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
155	48.3	In	80.0	-	68.7		76.2	-	64.1
167	12.7	In	75.1	-	66.1		66.3	-	59.0
156	42.1	In	79.4	-	70.1		78.5	-	68.2
Average	**34.4**		**78.6**	-	**68.6**		**75.9**	-	**65.2**
155	42.0	Out	85.1	-	71.3		78.9	-	66.3
163	48.9	Out	82.4	-	69.7		79.1	-	65.9
167	52.1	Out	83.3	-	72.7		82.0	-	71.5
156	39.7	Out	78.7	-	67.7		75.8	-	63.9
171	48.9	Out	85.0	-	72.6		84.5	-	72.0
Average	**46.3**		**83.4**	-	**71.2**		**81.1**	-	**69.1**

Table A.8: Metro Measurements - Open Field[1]

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
05-11	48.4	In	78.6	-	71.9		71.5	-	67.5
70-36	49.2	In	77.9	-	69.3		71.2	-	61.4
55-38	49.0	In	81.6	-	73.4		71.4	-	61.8
24-97	48.7	In	81.2	-	72.9		71.7	-	62.0
27-98	48.5	In	77.9	-	69.4		72.4	-	61.9
73-57	48.5	In	78.0	-	70.7		72.6	-	63.0
Average	**48.7**		**79.5**	-	**71.5**		**71.8**	-	**63.6**
38-55	49.5	Out	81.4	-	71.2		75.2	-	64.2
97-24	49.7	Out	80.5	-	71.1		74.6	-	64.1
98-27	49.8	Out	79.5	-	70.6		74.8	-	64.5
57-53	50.1	Out	79.1	-	69.7		75.0	-	64.2
68-29	47.7	Out	78.4	-	70.1		73.5	-	62.9
103-89	47.6	Out	77.4	-	68.6		74.2	-	63.5
Average	**49.1**		**79.6**	-	**70.3**		**74.6**	-	**63.9**

A.4 Measurements 27.02.18

A.4.1 Ground Impedance

Instrumentation

The equipment used for the ground impedance measurement is listed in Table 4.2. A sampling frequency of 44.1 kHz and bit rate of 16 are used for the SQuadriga II. The weather information is partly based on information from the temperature sensor from the car used to the measurement site as well as information from weather broadcast [1] from Bygdøy observation station, 4.4 km away from Jarmyra.

The calibrator is given with the value of 114 dB at 1 kHz, and both microphones are measured to have a value of 114.0 dB.

Meteorological Data

It is a lot wind this day (above 7-8 m/s), so it is not possible to do the ground impedance measurements. Therefore the measurements are done three days later, when the ground and temperature conditions approximately are the same. It is measured a temperature of -10 °C, and the relative humidity is 53 %. The wind velocity is 0-1 m/s, the atmospheric pressure is 1025 mb

[1] only two microphones work this day

and the sky is partly covered with clouds, but with no precipitation. The test area is covered with about 23 cm of snow, see Figure A.5.

Figure A.5: Snow depth at test area surrounded by vegetation.

Impedance Values

Table A.9: Acoustic Impedance

	Normalized Acoustic Impedance ($Z_s/\rho c$)	
Frequency (Hz)	**Real**	**Imaginary**
250	1.019	0.142
315	1.006	0.131
400	0.989	0.173
500	1.039	0.333
630	1.174	0.269
800	1.172	0.220
1000	1.069	0.262
1250	1.153	0.304
1600	1.427	0.252
2000	1.387	0.460
2500	1.030	0.338
3150	0.865	0.378
4000	0.812	0.662

Other Observations

Since the ground is made of snow, it is impossible to have a totally flat area around the test area which ANSI S1.18 recommends.

A.4.2 Sound Pressure Level

Table A.10: Tram Measurements - With Vegetation

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
145	49.5	In	78.4	71.3	68.9		73.5	65.6	62.1
154	26.5	In	79.4	71.5	69.0		77.6	68.9	66.4
169	41.0	In	80.2	71.8	68.5		75.6	66.8	63.5
168	46.4	In	77.2	70.5	67.7		67.7	61.5	59.1
Average	**39.3**		**78.9**	**71.5**	**69.0**		**75.7**	**67.9**	**65.1**
170	44.5	Out	90.0	78.3	73.7		83.6	74.9	70.1
151	43.8	Out	82.6	74.8	71.9		79.2	71.9	68.9
169	50.7	Out	88.0	78.8	73.9		83.2	75.6	71.2
168	46.0	Out	87.0	76.6	72.5		79.1	71.1	68.2
145	47.7	Out	88.1	77.9	72.8		82.5	72.4	68.9
150	44.3	Out	84.4	75.4	72.2		83.1	73.8	70.8
Average	**46.2**		**87.3**	**77.2**	**72.9**		**82.2**	**73.6**	**69.8**

Table A.11: Metro Measurements - With Vegetation

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
92-61	51.6	In	80.3	72.5	69.8		72.9	65.5	63.9
34-97	49.7	In	78.7	71.3	69.1		72.6	65.3	62.5
15-01	47.7	In	78.4	71.3	68.8		71.7	64.3	61.3
89-45	47.8	In	78.7	72.1	68.9		72.8	65.6	61.8
63-30	48.5	In	79.9	71.7	69.4		73.0	65.6	62.7
103-73	49.9	In	78.7	71.2	69.3		73.0	65.5	62.1
23-11	47.8	In	79.7	72.4	70.9		72.7	66.1	63.4
50-26	49.7	In	79.3	71.7	69.6		73.7	66.5	63.1
56-95	47.2	In	78.4	71.4	68.6		72.4	64.5	61.2
Average	**48.9**		**79.2**	**71.9**	**69.4**		**72.8**	**65.6**	**62.5**
01-15	59.7	Out	87.9	79.5	76.0		79.2	71.7	69.4
30-63	54.4	Out	87.9	78.6	76.0		79.6	72.0	69.6
73-103	26.5	Out	80.6	71.4	68.2		72.5	64.3	60.8
11-23	45.9	Out	84.0	76.3	72.2		76.0	68.2	65.6
97-48	58.8	Out	88.3	79.7	76.1		83.4	73.9	70.7
Average	**50.1**		**86.6**	**78.0**	**74.6**		**79.5**	**71.1**	**68.4**

A.5 Measurements 28.02.18

A.5.1 Ground Impedance

Instrumentation

The equipment used for the ground impedance measurement is listed in Table 4.2. A sampling frequency of 44.1 kHz and bit rate of 16 are used for the SQuadriga II. The weather information is partly based on information from the temperature sensor from the car used to the measurement site as well as information from weather broadcast [1] from Bygdøy observation station, 4.4 km away from Jarmyra.

The calibrator is given with the value of 114 dB at 1 kHz, and both microphones are measured to have a value of 114.0 dB.

Meteorological Data

It is pretty much wind this day (above 7-8 m/s), so it is not possible to do the ground impedance measurements. Therefore the measurements are done two days later, when the ground and temperature conditions approximately are the same. It is measured a temperature of -10 °C, and the relative humidity is 53 %. The wind velocity is 0-1 m/s, the atmospheric pressure is 1025 mb and the sky is partly covered with clouds, but with no precipitation. The test area is covered with about 33 cm of snow (see Figure A.6), where the top layer is a bit harder than the softer lower part.

Figure A.6: Snow depth at test area with open field conditions.

Impedance Values

Table A.12: Acoustic Impedance

	Normalized Acoustic Impedance ($Z_s/\rho c$)	
Frequency (Hz)	**Real part**	**Imaginary part**
250	0.960	0.131
315	0.939	0.185
400	1.022	0.293
500	1.039	0.298
630	1.067	0.341
800	1.111	0.408
1000	1.142	0.442
1250	1.093	0.389
1600	1.221	0.375
2000	1.130	0.373
2500	0.740	0.858
3150	0.531	0.697
4000	0.313	0.912

Other Observations

Since the ground is made of snow, it is impossible to have a totally flat area around the test area which ANSI S1.18 recommends.

A.5.2 Sound Pressure Level

Table A.13: Tram Measurements - Open Field

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
153	41.0	In	82.3	75.2	71.2		82.0	74.0	69.8
148	36.7	In	79.9	71.5	68.0		77.9	69.4	65.6
141	47.7	In	75.3	69.4	66.3		71.8	64.6	61.7
170	49.7	In	81.1	73.6	69.9		78.3	69.8	66.0
Average	**43.8**		**80.3**	**72.9**	**69.2**		**78.8**	**70.6**	**66.7**
148	43.4	Out	85.3	76.5	72.5		84.7	75.7	71.3
141	51.6	Out	85.9	76.3	72.7		86.0	76.2	72.5
170	49.7	Out	86.5	76.5	71.8		79.5	70.8	67.2
Average	**48.2**		**85.9**	**76.5**	**72.4**		**84.2**	**74.8**	**70.8**

Table A.14: Metro Measurements - Open Field

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
23-63	48.5	In	79.1	71.4	68.8		73.6	65.9	62.5
05-81	48.9	In	77.7	70.2	68.2		72.7	65.5	62.1
103-35	48.4	In	78.2	70.9	67.9		72.3	65.3	61.8
33-82	49.3	In	78.4	70.1	67.6		73.2	65.8	61.9
Average	**48.8**		**78.4**	**70.7**	**68.1**		**73.0**	**65.6**	**62.1**
-[2]	47.8	Out	80.4	71.1	69.1		74.6	67.4	63.6
82-33	49.3	Out	78.6	71.1	68.5		75.3	68.0	64.5
107-72	47.5	Out	80.3	71.8	69.2		77.3	69.3	66.0
98-112	49.5	Out	79.7	72.1	69.2		74.9	67.3	64.3
94-104	48.0	Out	77.9	70.3	67.9		73.6	65.9	62.7
Average	**48.4**		**79.5**	**71.3**	**68.8**		**75.3**	**67.7**	**64.4**

A.6 Measurements 17.04.18

A.6.1 Ground Impedance

Instrumentation

The equipment used for the ground impedance measurement is listed in Table 4.2. A sampling frequency of 44.1 kHz and bit rate of 16 are used for the SQuadriga II. The weather information is partly based on information from the temperature sensor from the car used to the measurement site as well as information from weather broadcast [1] from Bygdøy observation station, 4.4 km away from Jarmyra.

The calibrator is given with the value of 114 dB at 1 kHz, and both microphones are measured to have a value of 114.0 dB. Because of high background noise from someone using chainsaws in the area, the ground impedance is measured 18 April instead of 17 April.

Meteorological Data

The temperature this day is about 12 °C and there is no precipitation. The wind velocity is 1 m/s, the atmospheric pressure is 1023 mb, the sky is clear and the humidity is 75 %. Even if most of the snow is gone, the ground is a bit hard and covered with foliage.

[2] the identification number is missing

Figure A.7: Test area with open field conditions covered with foliage.

Impedance Values

Table A.15: Acoustic Impedance

	Normalized Acoustic Impedance ($Z_s/\rho c$)	
Frequency (Hz)	**Real part**	**Imaginary part**
250	0.446	-0.845
315	0.560	-1.232
400	7.009	-1.665
500	1.278	-2.393
630	3.021	-2.104
800	4.056	-1.432
1000	2.765	0.588
1250	3.774	5.385
1600	7.808	3.738
2000	2.228	1.882
2500	2.351	2.675
3150	1.701	1.859
4000	4.634	-0.282

Other Observations

The ground is not completely flat, and there are trees which are close to the test site which may influence the results.

A.6.2 Sound Pressure Level

Table A.16: Tram Measurements - Open Field

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
150	45.9	In	84.5	78.9	75.8		81.5	77.0	72.8
146	32.3	In	74.9	70.6	68.0		71.1	66.7	63.4
167	44.5	In	79.3	74.3	70.5		77.9	72.7	68.2
153	50.3	In	82.8	77.6	74.7		80.9	75.8	72.5
160	47.7	In	80.4	75.7	73.1		78.4	73.0	69.6
172	45.5	In	84.0	79.3	76.4		84.1	79.4	76.6
150	51.6	In	79.9	75.3	72.5		77.8	73.2	70.0
Average	**45.4**		**81.3**	**76.4**	**73.4**		**79.5**	**74.7**	**71.3**
146	44.5	Out	87.6	81.7	77.9		86.9	81.3	77.3
167	44.5	Out	84.6	78.4	75.2		83.3	77.0	72.8
153	50.3	Out	86.9	81.9	78.7		85.8	81.5	77.9
160	48.3	Out	86.1	80.1	76.5		85.0	78.9	74.8
172	41.4	Out	89.3	83.9	80.0		89.1	83.8	79.6
150	49.7	Out	87.0	81.9	77.9		86.5	81.2	77.3
Average	**46.5**		**87.0**	**81.5**	**77.8**		**86.3**	**80.9**	**76.9**

Table A.17: Metro Measurements - Open Field

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
85-44	48.5	In	79.9	76.4	74.5		77.9	73.3	69.1
47-92	48.7	In	80.9	77.3	74.4		78.2	73.5	69.6
74-96	48.2	In	80.6	76.5	74.1		79.0	74.2	70.6
23-51	48.9	In	80.6	77.0	74.7		78.9	74.1	69.9
114-109	47.8	In	79.9	76.4	73.6		78.0	73.7	69.7
29-65	47.4	In	80.7	77.1	74.4		77.9	73.6	69.8
25-39	48.5	In	81.3	77.4	75.2		79.4	73.9	70.6
65-29	48.4	In	81.6	78.3	75.6		77.7	73.7	69.9
97-14	48.4	In	80.2	76.6	74.0		78.4	73.9	69.8
85-44	48.5	In	79.7	76.0	73.8		77.7	72.9	68.9
Average	**48.3**		**80.6**	**76.9**	**74.5**		**78.3**	**73.7**	**69.8**
51-23	48.3	Out	81.9	78.1	75.7		80.4	75.9	72.4
109-114	47.1	Out	81.6	77.6	74.8		80.1	75.4	72.0
41-58	48.3	Out	81.4	77.6	75.3		79.2	74.9	71.7
39-25	50.3	Out	82.6	79.1	76.6		80.2	76.1	73.0
29-65	47.4	Out	82.6	78.6	76.0		79.1	74.6	71.4
14-97	49.5	Out	83.0	78.7	75.7		81.3	76.3	73.2
44-85	47.1	Out	81.0	76.7	74.3		79.0	74.3	71.1
92-47	49.3	Out	82.7	78.6	76.2		80.0	75.7	72.8
96-74	49.7	Out	82.5	78.1	75.9		80.3	75.6	72.7
51-23	46.9	Out	82.4	78.6	77.4		80.9	76.3	74.8
Average	**48.4**		**82.2**	**78.2**	**75.8**		**80.1**	**75.5**	**72.6**

A.7 Measurements 18.04.18

A.7.1 Ground Impedance

Instrumentation

The equipment used for the ground impedance measurement is listed in Table 4.2. A sampling frequency of 44.1 kHz and bit rate of 16 are used for the SQuadriga II. The weather information is partly based on information from the temperature sensor from the car used to the measurement site as well as information from weather broadcast [1] from Bygdøy observation station, 4.4 km away from Jarmyra.

The calibrator is given with the value of 114 dB at 1 kHz, and both microphones are measured to have a value of 114.0 dB.

Meteorological Data

The temperature this day is about 12 °C and there is no precipitation. The wind velocity is 1 m/s, the atmospheric pressure is 1023 mb, the sky is clear and the relative humidity is 75 %. As shown in Figure A.8, the ground is partially covered with snow and ice.

Figure A.8: Surrounding ground with forest conditions.

Impedance Values

Table A.18: Acoustic Impedance

	Normalized Acoustic Impedance ($Z_s/\rho c$)	
Frequency (Hz)	**Real part**	**Imaginary part**
250	0.458	-0.749
315	0.747	-0.749
400	2.535	-1.339
500	2.325	-0.784
630	2.998	-1.254
800	2.966	-2.225
1000	0.246	3.924
1250	0.789	2.145
1600	0.642	2.139
2000	1.015	2.567
2500	-0.989	-0.985
3150	-1.191	1.608
4000	-1.504	1.850

Other Observations

The ground is not completely flat, and there are trees which are close to the test site which may influence the results.

A.7.2 Sound Pressure Level

Table A.19: Tram Measurements - With Vegetation

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
154	43.4	In	80.4	73.7	70.8		76.7	70.9	67.2
142	35.3	In	80.6	75.0	70.6		78.6	72.8	67.6
165	38.6	In	83.2	78.0	74.4		80.4	75.4	71.3
150	37.4	In	83.8	77.5	74.5		81.8	74.8	70.7
170	36.7	In	85.7	79.5	76.8		80.9	76.0	71.7
145	43.8	In	83.5	78.1	74.3		80.9	75.6	71.5
154	36.7	In	77.5	72.4	69.9		73.8	68.6	64.3
142	37.4	In	82.2	76.2	71.8		81.4	74.9	69.9
165	38.1	In	82.9	78.5	74.2		80.6	76.4	71.7
Average	**38.6**		**82.5**	**76.8**	**73.3**		**79.8**	**74.2**	**69.9**
142	35.3	Out	87.0	80.6	76.6		85.5	78.6	74.1
165	47.7	Out	91.5	84.3	79.3		90.0	82.6	77.4
150	42.0	Out	88.6	80.5	77.7		86.3	79.0	75.8
170	31.5	Out	88.3	80.8	77.4		81.2	74.4	70.6
145	47.1	Out	87.9	80.9	77.5		85.7	78.6	75.1
154	52.1	Out	89.6	83.6	78.3		88.6	82.5	76.4
142	36.0	Out	85.5	78.0	75.2		83.1	75.6	72.7
165	48.9	Out	90.4	83.3	79.9		89.5	82.3	78.9
Average	**42.6**		**88.8**	**81.7**	**77.9**		**86.7**	**79.7**	**75.5**

Table A.20: Metro Measurements - With Vegetation

			$L_{p,Fmax}$ (dB)				$L_{p,AFmax}$ (dB)		
Identification	**Velocity (km/h)**	**In-/outbound**	x_1	x_2	x_3		x_1	x_2	x_3
29-65	49.7	In	85.9	84.6	80.1		79.5	74.4	70.4
98-64	48.5	In	82.2	78.5	77.4		79.3	74.1	70.0
99-59	50.3	In	82.6	80.3	77.6		79.8	74.8	71.1
52-55	49.5	In	84.9	83.7	81.7		79.2	74.3	70.5
85-103	49.5	In	81.7	78.6	76.5		79.3	74.1	70.2
57[3]	44.9	In	80.4	77.2	74.9		76.8	71.0	66.5
100-33	52.0	In	82.6	80.6	77.7		79.3	74.8	71.2
56-28	48.2	In	83.1	80.6	78.3		77.9	73.2	69.6
71-19	46.9	In	81.7	79.4	77.0		78.2	73.3	69.0
73-35	47.2	In	81.3	79.6	77.2		78.5	74.0	70.2
58-65	52.4	In	83.5	82.0	80.7		79.5	74.4	71.3
98-64	51.2	In	82.3	80.0	77.7		79.0	73.9	70.6
Average	**49.2**		**82.8**	**80.7**	**78.3**		**78.9**	**73.9**	**70.1**
59-99	57.0	Out	88.7	84.4	82.7		85.5	79.8	77.1
55-52	59.2	Out	90.8	86.4	85.5		85.5	79.6	77.4
103-85	47.4	Out	85.2	81.6	78.0		81.5	75.9	72.7
33-100	48.5	Out	85.5	82.2	79.3		82.2	76.5	73.9
28-56	50.3	Out	88.7	83.5	81.8		85.3	78.6	76.4
19-71	57.7	Out	89.4	84.7	83.2		85.3	79.7	77.2
35-73	57.2	Out	89.8	84.9	83.2		86.2	80.3	77.5
65-58	47.6	Out	87.2	83.9	82.2		81.2	75.3	72.8
64-98	58.8	Out	89.2	84.8	82.5		86.3	80.3	77.5
59-99	48.9	Out	85.6	82.7	79.9		82.4	77.1	74.3
55-52	53.4	Out	90.8	86.4	85.1		85.3	79.6	77.2
103-85	57.0	Out	88.8	84.2	82.1		85.8	79.8	77.3
Average	**53.6**		**88.5**	**84.3**	**82.4**		**84.6**	**78.7**	**76.1**

[3] this metro only consists of one set

Appendix B

MATLAB code

B.1 Interference Simulation

```
% Model of acoustic absorption of snow

x = [20 1000 1500 4000 8000 20000];
y = [0.1 0.9 1 0.85 1 1];
f = 20:20000;

snow_abs = interp1(x,y,f,'pchip');

figure
plot(f,snow_abs)

% Sound pressure simulation

Rd = 6.05;
Rr = 7.10;
T = -5;
c = 20.06*sqrt(273.15-T);
f = 20:20000;
k = 2*pi.*f./c;
Q = sqrt(1-snow_abs);

p = 1/Rd.*exp(1i*k*Rd) + Q/Rr.*exp(1i*k*Rr);

figure
semilogx(f,abs(p)-max(abs(p)))
```

```
title('Interference simulation'),xlabel('Frequency [Hz]'),...
    ylabel('Normalized amplitude')
grid on
% xlim([20 1000])
xticks([20 50 100 250 500 1000])
```

B.2 Open Field Analysis

```
%% TRAM AND METRO FREQUENCY ANALYSIS
% Analysis of the tram and metro pass-by when there is open field
% conditions. Data from each measurement day is sorted by inbound,
% outbound, tram and metro, then everything is concatenated

%% 30.01.18 SORTING (INBOUND/OUTBOUND)
% reads through every sheet with measurement data
[~,sheet_name]=xlsfinfo('3001_max_flat.xlsx');
for k=1:numel(sheet_name)
  data{k}=xlsread('3001_max_flat.xlsx',sheet_name{k});
end

for k=1:numel(sheet_name)
    pos1(:,k) = data{k}(17:end,2); % mic pos 1
    pos2(:,k) = data{k}(17:end,3); % mic pos 2
    pos3(:,k) = data{k}(17:end,4); % mic pos 3
end

% Trams
TN_in = [1 5 10 15 19 24]; % inbound
pos1_T_in3001 = pos1(:,TN_in);
pos2_T_in3001 = pos2(:,TN_in);
pos3_T_in3001 = pos3(:,TN_in);

TN_out = [3 7 12 17 21 26 29]; % outbound
pos1_T_out3001 = pos1(:,TN_out);
pos2_T_out3001 = pos2(:,TN_out);
pos3_T_out3001 = pos3(:,TN_out);

% Metros
MN_in = [4 8 11 14 18 22 25 27]; % inbound
pos1_M_in3001 = pos1(:,MN_in);
```

```
pos2_M_in3001 = pos2(:,MN_in);
pos3_M_in3001 = pos3(:,MN_in);

MN_out = [2 6 9 13 16 20 23 30]; % outbound
pos1_M_out3001 = pos1(:,MN_out);
pos2_M_out3001 = pos2(:,MN_out);
pos3_M_out3001 = pos3(:,MN_out);

%% 13.02.18 SORTING (INBOUND/OUTBOUND)
[~,sheet_name]=xlsfinfo('1302_max_flat.xlsx');
for k=1:numel(sheet_name)
  data{k}=xlsread('1302_max_flat.xlsx',sheet_name{k});
end

for k=1:numel(sheet_name)
    pos1(:,k) = data{k}(17:end,2); % mic pos 1
    pos3(:,k) = data{k}(17:end,3); % mic pos 3
end

% Trams
TN_in = [4 13 17]; % inbound
pos1_T_in1302 = pos1(:,TN_in);
pos3_T_in1302 = pos3(:,TN_in);

TN_out = [1 6 10 14 19]; % outbound
pos1_T_out1302 = pos1(:,TN_out);
pos3_T_out1302 = pos3(:,TN_out);

% Metros
MN_in = [3 7 9 12 16 20]; % inbound
pos1_M_in1302 = pos1(:,MN_in);
pos3_M_in1302 = pos3(:,MN_in);

MN_out = [2 5 8 11 15 18]; % outbound
pos1_M_out1302 = pos1(:,MN_out);
pos3_M_out1302 = pos3(:,MN_out);

%% 28.02.18 SORTING (INBOUND/OUTBOUND)
[~,sheet_name]=xlsfinfo('2802_max_flat.xlsx');
for k=1:numel(sheet_name)
```

```
    data{k}=xlsread('2802_max_flat.xlsx',sheet_name{k});
end

for k=1:numel(sheet_name)
        pos1(:,k) = data{k}(17:end,2); % mic pos 1
        pos2(:,k) = data{k}(17:end,3); % mic pos 2
        pos3(:,k) = data{k}(17:end,4); % mic pos 3
end

% Trams
TN_in = [2 7 11 16]; % inbound
pos1_T_in2802 = pos1(:,TN_in);
pos2_T_in2802 = pos2(:,TN_in);
pos3_T_in2802 = pos3(:,TN_in);

TN_out = [4 8 14]; % outbound
pos1_T_out2802 = pos1(:,TN_out);
pos2_T_out2802 = pos2(:,TN_out);
pos3_T_out2802 = pos3(:,TN_out);

% Metros
MN_in = [3 6 10 13]; % inbound
pos1_M_in2802 = pos1(:,MN_in);
pos2_M_in2802 = pos2(:,MN_in);
pos3_M_in2802 = pos3(:,MN_in);

MN_out = [1 5 9 12 15]; % outbound
pos1_M_out2802 = pos1(:,MN_out);
pos2_M_out2802 = pos2(:,MN_out);
pos3_M_out2802 = pos3(:,MN_out);

%% 17.04.18 SORTING (INBOUND/OUTBOUND)
[~,sheet_name]=xlsfinfo('1704_max_flat.xlsx');
for k=1:numel(sheet_name)
    data{k}=xlsread('1704_max_flat.xlsx',sheet_name{k});
end

for k=1:numel(sheet_name)
        pos1(:,k) = data{k}(17:end,2); % mic pos 1
        pos2(:,k) = data{k}(17:end,3); % mic pos 2
```

```
    pos3(:,k) = data{k}(17:end,4); % mic pos 3
end

% Trams 3
TN_in = [8 12 17 22 26 31]; % inbound
pos1_T_in1704 = pos1(:,TN_in);
pos2_T_in1704 = pos2(:,TN_in);
pos3_T_in1704 = pos3(:,TN_in);

TN_out = [5 9 15 19 24 28]; % outbound
pos1_T_out1704 = pos1(:,TN_out);
pos2_T_out1704 = pos2(:,TN_out);
pos3_T_out1704 = pos3(:,TN_out);

% Metros
MN_in = [1 4 7 11 14 18 21 25 29 32]; % inbound
pos1_M_in1704 = pos1(:,MN_in);
pos2_M_in1704 = pos2(:,MN_in);
pos3_M_in1704 = pos3(:,MN_in);

MN_out = [2 6 10 13 16 20 23 27 30 33]; % outbound
pos1_M_out1704 = pos1(:,MN_out);
pos2_M_out1704 = pos2(:,MN_out);
pos3_M_out1704 = pos3(:,MN_out);

%% CONCATENATING ALL MATRICES/MEASUREMENTS
pos1_M_in = [pos1_M_in3001, pos1_M_in1302, pos1_M_in2802, ...
    pos1_M_in1704];
pos2_M_in = [pos2_M_in3001+2, pos2_M_in2802, pos2_M_in1704];
pos3_M_in = [pos3_M_in3001, pos3_M_in1302, pos3_M_in2802, pos3_M_in1704];
pos1_M_out = [pos1_M_out3001, pos1_M_out1302, pos1_M_out2802, ...
    pos1_M_out1704];
pos2_M_out = [pos2_M_out3001+2, pos2_M_out2802, pos2_M_out1704];
pos3_M_out = [pos3_M_out3001, pos3_M_out1302, pos3_M_out2802, ...
    pos3_M_out1704];

pos1_T_in = [pos1_T_in3001, pos1_T_in1302, pos1_T_in2802, ...
    pos1_T_in1704];
pos2_T_in = [pos2_T_in3001+2, pos2_T_in2802, pos2_T_in1704];
pos3_T_in = [pos3_T_in3001, pos3_T_in1302, pos3_T_in2802, pos3_T_in1704];
```

```
pos1_T_out = [pos1_T_out3001, pos1_T_out1302, pos1_T_out2802, ...
    pos1_T_out1704];
pos2_T_out = [pos2_T_out3001+2, pos2_T_out2802, pos2_T_out1704];
pos3_T_out = [pos3_T_out3001, pos3_T_out1302, pos3_T_out2802, ...
    pos3_T_out1704];

% Average of all frequency spectra at each microphone position
pos1_TavgIn = 10*log10(mean(10.^(pos1_T_in./10),2));
pos2_TavgIn = 10*log10(mean(10.^(pos2_T_in./10),2));
pos3_TavgIn = 10*log10(mean(10.^(pos3_T_in./10),2));

pos1_MavgIn = 10*log10(mean(10.^(pos1_M_in./10),2));
pos2_MavgIn = 10*log10(mean(10.^(pos2_M_in./10),2));
pos3_MavgIn = 10*log10(mean(10.^(pos3_M_in./10),2));

pos1_TavgOut = 10*log10(mean(10.^(pos1_T_out./10),2));
pos2_TavgOut = 10*log10(mean(10.^(pos2_T_out./10),2));
pos3_TavgOut = 10*log10(mean(10.^(pos3_T_out./10),2));

pos1_MavgOut = 10*log10(mean(10.^(pos1_M_out./10),2));
pos2_MavgOut = 10*log10(mean(10.^(pos2_M_out./10),2));
pos3_MavgOut = 10*log10(mean(10.^(pos3_M_out./10),2));

f = data{1}(17:end,1); % frequency range from 20 Hz to 20 kHz

figure(1) % Figure 5.20
subplot(2,1,1)
bar(log10(f),pos1_TavgIn)
title('Inbound tram measurements - Open field'),xlabel('Frequency [Hz]'),...
    ylabel('L_{p,Fmax} [dB]')
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
hold on
bar(log10(f),pos2_TavgIn)
bar(log10(f),pos3_TavgIn)
legend('10 m','20 m','30 m','Location','SouthWest')
grid on

figure(2) % Figure 5.21
subplot(2,1,1)
```

```
bar(log10(f),pos1_TavgOut)
title('Outbound tram measurement - Open field'),xlabel('Frequency [Hz]'),...
    ylabel('L_{p,Fmax} [dB]')
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
hold on
bar(log10(f),pos2_TavgOut)
bar(log10(f),pos3_TavgOut)
legend('6 m','16 m','26 m','Location','SouthWest')
grid on

figure(3) % Figure 5.22
subplot(2,1,1)
bar(log10(f),pos1_MavgIn)
title('Inbound metro measurements - Open field'),xlabel('Frequency [Hz]'),...
    ylabel('L_{p,Fmax} [dB]')
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
hold on
bar(log10(f),pos2_MavgIn)
bar(log10(f),pos3_MavgIn)
legend('10 m','20 m','30 m','Location','SouthWest')
grid on

figure(4) % Figure 5.23
subplot(2,1,1)
bar(log10(f),pos1_MavgOut)
title('Outbound metro measurements - Open field'),xlabel('Frequency [Hz]'),...
    ylabel('L_{p,Fmax} [dB]')
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
hold on
bar(log10(f),pos2_MavgOut)
bar(log10(f),pos3_MavgOut)
legend('6 m','16 m','26 m','Location','SouthWest')
grid on

%% Max damping as a function of frequency - trams
freq_range = 18:31; % 20Hz-20kHz (1:31);     1-20kHz (18:31)

```

```
Tin_att = pos1_T_in(freq_range,:) - pos3_T_in(freq_range,:);
Tin_att_lin = mean(10.^( (Tin_att)./10), 2);
Tin_att_dB = 10*log10(Tin_att_lin);
Tin_att_avg = 10*log10(mean(Tin_att_lin));
Tin_std = (mean(std(Tin_att,0,2)));

Tout_att1 = pos1_T_out(freq_range,:) - pos2_T_out(freq_range,:);
Tout_att2 = pos1_T_out(freq_range,:) - pos3_T_out(freq_range,:);
Tout_att_lin1 = mean(10.^( (Tout_att1)./10), 2);
Tout_att_lin2 = mean(10.^( (Tout_att2)./10), 2);
Tout_att_dB = 10*log10(Tout_att_lin2);
Tout_att_avg1 = 10*log10(mean(Tout_att_lin1));
Tout_att_avg2 = 10*log10(mean(Tout_att_lin2));
Tout_std1 = (mean(std(Tout_att2,0,2)));
Tout_std2 = (mean(std(Tout_att2,0,2)));
Tof = [0 Tout_att_avg1 Tout_att_avg2];

hold on
figure(5)
subplot(2,1,1)
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
semilogx(f(freq_range),Tin_att_dB,'b')
hold on
title('Level difference for all inbound tram measurements'),...
    xlabel('Frequency [Hz]'),ylabel('Attenuation [dB]')
xticks(f(1:3:end))
grid on

subplot(2,1,2)
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
semilogx(f(freq_range),Tout_att_dB,'b')
hold on
title('Level difference for all outbound tram measurements'),...
    xlabel('Frequency [Hz]'),ylabel('Attenuation [dB]')
xticks(f(1:3:end))
grid on

%% Max damping as a function of frequency - metros
```

```
Min_att = pos1_M_in(freq_range,:) - pos3_M_in(freq_range,:);
Min_att_lin = mean(10.^( (Min_att)./10), 2);
Min_att_dB = 10*log10(Min_att_lin);
Min_att_avg = 10*log10(mean(Min_att_lin));
Min_std = (mean(std(Min_att,0,2)));

Mout_att1 = pos1_M_out(freq_range,:) - pos2_M_out(freq_range,:);
Mout_att2 = pos1_M_out(freq_range,:) - pos3_M_out(freq_range,:);
Mout_att_lin1 = mean(10.^( (Mout_att1)./10), 2);
Mout_att_lin2 = mean(10.^( (Mout_att2)./10), 2);
Mout_att_dB = 10*log10(Mout_att_lin2);
Mout_att_avg1 = 10*log10(mean(Mout_att_lin1));
Mout_att_avg2 = 10*log10(mean(Mout_att_lin2));
Mout_std1 = (mean(std(Mout_att1,0,2)));
Mout_std2 = (mean(std(Mout_att2,0,2)));
Mof = [0 Mout_att_avg1 Mout_att_avg2];

hold on
figure(6)
subplot(2,1,1)
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
semilogx(f(freq_range),Min_att_dB,'b')
hold on
title('Level difference for all inbound metro measurements'),...
    xlabel('Frequency [Hz]'),ylabel('Attenuation [dB]')
xticks(f(1:3:end))
grid on

subplot(2,1,2)
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
semilogx(f(freq_range),Mout_att_dB,'b')
hold on
title('Level difference for all outbound metro measurements'),...
    xlabel('Frequency [Hz]'),ylabel('Attenuation [dB]')
xticks(f(1:3:end))
grid on

% Level attenuation for outbound traffic, 1-20 kHz
```

```
dist = 0:50;
x = [0 10 20];
T_int = interp1(x,Tof,dist,'linear');
M_int = interp1(x,Mof,dist,'linear');

figure(8)
hold on
plot(dist,M_int)
title('Noise attenuation of metros (1-20 kHz)')
xlabel('Distance from the nearest microphone position [m]'),
ylabel('Attenuation [dB]')
grid on

figure(9)
hold on
plot(dist,T_int)
title('Noise attenuation of trams (1-20 kHz)')
xlabel('Distance from the nearest microphone position [m]'),
ylabel('Attenuation [dB]')
grid on


%% Statistical analysis
% Student's t-distribution based on a 90 % confidence interval
Tin_unc_upper2 = 10*log10((10^(Tin_att_avg/10) + ...
    1.729*Tin_std/sqrt(size(Tin_att,2))) / 10^(Tin_att_avg/10) );
Tin_unc_lower = 10*log10((10^(Tin_att_avg/10) - ...
    1.729*Tin_std/sqrt(size(Tin_att,2))) / 10^(Tin_att_avg/10) );

Tout_unc_upper1 = 10*log10((10^(Tout_att_avg1/10) + ...
    1.746*Tout_std1/sqrt(size(Tout_att1,2))) / 10^(Tout_att_avg1/10) );
Tout_unc_lower1 = 10*log10((10^(Tout_att_avg1/10) - ...
    1.746*Tout_std1/sqrt(size(Tout_att1,2))) / 10^(Tout_att_avg1/10) );
Tout_unc_upper2 = 10*log10((10^(Tout_att_avg2/10) + ...
    1.721*Tout_std2/sqrt(size(Tout_att2,2))) / 10^(Tout_att_avg2/10) );
Tout_unc_lower2 = 10*log10((10^(Tout_att_avg2/10) - ...
    1.721*Tout_std2/sqrt(size(Tout_att2,2))) / 10^(Tout_att_avg2/10) );

Min_unc_upper = 10*log10((10^(Min_att_avg/10) + ...
    1.701*Min_std/sqrt(size(Min_att,2))) / 10^(Min_att_avg/10) );
```

```
Min_unc_lower = 10*log10((10^(Min_att_avg/10) - ...
    1.701*Min_std/sqrt(size(Min_att,2))) / 10^(Min_att_avg/10) );

Mout_unc_upper1 = 10*log10((10^(Mout_att_avg1/10) + ...
    1.714*Mout_std1/sqrt(size(Mout_att1,2))) / 10^(Mout_att_avg1/10) );
Mout_unc_lower1 = 10*log10((10^(Mout_att_avg1/10) - ...
    1.714*Mout_std1/sqrt(size(Mout_att1,2))) / 10^(Mout_att_avg1/10) );
Mout_unc_upper2 = 10*log10((10^(Mout_att_avg2/10) + ...
    1.699*Mout_std2/sqrt(size(Mout_att2,2))) / 10^(Mout_att_avg2/10) );
Mout_unc_lower2 = 10*log10((10^(Mout_att_avg2/10) - ...
    1.699*Mout_std2/sqrt(size(Mout_att2,2))) / 10^(Mout_att_avg2/10) );

%% SPL as a function of distance
% Sum up all band frequencies to single value
Lp1_T_in = 10*log10(sum(10.^(pos1_T_in(1:end,:)./10)));
Lp2_T_in = 10*log10(sum(10.^(pos2_T_in(1:end,:)./10)));
Lp3_T_in = 10*log10(sum(10.^(pos3_T_in(1:end,:)./10)));

Lp1_T_out = 10*log10(sum(10.^(pos1_T_out(1:end,:)./10)));
Lp2_T_out = 10*log10(sum(10.^(pos2_T_out(1:end,:)./10)));
Lp3_T_out = 10*log10(sum(10.^(pos3_T_out(1:end,:)./10)));

Lp1_M_in = 10*log10(sum(10.^(pos1_M_in(1:end,:)./10)));
Lp2_M_in = 10*log10(sum(10.^(pos2_M_in(1:end,:)./10)));
Lp3_M_in = 10*log10(sum(10.^(pos3_M_in(1:end,:)./10)));

Lp1_M_out = 10*log10(sum(10.^(pos1_M_out(1:end,:)./10)));
Lp2_M_out = 10*log10(sum(10.^(pos2_M_out(1:end,:)./10)));
Lp3_M_out = 10*log10(sum(10.^(pos3_M_out(1:end,:)./10)));

%% STATISTICAL ANALYSIS
groupTin = [repmat({'10'}, length(Lp1_T_in), 1); repmat({'20'}, ...
    length(Lp2_T_in), 1); repmat({'30'}, length(Lp3_T_in), 1)];

groupTout = [repmat({'6'}, length(Lp1_T_out), 1);  repmat({'16'}, ...
    length(Lp2_T_out), 1); repmat({'26'}, length(Lp3_T_out), 1)];

figure(10)
boxplot([Lp1_T_in'; Lp2_T_in'; Lp3_T_in'], groupTin)
title('Box plot of inbound tram measurements - Open field'),...
```

```
    xlabel('Distance [m]'), ylabel('L_{p,Fmax} [dB]')
grid on

figure(11)
boxplot([Lp1_T_out'; Lp2_T_out'; Lp3_T_out'], groupTout)
title('Box plot of outbound tram measurements - Open field'),...
    xlabel('Distance [m]'), ylabel('L_{p,Fmax} [dB]')
grid on

%%
groupMin = [repmat({'10'}, length(Lp1_M_in), 1); repmat({'20'},...
    length(Lp2_M_in), 1); repmat({'30'}, length(Lp3_M_in), 1)];

groupMout = [repmat({'6'}, length(Lp1_M_out), 1); repmat({'16'}, ...
    length(Lp2_M_out), 1); repmat({'26'}, length(Lp3_M_out), 1)];

figure(12)
boxplot([Lp1_M_in'; Lp2_M_in'; Lp3_M_in'], groupMin)
title('Box plot of inbound metro measurements - Open field'),xlabel('Distance [m]
    '),...
    ylabel('L_{p,Fmax} [dB]')
grid on

figure(13)
boxplot([Lp1_M_out'; Lp2_M_out'; Lp3_M_out';], groupMout)
title('Box plot of outbound metro measurements - Open field'),xlabel('Distance [m
    ]'),...
    ylabel('L_{p,Fmax} [dB]')
grid on

% average SPL at each microphone position
avg1_T_in = 10*log10(mean(10.^(Lp1_T_in/10),2));
avg2_T_in = 10*log10(mean(10.^(Lp2_T_in/10),2));
avg3_T_in = 10*log10(mean(10.^(Lp3_T_in/10),2));

avg1_T_out = 10*log10(mean(10.^(Lp1_T_out/10),2));
avg2_T_out = 10*log10(mean(10.^(Lp2_T_out/10),2));
avg3_T_out = 10*log10(mean(10.^(Lp3_T_out/10),2));

avg1_M_in = 10*log10(mean(10.^(Lp1_M_in/10),2));
```

```
avg2_M_in = 10*log10(mean(10.^(Lp2_M_in/10),2));
avg3_M_in = 10*log10(mean(10.^(Lp3_M_in/10),2));

avg1_M_out = 10*log10(mean(10.^(Lp1_M_out/10),2));
avg2_M_out = 10*log10(mean(10.^(Lp2_M_out/10),2));
avg3_M_out = 10*log10(mean(10.^(Lp3_M_out/10),2));

T_max_in = [avg1_T_in avg2_T_in avg3_T_in];
T_max_out = [avg1_T_out avg2_T_out avg3_T_out];
T_max = [T_max_out(1) T_max_in(1) T_max_out(2) T_max_in(2) T_max_out(3) ...
    T_max_in(3)];
M_max_in = [avg1_M_in avg2_M_in avg3_M_in];
M_max_out = [avg1_M_out avg2_M_out avg3_M_out];
M_max = [M_max_out(1) M_max_in(1) M_max_out(2) M_max_in(2) M_max_out(3) ...
    M_max_in(3)];

% Measurement distances in meters
xin = [10 20 30];
xout = [6 16 26];
x = [6 10 16 20 26 30];
r = 1:0.5:30;

% Linear interpolation of trams
T_max_in_of = interp1(xin,T_max_in,r,'linear');
T_max_out_of = interp1(xout,T_max_out,r,'linear');
T = interp1(x,T_max,r,'linear');

% Regression calculation
FTreg = @(y,ydata)y(1)*exp(-y(2)*ydata) + y(3)*exp(-y(4)*ydata);
y0 = [1 1 1 0];
[yT,resnorm,~,exitflag,output] = lsqcurvefit(FTreg,y0,x,T_max);

FMreg = @(y,ydata)y(1)*exp(-y(2)*ydata) + y(3)*exp(-y(4)*ydata);
[yM,resnorm,~,exitflag,output] = lsqcurvefit(FTreg,y0,x,M_max);

% Linear interpolation of metros
M_max_in_of = interp1(xin,M_max_in,r,'linear');
M_max_out_of = interp1(xout,M_max_out,r,'linear');
M = interp1(x,M_max,r,'linear');
```

```
figure(18)
title('Maximum unweighted SPL of all tram measurements')
hold on
plot(r,T,'b')
plot(x,FTreg(yT,x),'b--')
grid on
xlim([xout(1) xin(3)])
xlabel('Distance [m]')
ylabel('L_{p,Fmax} [dB]')

figure(19)
title('Maximum unweighted SPL of all metro measurements')
hold on
plot(r,M,'b')
plot(x,FMreg(yM,x),'b--')
grid on
xlim([xout(1) xin(3)])
xlabel('Distance [m]')
ylabel('L_{p,Fmax} [dB]')
```

B.3 Forest Analysis

```
%% TRAM AND METRO FREQUENCY ANALYSIS
% Analysis of the tram and metro pass-by when there is forest
% conditions. Data from each measurement day is sorted by inbound,
% outbound, tram and metro, then everything is concatenated

%% SORTING (INBOUND/OUTBOUND)
% reads through every sheet with measurement data
[~,sheet_name]=xlsfinfo('0602_max_flat.xlsx');
for k=1:numel(sheet_name)
  data{k}=xlsread('0602_max_flat.xlsx',sheet_name{k});
end

for k=1:numel(sheet_name)
    pos1(:,k) = data{k}(17:end,2); % mic pos 1
    pos2(:,k) = data{k}(17:end,3); % mic pos 2
    pos3(:,k) = data{k}(17:end,4); % mic pos 3
end

```

```
% Trams
TN_in = [4 9 13 18 22 28 32]; % inbound
pos1_T_in0602 = pos1(:,TN_in);
pos2_T_in0602 = pos2(:,TN_in);
pos3_T_in0602 = pos3(:,TN_in);

TN_out = [1 6 10 16 24 29]; % outbound
pos1_T_out0602 = pos1(:,TN_out);
pos2_T_out0602 = pos2(:,TN_out);
pos3_T_out0602 = pos3(:,TN_out);

% Metros
MN_in = [2 5 8 12 15 21 27 30 33]; % inbound
pos1_M_in0602 = pos1(:,MN_in);
pos2_M_in0602 = pos2(:,MN_in);
pos3_M_in0602 = pos3(:,MN_in);

MN_out = [3 7 11 14 17 20 25 31]; % outbound
pos1_M_out0602 = pos1(:,MN_out);
pos2_M_out0602 = pos2(:,MN_out);
pos3_M_out0602 = pos3(:,MN_out);

%% 27.02.18 SORTING (INBOUND/OUTBOUND)
[~,sheet_name]=xlsfinfo('2702_max_flat.xlsx');
for k=1:numel(sheet_name)
  data{k}=xlsread('2702_max_flat.xlsx',sheet_name{k});
end

for k=1:numel(sheet_name)
    pos1(:,k) = data{k}(17:end,2); % mic pos 1
    pos2(:,k) = data{k}(17:end,3); % mic pos 2
    pos3(:,k) = data{k}(17:end,4); % mic pos 3
end

% Trams
TN_in = [11 15 20 29]; % inbound
pos1_T_in2702 = pos1(:,TN_in);
pos2_T_in2702 = pos2(:,TN_in);
pos3_T_in2702 = pos3(:,TN_in);

```

```
TN_out = [3 13 17 22 27 30]; % outbound
pos1_T_out2702 = pos1(:,TN_out);
pos2_T_out2702 = pos2(:,TN_out);
pos3_T_out2702 = pos3(:,TN_out);

% Metros
MN_in = [2 5 8 10 14 18 21 24 28]; % inbound
pos1_M_in2702 = pos1(:,MN_in);
pos2_M_in2702 = pos2(:,MN_in);
pos3_M_in2702 = pos3(:,MN_in);

MN_out = [1 6 9 12 26]; % outbound
pos1_M_out2702 = pos1(:,MN_out);
pos2_M_out2702 = pos2(:,MN_out);
pos3_M_out2702 = pos3(:,MN_out);

%% 18.04.18 SORTING (INBOUND/OUTBOUND)
[~,sheet_name]=xlsfinfo('1804_max_flat.xlsx');
for k=1:numel(sheet_name)
  data{k}=xlsread('1804_max_flat.xlsx',sheet_name{k});
end

for k=1:numel(sheet_name)
    pos1(:,k) = data{k}(17:end,2); % mic pos 1
    pos2(:,k) = data{k}(17:end,3); % mic pos 2
    pos3(:,k) = data{k}(17:end,4); % mic pos 3
end

% Trams
TN_in = [3 7 12 17 22 27 32 36 41]; % inbound
pos1_T_in1804 = pos1(:,TN_in);
pos2_T_in1804 = pos2(:,TN_in);
pos3_T_in1804 = pos3(:,TN_in);

TN_out = [4 9 14 18 24 29 33 38]; % outbound
pos1_T_out1804 = pos1(:,TN_out);
pos2_T_out1804 = pos2(:,TN_out);
pos3_T_out1804 = pos3(:,TN_out);

% Metros
```

```
MN_in = [2 6 10 13 16 20 21 25 28 31 35 39]; % inbound
pos1_M_in1804 = pos1(:,MN_in);
pos2_M_in1804 = pos2(:,MN_in);
pos3_M_in1804 = pos3(:,MN_in);

MN_out = [1 5 8 11 15 19 23 26 30 34 37 40]; % outbound
pos1_M_out1804 = pos1(:,MN_out);
pos2_M_out1804 = pos2(:,MN_out);
pos3_M_out1804 = pos3(:,MN_out);

%% CONCATENATING ALL MATRICES/MEASUREMENTS
pos1_M_in = [pos1_M_in0602, pos1_M_in2702, pos1_M_in1804];
pos2_M_in = [pos2_M_in0602, pos2_M_in2702, pos2_M_in1804];
pos3_M_in = [pos3_M_in0602, pos3_M_in2702, pos3_M_in1804];
pos1_M_out = [pos1_M_out0602, pos1_M_out2702, pos1_M_out1804];
pos2_M_out = [pos2_M_out0602, pos2_M_out2702, pos2_M_out1804];
pos3_M_out = [pos3_M_out0602, pos3_M_out2702, pos3_M_out1804];

pos1_T_in = [pos1_T_in0602, pos1_T_in2702, pos1_T_in1804];
pos2_T_in = [pos2_T_in0602, pos2_T_in2702, pos2_T_in1804];
pos3_T_in = [pos3_T_in0602, pos3_T_in2702, pos3_T_in1804];
pos1_T_out = [pos1_T_out0602, pos1_T_out2702, pos1_T_out1804];
pos2_T_out = [pos2_T_out0602, pos2_T_out2702, pos2_T_out1804];
pos3_T_out = [pos3_T_out0602, pos3_T_out2702, pos3_T_out1804];

% Average of all frequency spectra at each microphone position
pos1_TavgIn = 10*log10(mean(10.^(pos1_T_in/10),2));
pos2_TavgIn = 10*log10(mean(10.^(pos2_T_in/10),2));
pos3_TavgIn = 10*log10(mean(10.^(pos3_T_in/10),2));

pos1_MavgIn = 10*log10(mean(10.^(pos1_M_in/10),2));
pos2_MavgIn = 10*log10(mean(10.^(pos2_M_in/10),2));
pos3_MavgIn = 10*log10(mean(10.^(pos3_M_in/10),2));

pos1_TavgOut = 10*log10(mean(10.^(pos1_T_out/10),2));
pos2_TavgOut = 10*log10(mean(10.^(pos2_T_out/10),2));
pos3_TavgOut = 10*log10(mean(10.^(pos3_T_out/10),2));

pos1_MavgOut = 10*log10(mean(10.^(pos1_M_out/10),2));
pos2_MavgOut = 10*log10(mean(10.^(pos2_M_out/10),2));
```

```
pos3_MavgOut = 10*log10(mean(10.^(pos3_M_out/10),2));

f = data{1}(17:end,1); % frequency range from 20 Hz to 20 kHz

figure(1) % Figure 5.19
subplot(2,1,2)
bar(log10(f),pos1_TavgIn)
title('Inbound tram measurements - Forest'),xlabel('Frequency [Hz]'),...
    ylabel('L_{p,Fmax} [dB]')
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
hold on
bar(log10(f),pos2_TavgIn)
bar(log10(f),pos3_TavgIn)
legend('10 m','20 m','30 m','Location','SouthWest')
grid on
ylim([16.5 81])

figure(2) % Figure 5.20
subplot(2,1,2)
bar(log10(f),pos1_TavgOut)
title('Outbound tram measurements - Forest'),xlabel('Frequency [Hz]'),...
    ylabel('L_{p,Fmax} [dB]')
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
hold on
bar(log10(f),pos2_TavgOut)
bar(log10(f),pos3_TavgOut)
legend('6 m','16 m','26 m','Location','SouthWest')
grid on
ylim([16.5 81])

figure(3) % Figure 5.21
subplot(2,1,2)
bar(log10(f),pos1_MavgIn)
title('Inbound metro measurements - Forest'),xlabel('Frequency [Hz]'),...
    ylabel('L_{p,Fmax} [dB]')
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
hold on
```

```
bar(log10(f),pos2_MavgIn)
bar(log10(f),pos3_MavgIn)
legend('10 m','20 m','30 m','Location','SouthWest')
grid on
ylim([16.5 81])

figure(4) % Figure 5.22
subplot(2,1,2)
bar(log10(f),pos1_MavgOut)
title('Outbound metro measurements - Forest'),xlabel('Frequency [Hz]'),...
    ylabel('L_{p,Fmax} [dB]')
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
hold on
bar(log10(f),pos2_MavgOut)
bar(log10(f),pos3_MavgOut)
legend('6 m','16 m','26 m','Location','SouthWest')
grid on
ylim([16.5 81])

%% Max damping as a function of frequency - trams
freq_range = 18:31; % 20Hz-20kHz (1:31);    1-20kHz (18:31)

Tin_att = pos1_T_in(freq_range,:) - pos3_T_in(freq_range,:);
Tin_att_lin = mean(10.^( (Tin_att)./10), 2);
Tin_att_dB = 10*log10(Tin_att_lin);
Tin_att_avg = 10*log10(mean(Tin_att_lin));
Tin_std = (mean(std(Tin_att,0,2)));

Tout_att1 = pos1_T_out(freq_range,:) - pos2_T_out(freq_range,:);
Tout_att2 = pos1_T_out(freq_range,:) - pos3_T_out(freq_range,:);
Tout_att_lin1 = mean(10.^( (Tout_att1)./10), 2);
Tout_att_lin2 = mean(10.^( (Tout_att2)./10), 2);
Tout_att_dB = 10*log10(Tout_att_lin2);
Tout_att_avg1 = 10*log10(mean(Tout_att_lin1));
Tout_att_avg2 = 10*log10(mean(Tout_att_lin2));
Tout_std1 = (mean(std(Tout_att2,0,2)));
Tout_std2 = (mean(std(Tout_att2,0,2)));
Tveg = [0 Tout_att_avg1 Tout_att_avg2];
```

```
hold on
figure(5)
subplot(2,1,1)
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
semilogx(f(freq_range),Tin_att_dB,'r')
hold on
title('Level difference for all inbound tram measurements'),...
    xlabel('Frequency [Hz]'),ylabel('Attenuation [dB]')
xlim([20 20e3])
xticks(f(1:3:end))
legend('Open field','Forest','Location','Best')
grid on


subplot(2,1,2)
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
semilogx(f(freq_range),Tout_att_dB,'r')
title('Level difference for all outbound tram measurements'),...
    xlabel('Frequency [Hz]'),ylabel('Attenuation [dB]')
xlim([20 20e3])
xticks(f(1:3:end))
legend('Open Field','Forest','Location','Best')
grid on

%% Max damping as a function of frequency - metros
Min_att = pos1_M_in(freq_range,:) - pos3_M_in(freq_range,:);
Min_att_lin = mean(10.^( (Min_att)./10), 2);
Min_att_dB = 10*log10(Min_att_lin);
Min_att_avg = 10*log10(mean(Min_att_lin));
Min_std = (mean(std(Min_att,0,2)));

Mout_att1 = pos1_M_out(freq_range,:) - pos2_M_out(freq_range,:);
Mout_att2 = pos1_M_out(freq_range,:) - pos3_M_out(freq_range,:);
Mout_att_lin1 = mean(10.^( (Mout_att1)./10), 2);
Mout_att_lin2 = mean(10.^( (Mout_att2)./10), 2);
Mout_att_dB = 10*log10(Mout_att_lin2);
Mout_att_avg1 = 10*log10(mean(Mout_att_lin1));
Mout_att_avg2 = 10*log10(mean(Mout_att_lin2));
```

```
Mout_std1 = (mean(std(Mout_att1,0,2)));
Mout_std2 = (mean(std(Mout_att2,0,2)));
Mveg = [0 Mout_att_avg1 Mout_att_avg2];

hold on
figure(6)
subplot(2,1,1)
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
semilogx(f(freq_range),Min_att_dB,'r')
title('Level difference for all inbound metro measurements'),...
    xlabel('Frequency [Hz]'),ylabel('Attenuation [dB]')
xlim([20 20e3])
xticks(f(1:3:end))
legend('Open field','Forest','Location','Best')
grid on

subplot(2,1,2)
set(gca,'Xtick',log10(f(1:3:end)));
set(gca,'Xticklabel',10.^get(gca,'Xtick'));
semilogx(f(freq_range),Mout_att_dB,'r')
title('Level difference for all outbound metro measurements'),...
    xlabel('Frequency [Hz]'),ylabel('Attenuation [dB]')
xlim([20 20e3])
xticks(f(1:3:end))
legend('Open Field','Forest','Location','Best')
grid on

% Level attenuation for outbound traffic, 1-20 kHz
dist = 0:50;
x = [0 10 20];
T_int = interp1(x,Tveg,dist,'linear');
M_int = interp1(x,Mveg,dist,'linear');

figure(8)
hold on
plot(dist,M_int)
title('Noise attenuation of metros (1-20 kHz)')
xlabel('Distance from the nearest microphone position [m]'),
ylabel('Attenuation [dB]')
```

```
grid on
legend('Open field','Forest','Location','Best')

figure(9)
hold on
plot(dist,T_int)
title('Noise attenuation of trams (1-20 kHz)')
xlabel('Distance from the nearest microphone position [m]'),
ylabel('Attenuation [dB]')
grid on
legend('Open field','Forest','Location','Best')

%% Statistical analysis
% Student's t-distribution based on a 90 % confidence interval
Tin_unc_upper2 = 10*log10((10^(Tin_att_avg/10) + ...
    1.729*Tin_std/sqrt(size(Tin_att,2))) / 10^(Tin_att_avg/10) );
Tin_unc_lower = 10*log10((10^(Tin_att_avg/10) - ...
    1.729*Tin_std/sqrt(size(Tin_att,2))) / 10^(Tin_att_avg/10) );

Tout_unc_upper1 = 10*log10((10^(Tout_att_avg1/10) + ...
    1.725*Tout_std1/sqrt(size(Tout_att1,2))) / 10^(Tout_att_avg1/10) );
Tout_unc_lower1 = 10*log10((10^(Tout_att_avg1/10) - ...
    1.725*Tout_std1/sqrt(size(Tout_att1,2))) / 10^(Tout_att_avg1/10) );
Tout_unc_upper2 = 10*log10((10^(Tout_att_avg2/10) + ...
    1.721*Tout_std2/sqrt(size(Tout_att2,2))) / 10^(Tout_att_avg2/10) );
Tout_unc_lower2 = 10*log10((10^(Tout_att_avg2/10) - ...
    1.721*Tout_std2/sqrt(size(Tout_att2,2))) / 10^(Tout_att_avg2/10) );

Min_unc_upper = 10*log10((10^(Min_att_avg/10) + ...
    1.701*Min_std/sqrt(size(Min_att,2))) / 10^(Min_att_avg/10) );
Min_unc_lower = 10*log10((10^(Min_att_avg/10) - ...
    1.701*Min_std/sqrt(size(Min_att,2))) / 10^(Min_att_avg/10) );

Mout_unc_upper1 = 10*log10((10^(Mout_att_avg1/10) + ...
    1.708*Mout_std1/sqrt(size(Mout_att1,2))) / 10^(Mout_att_avg1/10) );
Mout_unc_lower1 = 10*log10((10^(Mout_att_avg1/10) - ...
    1.708*Mout_std1/sqrt(size(Mout_att1,2))) / 10^(Mout_att_avg1/10) );
Mout_unc_upper2 = 10*log10((10^(Mout_att_avg2/10) + ...
    1.699*Mout_std2/sqrt(size(Mout_att2,2))) / 10^(Mout_att_avg2/10) );
Mout_unc_lower2 = 10*log10((10^(Mout_att_avg2/10) - ...
```

```
    1.699*Mout_std2/sqrt(size(Mout_att2,2))) / 10^(Mout_att_avg2/10) );

%% SPL as a function of distance
% Sum up all band frequencies to single value
Lp1_T_in = 10*log10(sum(10.^(pos1_T_in(1:end,:)./10)));
Lp2_T_in = 10*log10(sum(10.^(pos2_T_in(1:end,:)./10)));
Lp3_T_in = 10*log10(sum(10.^(pos3_T_in(1:end,:)./10)));

Lp1_T_out = 10*log10(sum(10.^(pos1_T_out(1:end,:)./10)));
Lp2_T_out = 10*log10(sum(10.^(pos2_T_out(1:end,:)./10)));
Lp3_T_out = 10*log10(sum(10.^(pos3_T_out(1:end,:)./10)));

Lp1_M_in = 10*log10(sum(10.^(pos1_M_in(1:end,:)./10)));
Lp2_M_in = 10*log10(sum(10.^(pos2_M_in(1:end,:)./10)));
Lp3_M_in = 10*log10(sum(10.^(pos3_M_in(1:end,:)./10)));

Lp1_M_out = 10*log10(sum(10.^(pos1_M_out(1:end,:)./10)));
Lp2_M_out = 10*log10(sum(10.^(pos2_M_out(1:end,:)./10)));
Lp3_M_out = 10*log10(sum(10.^(pos3_M_out(1:end,:)./10)));

%% STATISTICAL ANALYSIS
groupTin = [repmat({'10'}, length(Lp1_T_in), 1); repmat({'20'}, ...
    length(Lp2_T_in), 1); repmat({'30'}, length(Lp3_T_in), 1)];

groupTout = [repmat({'6'}, length(Lp1_T_out), 1);  repmat({'16'}, ...
    length(Lp2_T_out), 1); repmat({'26'}, length(Lp3_T_out), 1)];

figure(14)
boxplot([Lp1_T_in'; Lp2_T_in'; Lp3_T_in'], groupTin)
title('Box plot of inbound tram measurements - Forest'),xlabel('Distance [m]')
    ,...
    ylabel('L_{p,Fmax} [dB]')
grid on

figure(15)
boxplot([Lp1_T_out'; Lp2_T_out';  Lp3_T_out'], groupTout)
title('Box plot of outbound tram measurements - Forest'),xlabel('Distance [m]')
    ,...
    ylabel('L_{p,Fmax} [dB]')
grid on
```

```
%%
groupMin = [repmat({'10'}, length(Lp1_M_in), 1); repmat({'20'},...
    length(Lp2_M_in), 1); repmat({'30'}, length(Lp3_M_in), 1)];

groupMout = [repmat({'6'}, length(Lp1_M_out), 1);  repmat({'16'}, ...
    length(Lp2_M_out), 1); repmat({'26'}, length(Lp3_M_out), 1)];

figure(16)
boxplot([Lp1_M_in'; Lp2_M_in'; Lp3_M_in'], groupMin)
title('Box plot of inbound metro measurements - Forest'),xlabel('Distance [m]')
    ,...
    ylabel('L_{p,Fmax} [dB]')
grid on

figure(17)
boxplot([Lp1_M_out'; Lp2_M_out'; Lp3_M_out';], groupMout)
title('Box plot of outbound metro measurements - Forest'),xlabel('Distance [m]')
    ,...
    ylabel('L_{p,Fmax} [dB]')
grid on

% average SPL at each microphone position
avg1_T_in = 10*log10(mean(10.^(Lp1_T_in/10),2));
avg2_T_in = 10*log10(mean(10.^(Lp2_T_in/10),2));
avg3_T_in = 10*log10(mean(10.^(Lp3_T_in/10),2));

avg1_T_out = 10*log10(mean(10.^(Lp1_T_out/10),2));
avg2_T_out = 10*log10(mean(10.^(Lp2_T_out/10),2));
avg3_T_out = 10*log10(mean(10.^(Lp3_T_out/10),2));

avg1_M_in = 10*log10(mean(10.^(Lp1_M_in/10),2));
avg2_M_in = 10*log10(mean(10.^(Lp2_M_in/10),2));
avg3_M_in = 10*log10(mean(10.^(Lp3_M_in/10),2));

avg1_M_out = 10*log10(mean(10.^(Lp1_M_out/10),2));
avg2_M_out = 10*log10(mean(10.^(Lp2_M_out/10),2));
avg3_M_out = 10*log10(mean(10.^(Lp3_M_out/10),2));

T_max_in = [avg1_T_in avg2_T_in avg3_T_in];
```

```
T_max_out = [avg1_T_out avg2_T_out avg3_T_out];
T_max = [T_max_out(1) T_max_in(1) T_max_out(2) T_max_in(2) T_max_out(3)...
    T_max_in(3)];
M_max_in = [avg1_M_in avg2_M_in avg3_M_in];
M_max_out = [avg1_M_out avg2_M_out avg3_M_out];
M_max = [M_max_out(1) M_max_in(1) M_max_out(2) M_max_in(2) M_max_out(3)...
    M_max_in(3)];

% Measurement distances in meters
xin = [10 20 30];
xout = [6 16 26];
x = [6 10 16 20 26 30];
r = 1:0.5:30;

% Linear interpolation of trams
T_max_in_veg = interp1(xin,T_max_in,r,'linear');
T_max_out_veg = interp1(xout,T_max_out,r,'linear');
T_veg = interp1(x,T_max,r,'linear');

% Linear interpolation of metros
M_max_in_veg = interp1(xin,M_max_in,r,'linear');
M_max_out_veg = interp1(xout,M_max_out,r,'linear');
M_veg = interp1(x,M_max,r,'linear');

% Regression calculation
FTreg = @(y,ydata)y(1)*exp(-y(2)*ydata) + y(3)*exp(-y(4)*ydata);
y0 = [1 1 1 0];
[yT,resnorm,~,exitflag,output] = lsqcurvefit(FTreg,y0,x,T_max);

FMreg = @(y,ydata)y(1)*exp(-y(2)*ydata) + y(3)*exp(-y(4)*ydata);
[yM,resnorm,~,exitflag,output] = lsqcurvefit(FTreg,y0,x,M_max);

figure(18)
title('Maximum unweighted SPL of all tram measurements')
hold on
plot(r,T_veg,'r')
plot(x,FTreg(yT,x),'r--')
grid on
xlim([xout(1) xin(3)])
xlabel('Distance [m]')
```

```
ylabel('L_{p,Fmax} [dB]')
legend('Open field','Regression model','Forest','Regression model')

figure(19)
title('Maximum unweighted SPL of all metro measurements')
hold on
plot(r,M_veg,'r')
plot(x,FMreg(yM,x),'r--')
grid on
xlim([xout(1) xin(3)])
xlabel('Distance [m]')
ylabel('L_{p,Fmax} [dB]')
legend('Open field','Regression model','Forest','Regression model')
```

B.4 Impedance Calculations

```
%% Ground impedance calculations
[pu,fs] = audioread('forest1B_u.wav'); % upper microphone
[pl,fs] = audioread('forest1B_l.wav'); % lower microphone
Nyquist = fs/2;
pu = pu(1e5:2e5);
pl = pl(1e5:2e5);
L = length(pu);

ht_FT = fft(pu)/L;
hb_FT = fft(pl)/L;
f = linspace(0, 1, fix(L/2)+1)*Nyquist;
Iv = 1:length(f);
step = 129;
range = 568:step:9071;

Transf = ht_FT./hb_FT;

T = [f(range); real(Transf(round(Iv(range))))'*2; ...
     imag(Transf(round(Iv(range))))'*2];

fileID = fopen('T_1804.txt','w');
fprintf(fileID,'%4.0f\t %f\t %f\n',T);
fclose(fileID);

```

```
%%
impLD2009 % function/script developed by National Research Council of
% Canada. Input: Transfer function T, geometry A or B and temperature of
% air in Celcius. Outout: text file containing specific aacoustic impedance
% with three columns consisting of frequency, real and imaginary part.

%% CALCULATION OF ABSORPTION COEFFICIENT
T = 0; % temperature of measurement field
RH = 75; % relative humidity
c = 20.06*sqrt(273.15+T); % speed of sound (m/s) as a function of temp
Z0 = 428/(sqrt((T+273.15)/273.15)*(1+1.95e-5*RH) ); % specific acoustic impedance
Zs = importdata('Z_1704.txt'); % normalized specific acoustic impedance of
% medium
L = length(Zs); % to find same length as for air
Zs_air = Z0*ones(L,1); % ambient specific acoustic impedance of air
f = Zs(:,1); % frequency vector
Zs = (Zs(:,2) + 1i*Zs(:,3)).*416.45; % real and imaginary part of specific
% acoustic impedance of medium
R = (Zs - Zs_air)./(Zs + Zs_air); % reflection coefficient, norm incidence
alpha = 1 - (abs(R)).^2; % absorption coefficient, normal incidence

hold on
figure(20)
semilogx(f,(alpha))
grid on
xlim([250 4000])
ylim([0 1])
title('Absorption coefficient of ground in forest')
xlabel('Frequency [Hz]')
ylabel('\alpha_{gr}')
legend('06.02','27.02','18.04','Location','Best')
xticks([250 630 1250 2000 2500 3150 4000])

hold on
figure(21)
semilogx(f,(alpha))
grid on
xlim([250 4000])
ylim([0 1])
title('Absorption coefficient of ground in open field')
```

```
xlabel('Frequency [Hz]')
ylabel('\alpha_{gr}')
legend('13.02','28.02','17.04','Location','Best')
xticks([250 630 1250 2000 2500 3150 4000])
```

Appendix C

ArtemiS SUITE

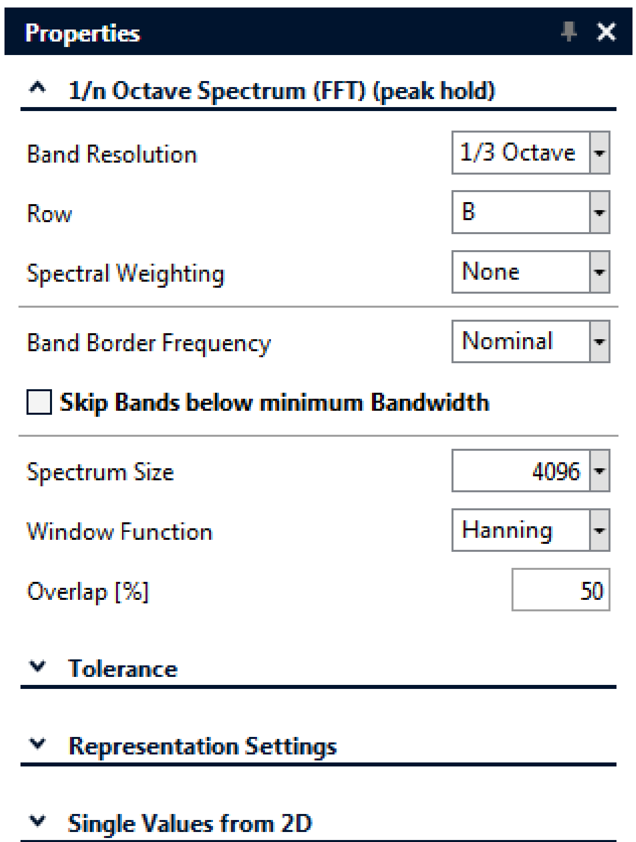


Figure C.1: Properties used for the calculation of the maximum SPL. The same properties are used for the calculation of the transfer function.

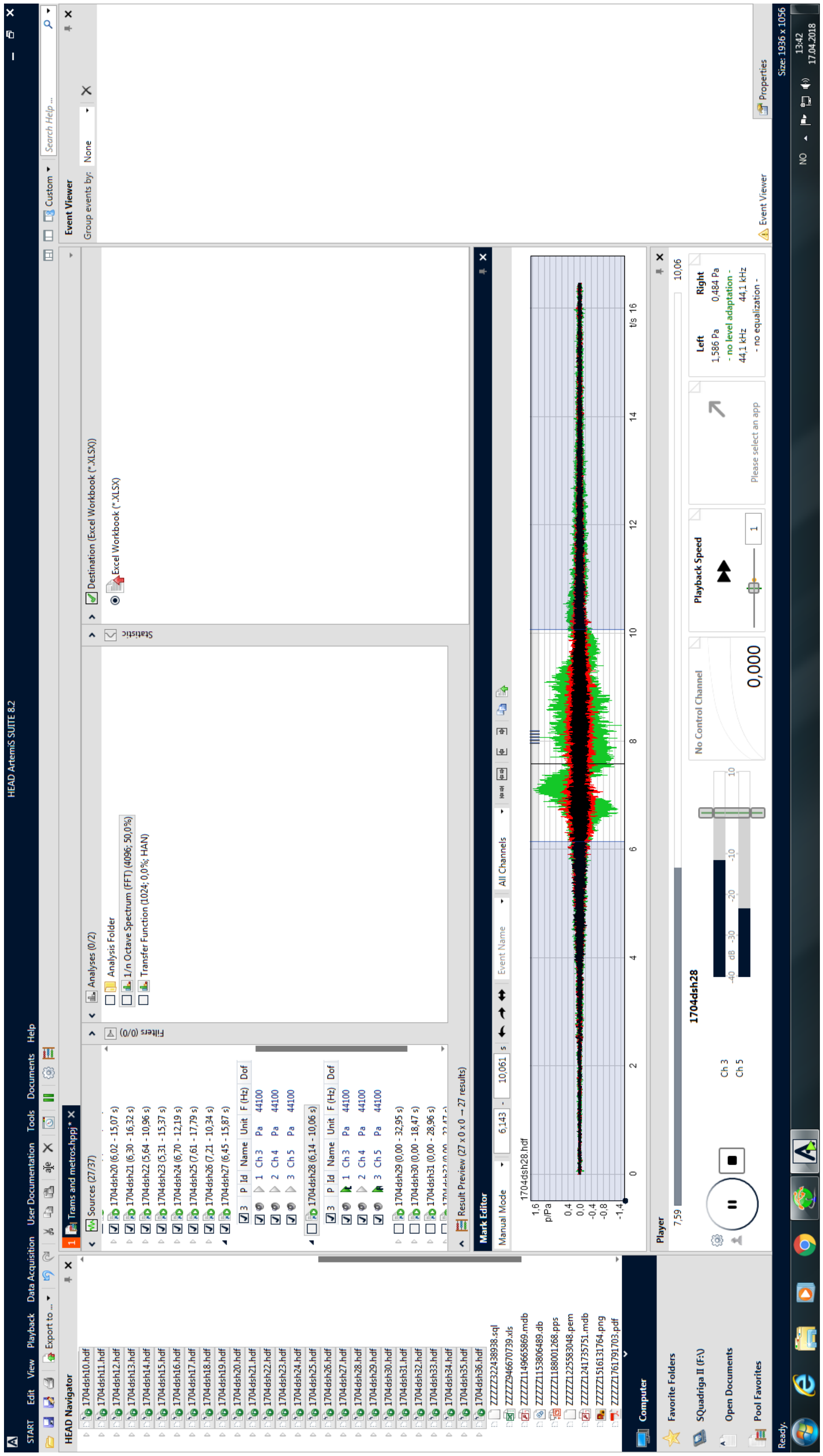
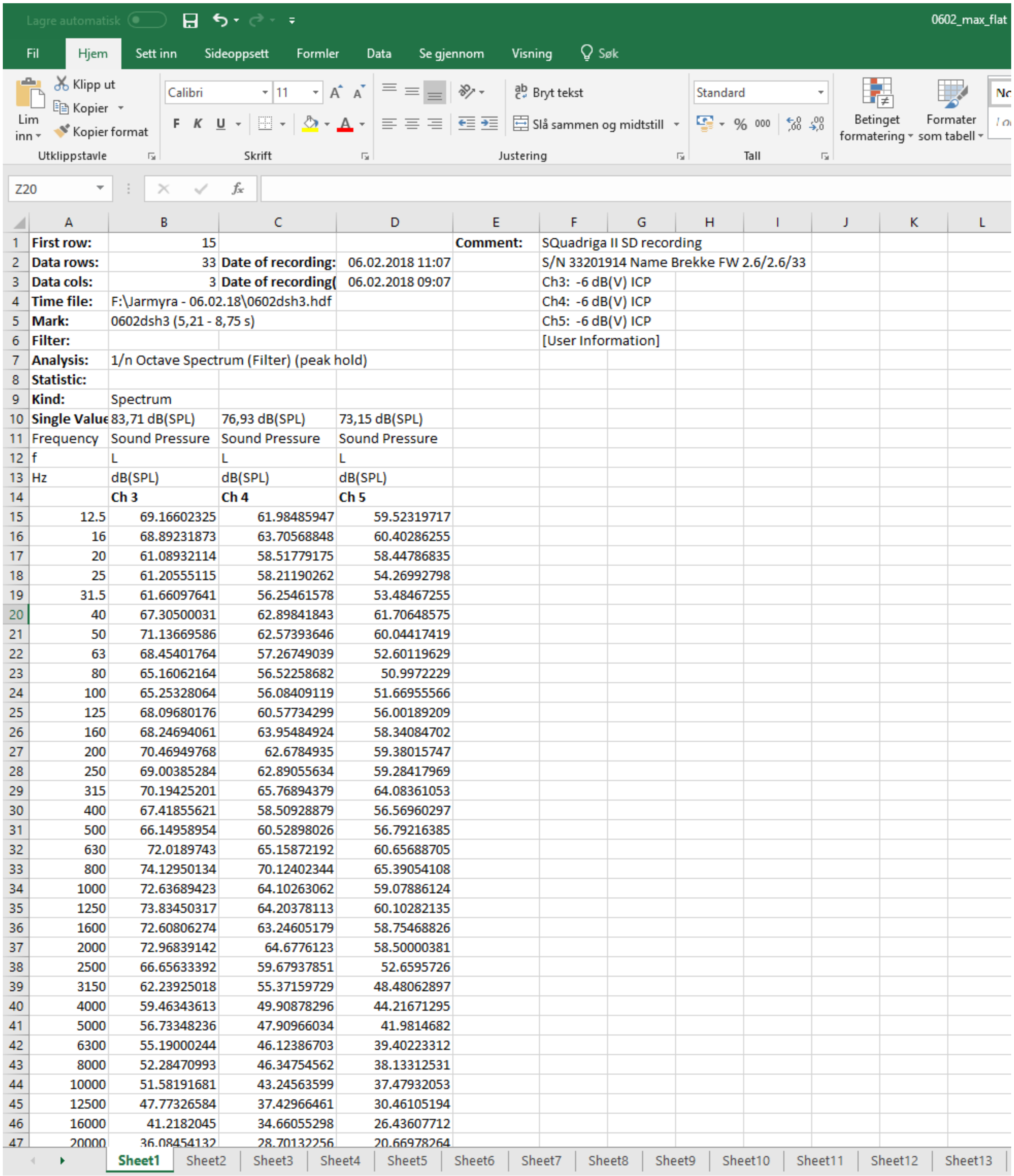


Figure C.2: Screenshot of ArtemiS suite interface including a cropped time signal. The measurement files are to the left and the analysis function in the middle. Here the recorded signal can be played, and in this example the recordings from microphone position 1 and 3 (channel 3 and 5) are selected as left and right output channel.



	A	B	C	D	E	F
1	**First row:**	15			**Comment:**	SQuadriga II SD recording
2	**Data rows:**	33	**Date of recording:**	06.02.2018 11:07		S/N 33201914 Name Brekke FW 2.6/2.6/33
3	**Data cols:**	3	**Date of recording(**	06.02.2018 09:07		Ch3: -6 dB(V) ICP
4	**Time file:**	F:\Jarmyra - 06.02.18\0602dsh3.hdf				Ch4: -6 dB(V) ICP
5	**Mark:**	0602dsh3 (5,21 - 8,75 s)				Ch5: -6 dB(V) ICP
6	**Filter:**					[User Information]
7	**Analysis:**	1/n Octave Spectrum (Filter) (peak hold)				
8	**Statistic:**					
9	**Kind:**	Spectrum				
10	**Single Value**	83,71 dB(SPL)	76,93 dB(SPL)	73,15 dB(SPL)		
11	Frequency	Sound Pressure	Sound Pressure	Sound Pressure		
12	f	L	L	L		
13	Hz	dB(SPL)	dB(SPL)	dB(SPL)		
14		**Ch 3**	**Ch 4**	**Ch 5**		
15	12.5	69.16602325	61.98485947	59.52319717		
16	16	68.89231873	63.70568848	60.40286255		
17	20	61.08932114	58.51779175	58.44786835		
18	25	61.20555115	58.21190262	54.26992798		
19	31.5	61.66097641	56.25461578	53.48467255		
20	40	67.30500031	62.89841843	61.70648575		
21	50	71.13669586	62.57393646	60.04417419		
22	63	68.45401764	57.26749039	52.60119629		
23	80	65.16062164	56.52258682	50.9972229		
24	100	65.25328064	56.08409119	51.66955566		
25	125	68.09680176	60.57734299	56.00189209		
26	160	68.24694061	63.95484924	58.34084702		
27	200	70.46949768	62.6784935	59.38015747		
28	250	69.00385284	62.89055634	59.28417969		
29	315	70.19425201	65.76894379	64.08361053		
30	400	67.41855621	58.50928879	56.56960297		
31	500	66.14958954	60.52898026	56.79216385		
32	630	72.0189743	65.15872192	60.65688705		
33	800	74.12950134	70.12402344	65.39054108		
34	1000	72.63689423	64.10263062	59.07886124		
35	1250	73.83450317	64.20378113	60.10282135		
36	1600	72.60806274	63.24605179	58.75468826		
37	2000	72.96839142	64.6776123	58.50000381		
38	2500	66.65633392	59.67937851	52.6595726		
39	3150	62.23925018	55.37159729	48.48062897		
40	4000	59.46343613	49.90878296	44.21671295		
41	5000	56.73348236	47.90966034	41.9814682		
42	6300	55.19000244	46.12386703	39.40223312		
43	8000	52.28470993	46.34754562	38.13312531		
44	10000	51.58191681	43.24563599	37.47932053		
45	12500	47.77326584	37.42966461	30.46105194		
46	16000	41.2182045	34.66055298	26.43607712		
47	20000	36.08454132	28.70132256	20.66978264		

Figure C.3: Screenshot of excel output from ArtemiS suite. This is an example of how the measurements are represented as a function of frequency, and each tram or metro pass-by is given in individual sheets. This example is measured 06.02.18.

Appendix D

Time- and Frequency-Weighting

The time-weighting F (fast) has an exponential time constant of 0.125 s. This means that the measured sound pressure level with time-weighting F will be showing the time-varying noise quickly, opposite to the time-weighting S (slow) that has a time constant of 1 s. [24]

For environmental noise, the A-weighted sound level L_A is probably the most used measure. It is commonly expressed in dBA, and the reference pressure is 20 μPa which often is left implicit (also in this report). This A-weighting is related to the sensitivity of the ear at a given frequency, and it originates from the mirror of the 40 phon equal-loudness-level contour (will not be described here).

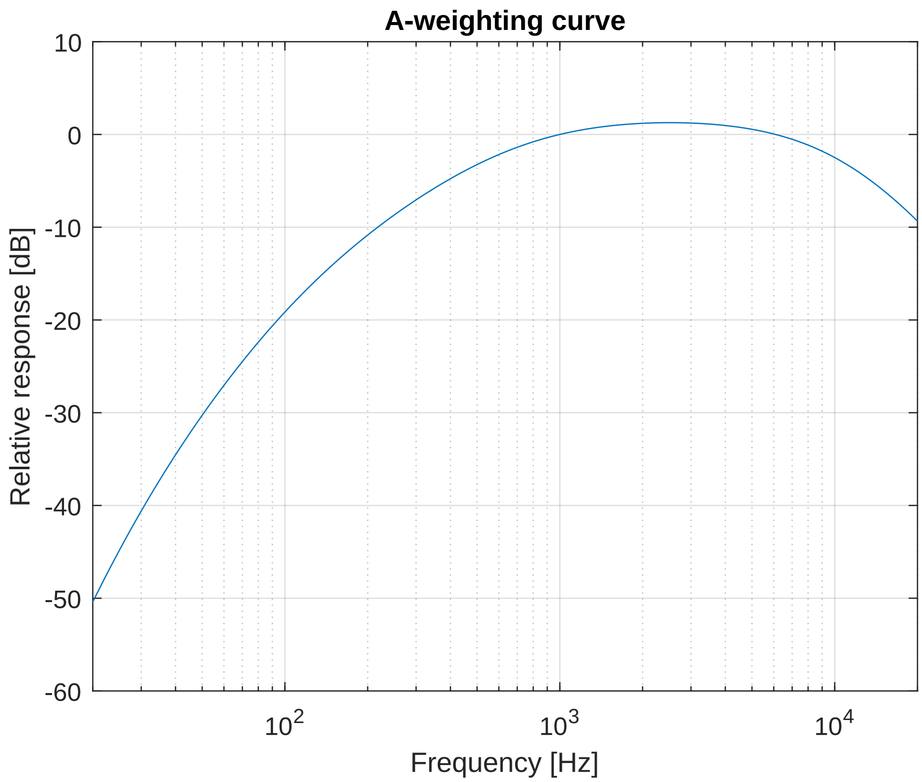


Figure D.1: A-weighting curve corrections as a function of frequency with a range from 20 Hz to 20 kHz [24].

The filter characteristics of the A-weighted sound levels are shown in Figure D.1. This figure shows that low frequencies have a big negative correction and the frequencies between 1 and 5 kHz have a positive correction. [29]

Appendix E

Box Plot

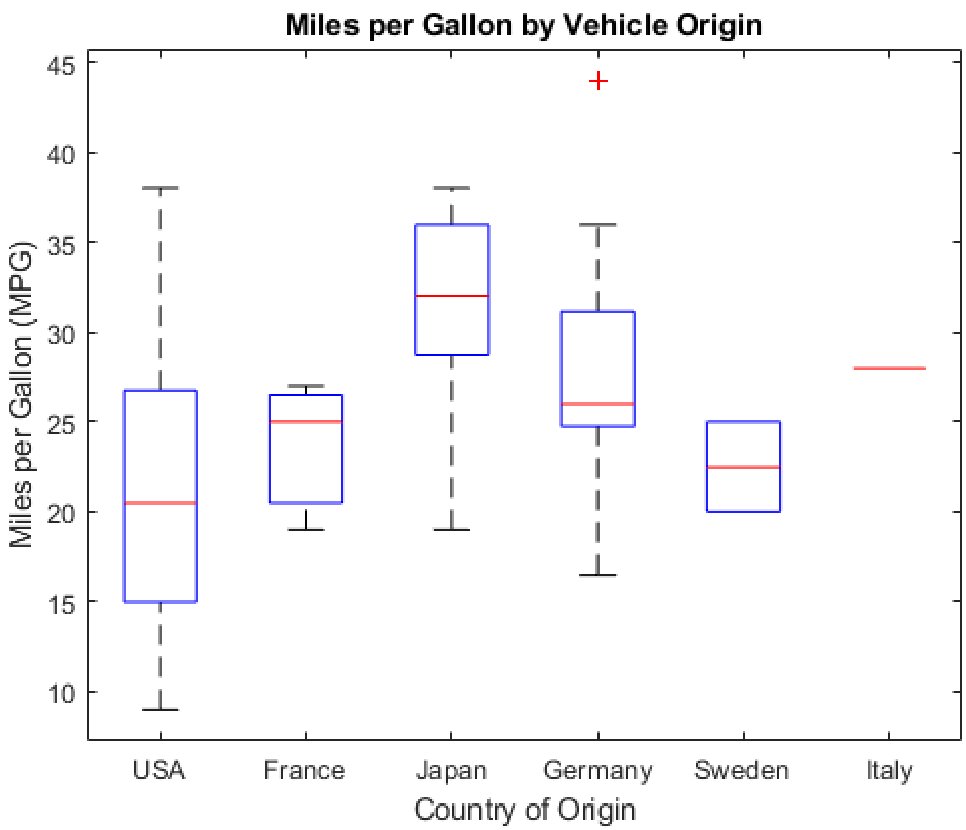


Figure E.1: An example of a box plot [31].

A box plot gives a graphic summary of the statistics for a sample data (see Figure E.1). This is a useful tool when analyzing measurement data where an uncertainty is present.

The upper and lower part of the "box" gives the 25th and 75th percentiles of the samples respectively. The interquartile ranges are the distances between the upper and lower part of the boxes. The line inside the box is the median of the sample, and if the line is not centered inside the box, there is a sample bias.

The lines which are extending above and below each box are the whiskers, and observations outside the whisker length are said to be outliers. If a value is more than 1.5 times the interquartile range away from the top or bottom of the box, the data point is a outlier. Outliers are shown as red “+” signs. [31]

Nomenclatures

Abbreviations

SPL Sound pressure level

List of Symbols

α_{gr} Absorption coefficient of ground

α_{wood} Absorption coefficient of woods

β Surface admittance

λ Wavelength

ρ Mass density

a Largest dimension of an object

c Speed of sound

d Sound propagation distance

f Frequency of sound

H Transfer function

h_b Height of bottom microphone

h_s Height of source

h_t Height of top microphone

k Wave number

L_p Sound pressure level

$L_{p,AFmax}$ A-weighted maximum sound pressure level with time weighting F (fast)

$L_{p,Fmax}$ Maximum sound pressure level with time weighting F (fast)

P Sound power

p Complex sound pressure

p_l Complex sound pressure of lower microphone position

p_u Complex sound pressure of upper microphone position

Q Reflection coefficient

R Sound receiver

R_d Direct sound travel distance

R_r Reflected sound travel distance

RH Relative humidity

S Sound source

S' Image sound source

T Absolute temperature

u Complex particle velocity

Z_s Specific acoustic impedance

Z_{norm} Normalized specific acoustic impedance

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