TEKNILLINEN KORKEAKOULU
Department of Electrical and Communications Engineering
Laboratory of Acoustics and Audio Signal Processing

Timo Markula

Propagation, measurement and assessment of shooting noise

Master's thesis submitted in partial fulfilment of the requirements for
the degree of Master of Science in Technology

Espoo, May 8, 2006

Supervisor: Professor Matti Karjalainen
Instructor: Dr.Sc. (Tech.) Tapio Lahti

TEKNILLINEN KORKEAKOULU	ABSTRACT OF THE MASTER'S THESIS

Author:	Timo Markula
Name of the thesis:	Propagation, measurement and assessment of shooting noise
Date:	May 8, 2006 **Number of pages:** 73
Department:	Electrical and Communications Engineering
Professorship:	S-89 Acoustics and Audio Signal Processing
Supervisor:	Prof. Matti Karjalainen
Instructor:	Dr.Sc. (Tech.) Tapio Lahti

Environmental noise from shooting ranges and areas was considered. Both small arms and heavy weapons noise was studied. Shooting noise is very impulsive and strong and it differs considerably in many respects from other environmental noises. Special methods are needed in order to measure, model and assess shooting noise in the environment accurately.

Temporal loudness integration and the equal-loudness contours support the use of the F- and A- weightings for the assessment of annoyance at long distance. From technical measurement and modelling point of view, energy-based level quantities are preferred over maximum level quantities.

In this work, simulations and measurements were made using two competing emission measurement methods. It was found that small-calibre weapon emission should preferably be measured by placing the microphone on flat hard ground according to Nordtest method. Raising the microphone above the ground produces unwanted interference. With heavy weapons, nevertheless, the microphone needs to be raised and the ground reflection compensated afterwards.

The measurement data analyses in this thesis showed that the scattering in the environment makes the impulses spread in time with increasing distance. This affects the maximum level quantities considerably. Conventional propagation models predict fairly accurately energy-based levels in downwind conditions. With the ISO and Nordic calculation models the propagation of shooting noise is calculated similarly except for the barrier effect.

Based on theory and measurements, the noise resulting from supersonic bullets can be stronger than the muzzle blast, at least with small-calibre weapons.

Keywords: shooting noise, emission measurement, propagation, assessment of annoyance

TEKNILLINEN KORKEAKOULU DIPLOMITYÖN TIIVISTELMÄ

Tekijä: **Työn nimi:** **Päivämäärä:**	Timo Markula Propagation, measurement and assessment of shooting noise 8.5.2006 **Sivuja:** 73
Osasto: **Professuuri:**	Sähkö- ja tietoliikennetekniikka S-89 Akustiikka ja äänenkäsittelytekniikka
Työn valvoja: **Työn ohjaaja:**	Prof. Matti Karjalainen TkT Tapio Lahti

Ampumamelua tässä työssä käsiteltiin lähinnä ampumaratojen ja alueiden ympäristön kannalta, mahdollisena ympäristöhaittana. Työssä tarkasteltiin sekä kevyiden että raskaiden aseiden melua. Ampumamelu on hyvin impulsiivista ja voimakasta ja se eroaa monin tavoin merkittävästi muista ympäristömelulajeista. Erityisiä menetelmiä tarvitaan tarkkaan tehtävässä ampumamelun mittauksessa, leviämisen mallinnuksessa ja häiritsevyyden arvioinnissa.

Ihmisen kuulon äänekkyyden aikaintegrointi ja vakioäänekkyyskäyrästöt tukevat F- ja A-painotusten käyttöä. Mittaus- ja mallinnusteknisestä näkökulmasta energiapohjaisten äänitasojen käyttö on suositeltavampaa kuin enimmäisäänitasojen käyttö.

Tässä työssä tehdyt kahden kilpailevan emissiomittausmenetelmän simuloinnit ja mittaukset osoittivat, että kevyiden aseiden melupäästöt pitäisi mitata kovalla maalla mikrofoni lähellä maanpintaa Nordtestin menetelmän mukaisesti. Mikrofonin korkeuden nostaminen aiheuttaa ei-toivotun interferenssin. Raskailla aseilla mikrofoni kuitenkin pitää käytännössä nostaa ylös, jolloin maaheijastuksen vaikutus pitää laskea jälkikäteen pois tuloksesta.

Tämän työn mittaustulosten analyysit osoittavat, että ympäristön aiheuttama sironta levittää impulssia ajassa etäisyyden kasvaessa, mikä vaikuttaa enimmäisäänitasoihin merkittävästi. Tavalliset laskentamallit ennustavat leviämistä melko tarkasti myötä-tuuliolosuhteissa energiatasoja laskettaessa. Pohjoismaisessa ja ISO:n laskenta-malleissa ampumamelun etenemisen laskenta on samanlainen estevaimennusta lukuun ottamatta.

Teorian ja mittausten perusteella luodin aiheuttama yliäänipamaus voi olla jopa voimakkaampi kuin suupamaus ainakin kevyillä aseilla.

Avainsanat: ampumamelu, emissiomittaus, eteneminen, häiritsevyyden arviointi

ACKNOWLEDGEMENTS

This Master's thesis was done in Akukon Engineering Consultants Inc. from the order of the Finnish Defence Forces and it was funded by the two organisations.

The problems studied in this thesis arose in 2005 while making measurements and noise assessment of shooting ranges and areas of the Finnish Defence Forces. The small-calibre weapon emission measurements were done by the Finnish Defence Forces and the other measurement and modelling by Akukon. Although military weapon data is used throughout the thesis, the results can be proven useful in assessing recreational shooting noise as well.

I want to express my gratitude to Dr.Sc. (Tech.) Tapio Lahti in Akukon for providing the opportunity and for the whole guidance in the making of the thesis. Without his enthusiastic mentoring the work would not have been possible.

I wish to thank Mrs. Raakel Jaloniemi and Mr. Asko Parri in the Finnish Defence Forces and Dr.Sc. (Tech.) Rauno Pääkkönen in the Institute of the Occupational Health for providing the funding that made this work possible. I wish to also thank them for the valuable knowledge, especially about the practical side of the subject, which helped greatly in understanding the full context.

I would like to thank Professor Matti Karjalainen for supervising the work and for the feedback during the writing process.

Thanks are also addressed to Mr. Timo Peltonen for helping in the analyses and Mrs. Jaana Jokitulppo for giving further insight into the assessment part.

I wish to thank also my parents and my whole family for the support throughout my studies.

Finally, I thank my beloved Annina for all the encouragement in the past years.

Espoo, May 8, 2006

TABLE OF CONTENTS

ABBREVIATIONS

B&K	Brüel & Kjær
DAT	Digital Audio Tape
F	Time weighting F (fast)
FDF	Finnish Defence Forces
I	Time weighting I (impulse)
IEC	International Engineering Consortium
IR	Impulse Response
ISO	International Organization for Standardization
JASA	Journal of the Acoustical Society of America
LCW	Large-calibre weapon
NATO	North Atlantic Treaty Organisation
NGPM	Nordic General Prediction Method
NT	Nordtest
S	Time weighting S (slow)
SCW	Small-calibre weapon
SLM	Sound Level Meter
SPL	Sound Pressure Level
STM	Sosiaali- ja terveysministeriö, Ministry of Social Affairs and Health
TNT	Trinitrotoluene
VNp	Valtioneuvoston päätös, decision of the Council of State
VTT	Valtion Teknillinen Tutkimuskeskus, Technical Research Centre of Finland
YM	Ympäristöministeriö, Ministry of the Environment

SYMBOLS

L_{Ade}	A-weighted day-evening equivalent level
L_{Aden}	A-weighted day-evening-night equivalent level
L_{AE}	A-weighted sound exposure level
L_{Aeq}	A-weighted equivalent continuous sound pressure level
L_{AFmax}	Maximum F- and A-weighted sound pressure level
L_{AImax}	Maximum I- and A-weighted sound pressure level
L_{ASmax}	Maximum S- and A-weighted sound pressure level
L_{Cden}	C-weighted day-evening-night equivalent level
L_{Cdn}	C-weighted day-night equivalent level
L_{CE}	C-weighted sound exposure level
L_{Cpeak}	C-weighted peak sound pressure level
L_E	Sound energy level
L_{E}	Sound exposure level
L_{eq}	Equivalent continuous sound pressure level
L_{Fmax}	Maximum F-weighted sound pressure level
L_{Imax}	Maximum I-weighted sound pressure level
L_p	Sound pressure level
L_{peak}	Peak sound pressure level
L_{W}	Sound power level

1 INTRODUCTION

The shooting areas of the Finnish Defence Forces (FDF) are currently being under investigation due to new regulations concerning environmental noise. Earlier, the noise around shooting ranges and areas was assessed using only immission measurements. Nowadays, the more widely used method is to model the noise propagation using computer software. Such extensive work for large areas has not been done before in Finland and several new issues have emerged alongside with the investigations. The problems concern the whole chain of the investigation; from the emission measurements to the final assessment. The third main link in between is the noise propagation. All of these issues are quite well understood in the context of traffic and industrial noise but not so well in the context of shooting noise.

In Finland, the regulation of the measurement and assessment of the environmental noise produced by shooting ranges and areas depend on the weapons calibre. There are two primary documents. One is an official regulation for the environmental noise from the shooting ranges of small-calibre weapons (SCW). Another is an internal recommendation of the FDF for the environmental noise of large-calibre weapons (LCW) and blasts. The assessment of noise from the shooting ranges is regulated in (Valtioneuvoston päätös [VNp] 53/1997) and the recommended guidelines for the large-calibre military weapon noise are given in (Jaloniemi et al. 2005). Both of these guidelines are based on the regulations and practices in other countries. Indeed, there are several standards, recommendations and practices even inside Europe. Unfortunately, the scientific background and justifications of the choices made in the regulations and their associated methods are largely rather superficial. Often small- and large-calibre weapon methods are different.

The main questions that need to be answered before accurate assessment of shooting noise can be made are:

- What is the best available annoyance descriptor or descriptors?
- How to measure the noise emission from different weapons accurately?
- How does the impulsive noise propagate in the environment?
- How (well) do the propagation models work?

In this thesis, the assessment of annoyance is studied solely based on previous research. In an effort to obtain further insight into the assessment of annoyance, some of the most prominent publications are discussed from an engineering point of view. Temporal integration and equal-loudness-level contours form the basis of the discussion.

In this work, the emission measurement methods are compared using both simulations and measurements. The microphone height and the ground impedance are some of the key issues affecting the emission measurement. The measurement methods for the emission of SCWs and LCWs are treated separately because the test sites for the LCWs are far less ideal than those for the SCWs due to the longer distance.

The investigations on the propagation in this thesis are concentrated on impulse noise, which has some different properties compared to continuous noise. The propagation is studied using mainly simulations. In addition, also some measurement and modelling data of FDF shooting ranges and areas are used. One often neglected effect during propagation is that due to scattering and the resulting spreading of the impulse in time. In addition to the muzzle blast noise, also projectile noise is considered. The propagation of these two noise types is compared using both theory and measurements. All of the interesting propagation models, unfortunately, were not available for testing with shooting noise. Thus, a final selection of the most accurate propagation model could not be included in this thesis.

In the thesis, the weapons with a calibre of ≥ 12.7 mm, as well as the explosives and tools including explosive material at least equal to 60 g trinitrotoluene (TNT) are treated as LCWs as in (Jaloniemi et al. 2005). Such weapons are for example cannons, howitzers, mortars, heavy and light bazookas, armoured cannons, rockets, missiles, explosives and mines. The other weapons are treated as SCWs.

1.1 Outline

This thesis is constructed as follows. Section 2 includes the relevant theory of the acoustics of shooting noise. Noise sources and propagation are divided into two subsections. In Sec. 3, the annoyance and its relation to different types of sound levels is assessed. The subject is approached from a technical point of view and issues such as the time and frequency weighting are the primary concerns. In addition, the Finnish regulations are summarized. Sections 4 and 5 are critical reviews of the emission measurement methods and the available propagation models, respectively. In Sec. 6, the emission measurement methods and propagation effects are simulated using theoretical frequency responses. In Sec. 7, the data from emission and immission measurements and modelling are analysed. Also, the propagation of projectile noise is simulated using both measurement results and theory. In addition, the effect of octave filtering on different time weightings is tested.

2 ACOUSTICS OF SHOOTING NOISE

The beginning of the section covers the basic acoustic principles of shooting noise sources. In this thesis, they are divided into three categories: muzzle blast, projectile noise and impact noise.

In any environment, several different aspects of the atmosphere and terrain affect the propagation of the sound. In the conventional prediction models, physical phenomena are treated separately each as its own attenuation coefficient affecting only the sound energy. In this section, the effects are treated with similar division as in the models.

2.1 Noise sources

2.1.1 Muzzle blast

Muzzle blast is the sound that is produced by an explosion inside the barrel of a gun. The deflagration of an explosive in a cartridge produces a sudden increase in the volume of a gas. This rapid increase in volume causes pressure waves which send the projectile into flight. The same pressure waves are heard as a muzzle blast.

The muzzle blast has two main properties that make it different from common environmental noise: short duration and large amplitude. The sound waves, especially near the emplacement, are short and impulsive. The duration of the impulse is generally only of the order of milliseconds close to the source. For SCWs the first positive pulse duration can be less than 0.5 ms and for heavy weapons few milliseconds (see Sec. 7.3). At the same time the peak sound pressure level L_{peak} can be 150-165 dB.

From the modelling point of view, muzzle blast can be considered to be a point source that produces a spherical wave when perceived at a distance. Although the muzzle blast is a point source, it does not radiate sound energy symmetrically. Weapons often have a strong directivity. For some weapons this can be even 20 dB (Pääkkönen et al. 2001). The directivity differs significantly between different types of weapons. For example in the case of bazookas the most prominent direction is backwards whereas with guns the maximum is the direction where the gun is pointing at. Muzzle brake is one of the main parts affecting the directivity. In addition, the directivity is also frequency-dependent so that low frequencies are more unidirectional than high frequencies.

When strong sounds are measured at a close distance, one has to consider nonlinear physical phenomena that predominate before the formation of the actual sound wave. Strongly nonlinear waves, shock waves, are generated in situations where the dynamic pressure is relatively close to the static pressure of 100 kPa (194 dB) or above it. At such sound pressures, sound waves perturb air leading to a changing speed of sound at different parts of the wave. The velocity increases as a function of the pressure. Thus, at certain distance the crest overtakes the trough and infinite velocity gradient results. This phenomenon is called shock formation and it produces a saw-tooth shaped wave. (Morse and Ingard 1968)

It would be beneficial to know the sound pressure level where the nonlinear effects are not significant anymore and the wave propagation can be characterised as a linear phenomenon. In emission measurements this means long enough measurement distances. In propagation models only linear effects are taken into account and therefore nonlinearity needs to be compensated if it is included in the emission value. In other words, the faster attenuation of the sound pressure level (SPL) needs to be considered close to the source. The limits vary among emission measurement methods. In (Miljøstyrelsen 1997) the limit is C-weighted peak sound pressure level L_{Cpeak} = 165 dB and the distance should be 2-3 times longer than the longest wavelength in order for the lowest frequencies to be fully developed. In the ISO (International Organization for Standardization) draft standard (ISO/FDIS 17201-1), the peak limit is 1 kPa or 154 dB. In the Nordtest method NT ACOU 099 (2002), a correction term is used when L_{peak} exceeds 130 dB.

2.1.2 Projectile noise

The most prominent part of projectile noise is the sonic boom of supersonic projectiles. Another noise generating phenomenon is turbulence, which is most easily audible with grenades generating a whistle type of sound. In this thesis, projectile noise and bullet noise are used to mean only the sonic boom part of the projectile noise.

The pressure wave of a supersonic projectile is called an N-wave due to the waveform. Because the leading overpressure cannot get out of the way of the projectile, due to its supersonic speed, the sound wave becomes a conically expanding shock wave. Its temporal waveform, "the N", is very sharp at close distances, when the peak sound pressure p_{peak} is close to the atmospheric pressure. When the N-wave propagates, the positive and negative phases travel at slightly different velocities as in the case of any nonlinear wave. This leads to spreading in time and in attenuation of the peaks. The spreading takes place as long as the pressures are high enough compared to the static pressure. Spreading is illustrated in Fig. 1. (Pierce 1981)

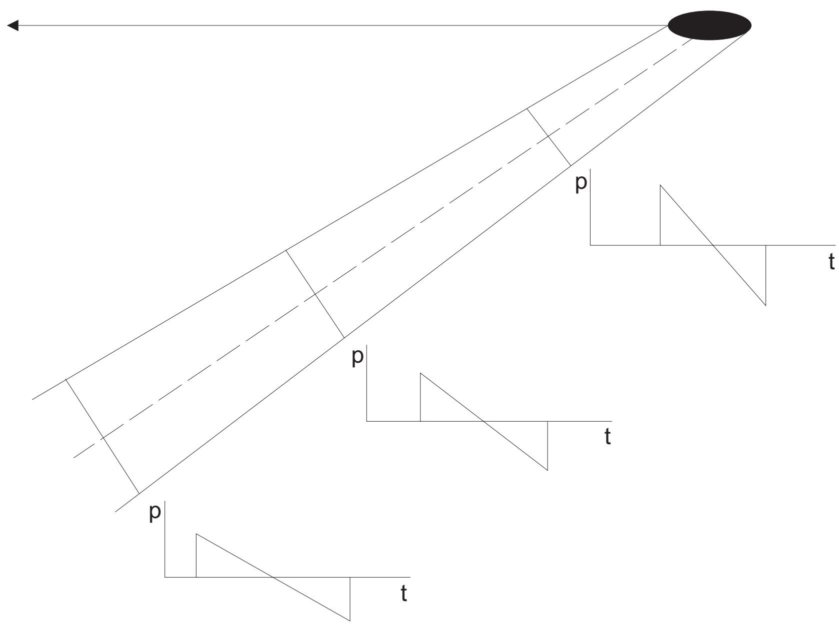

Figure 1. Illustration of a projectile noise wave (N-wave) shape spreading in time at different distances on the region of the sonic boom (Pierce 1981).

The theory of N-waves in (Pierce 1981), shows that the positive phase duration T is given by

$$T = \frac{2^{3/4} \beta^{1/2} M S_{\max}^{1/2} K r^{1/4}}{L^{1/4} c (M^2 - 1)^{3/8}} \qquad (1)$$

where β is the coefficient of thermal expansion (about 1.2 for air), M is the Mach number, $S_{\max}$ is the maximum cross-sectional area of the projectile, K is a dimensionless constant of the projectile shape [~0.6 for a bullet (NT ACOU 099 2002)], r is the distance, L is the length of the projectile and c the speed of sound. The same theory shows that the peak overpressure p_{peak} is given by

$$p_{\text{peak}} = \frac{\rho c^2 (M^2 - 1)^{1/8} S_{\max}^{1/2}}{2^{1/4} \beta^{1/2} r^{3/4} L^{1/4}} K \qquad (2)$$

where ρ is the medium density. The $r^{4/3}$ dependence of the distance for the peak pressure is different to the $r^{5/4}$ dependence of the distance of energy. This is due to the spreading of the wave in time. The $r^{5/4}$ dependence follows from Eqs. (1) and (2).

The phenomenon is called the sonic boom. With supersonic projectiles it is limited to a region in front of the gun. The geometry of the region depends on the travelling distance and the Mach angle

$$\psi = \sin^{-1} \frac{c}{v} \qquad (3)$$

where v is the velocity of the projectile (Pierce 1981). For one immission point there is only one source point in the flight path. The angle between the line connecting the immission and the source point and a normal of the flight path is the Mach angle. The geometry is illustrated in Fig. 2 (NT ACOU 099 2002).

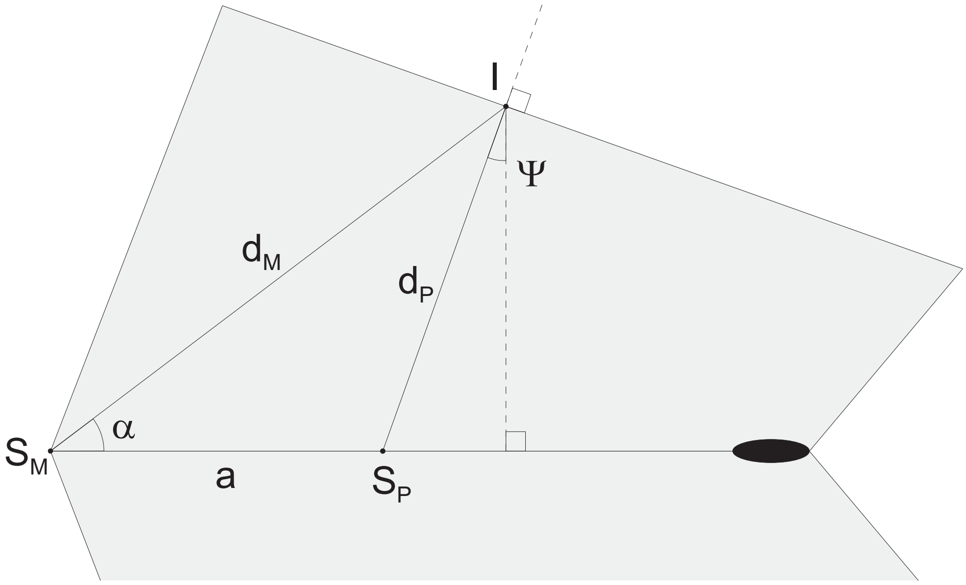

Figure 2. Projectile noise geometry between the muzzle noise source S_M, the projectile noise source S_P and the immission point I. d_M is the distance from the muzzle source to the immission point, d_P is the distance from the bullet noise source to the immission point, a is the distance between the muzzle and bullet noise sources and Ψ is the Mach angle. (NT ACOU 099 2002)

It is trivial to note that the sonic boom always reaches the receiver before the muzzle blast. The time difference t can be calculated using

$$t = \frac{a}{v_0 - \Delta v \cdot a / 2} + \frac{d_P}{c} \tag{4}$$

$$a = d_M (\cos\alpha - \sin\alpha \frac{c}{\sqrt{(v^2 - c^2)}}) \tag{5}$$

$$v = v_0 - \Delta v \cdot a \tag{6}$$

where v_0 is the initial velocity and Δv is the velocity reduction per unit distance. (NT ACOU 099 2002)

A significantly different prediction method of the projectile noise is presented in ISO/DIS 17201-4:2004 but it is not discussed nor tested in this thesis.

2.1.3 Impact noise

The impact noise is generated by a collision of the projectile into a target. For SCWs this is of low importance but for grenades, rockets, missiles and other exploding projectiles this can be a predominant part of the shooting noise. For impact noise, the same principles apply as for muzzle blast. Of course, emission needs to be measured from longer distance and thus, the result is not as accurate as for muzzle blast. For most exploding projectiles, the emission can be assumed to be the same to all directions.

2.2 Propagation

2.2.1 Divergence

The ideal point sound source in an ideal free field radiates equally in all directions. Hence when observed at a particular distance in any direction, the sound pressure is equal and a given sound power level L_W distributes equally over the surface of an expanding sphere (with area of $4\pi r^2$). Thus the intensity I is given by

$$I = \frac{W}{4\pi r^2} \tag{7}$$

where W is the source power and r the distance. The attenuation due to divergence ΔL_d is then

$$\Delta L_d = 10 \log_{10} \left(\frac{1}{4\pi r^2}\right) \tag{8}$$

The $1/r^2$ dependence on the distance means that by doubling the distance, the SPL is attenuated by 6 dB. (Rossing et al. 2002)

2.2.2 Air absorption

The air, or atmospheric, absorption is significant on long distances. Kinetic energy dissipation into thermal energy and molecular relaxation are the mechanisms absorbing sound energy. The relaxation losses originate from the inertia of gas molecules. The magnitude of air absorption is affected by the distance, temperature, atmospheric pressure and humidity. Scattering from air molecules is not known to have important attenuating effect in the frequency range of interest. (Lahti 1979)

In prediction models the estimate of the attenuation due to air absorption ΔL_a is given by

$$\Delta L_a = -\alpha r \tag{9}$$

where α is frequency dependent attenuation coefficient and r the distance. High frequencies are attenuated more than low frequencies. The magnitude of air absorption for different humidity, atmospheric pressure and temperature conditions is well known and it has been standardized in (ISO 9613-1:1993). Air absorption in typical conditions (temperature 15°C, humidity 70%, atmospheric pressure 101.325 kPa) at four distances is presented in Fig. 3. (ISO 9613-1:1993)

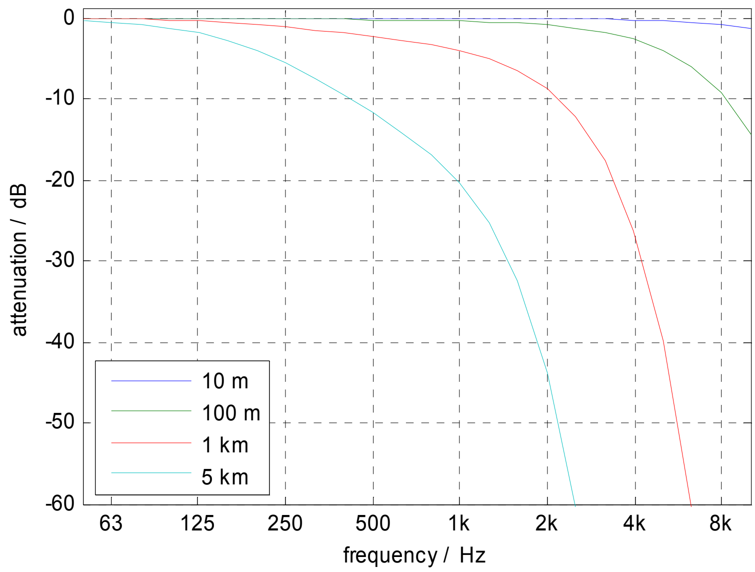

Figure 3. Attenuation due to air absorption according to (ISO 9613-1:1993) at 10 m, 100 m, 1 km and 5 km distances calculated in one-third-octave bands. In the figure, typical Finnish weather conditions are assumed (temperature 15°C, humidity 70% and atmospheric pressure 101.325 kPa).

The air absorption starts to be significant at distances over 100 m above 2 kHz. The muzzle blast energy is usually below 2 kHz but the main frequency range of bullet noise can be above that (as noticed later). At 1 km distance frequencies above 250 Hz are attenuated and the air absorption has an important part in the total attenuation even with LCW noise.

The rain and fog, i.e. water drops have been proved not to produce as strong absorption mechanisms as the air. Although theoretical analysis has indicated that the fog may attenuate sound up to 20 dB per kilometre at 1 kHz, practical measurements have shown fog to produce only about 1 dB per kilometre attenuation. Also the scattering effect of water drops is minimal due to the small size in relation to the interesting wavelengths. The more important effect affecting sound propagation during foggy weather is indirect: temperature and wind gradients do not occur, resulting in a straight propagation path. (Lahti 1979)

The attenuation due to rain has not been studied extensively. It is not very interesting either, because measurements are usually made only in dry weather to protect the equipment. There is no reason to expect that rain should attenuate the sound significantly.

2.2.3 Reflection

Reflection of sound is often modelled using the ray-acoustic approach to the problem. The estimation of the incident wave with a plane wave makes the sound reflection equal to the specular reflection of light when the surface is ideally hard and flat. When the conditions apply, the mirror image appears to be at the same distance from the interface as the source. In the case of sound, it means that a mirror image with the same source properties is observed in addition to the real sound source. If the reflecting surface is not hard, the reflection coefficient R needs to be estimated. Its definition for a plane wave is

$$R = \frac{Z_2 \cos\theta_1 - Z_1 \cos\theta_2}{Z_2 \cos\theta_1 + Z_1 \cos\theta_2} \tag{10}$$

where Z_1 and Z_2 are the acoustical impedances of the two media, θ_1 is the angle of incidence and θ_2 is the angle of refraction. The reflected pressure p_1 is obtained by multiplying the pressure of incidence p_0 with the reflection coefficient R. The geometry is illustrated in Fig. 4.

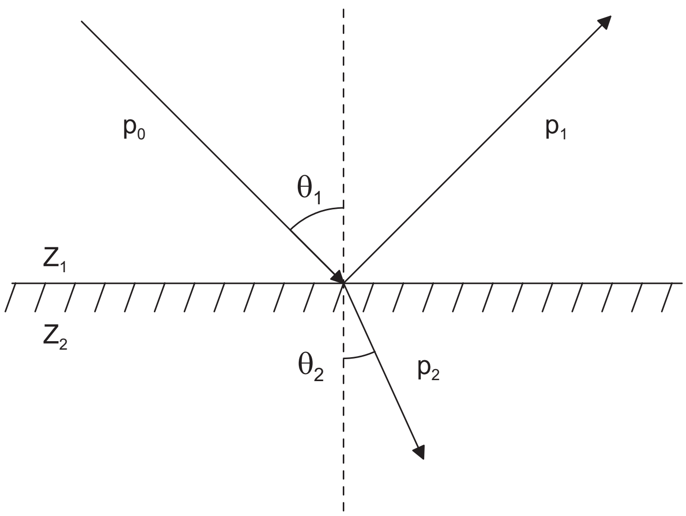

Figure 4. Illustration of specular reflection from the ground. p_0 is the incident pressure, p_1 the reflected pressure, p_2 the refracted pressure, θ_1 the angle of incidence, θ_2 the angle of refraction and Z_1 and Z_2 the corresponding impedances of the two media.

When the sound source is close to the ground, the plane wave assumption does not apply anymore for surfaces with finite impedance. Rather than being planar the wave is curved. Therefore a solution for a spherical wave is needed. The solution is rather complicated especially for inhomogeneous surfaces and is bypassed here. The resulting magnitude response of the reflection is compared to the magnitude response of the reflection from a hard ground in Fig. 5. With hard ground, the interference between the direct and reflected waves produces a sharp comb-filter effect. With porous ground, the interference is clearly smoothed so that the troughs are shallower, wider and shifted to lower frequencies.

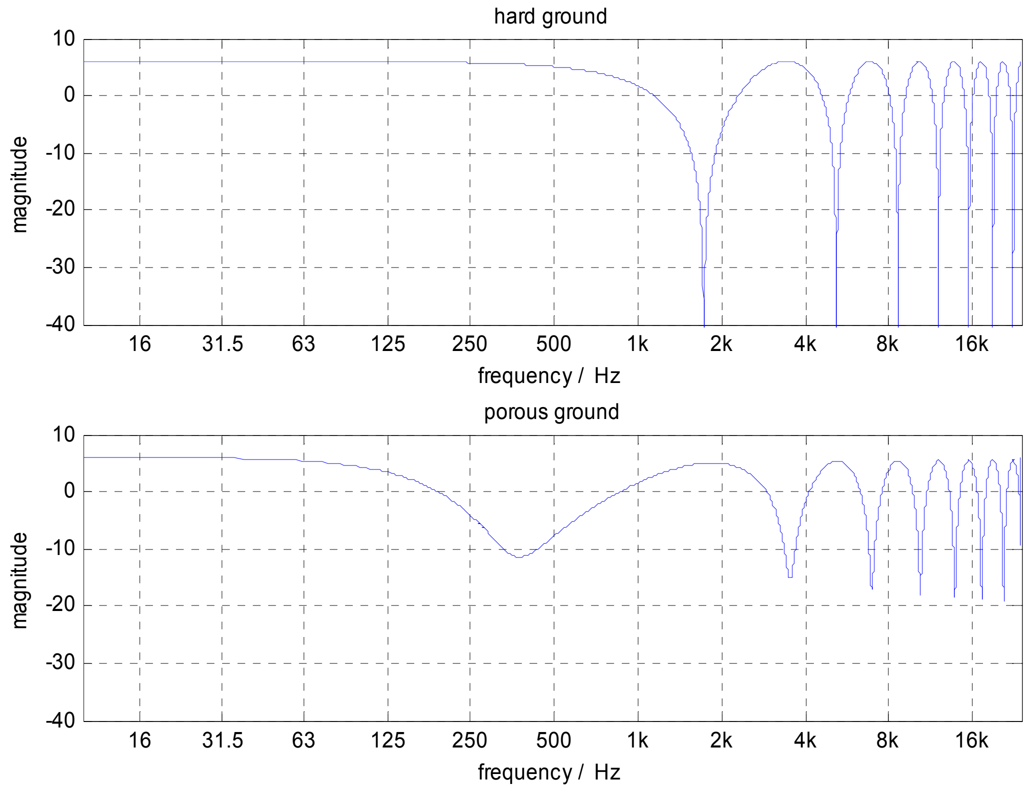

Figure 5. Theoretical magnitude responses of hard and porous grounds at 100 m distance. Source height is 2.5 m and receiver height 2 m. The porous ground differs from hard ground in wider and shallower troughs that are shifted to lower frequencies.

2.2.4 Refraction in the atmosphere

The wind and temperature gradients are known to have strong effect on sound propagation. A positive temperature gradient means that the temperature decreases as a function of the height from the ground. Since the speed of sound is a function of the temperature, close to the ground the velocity is greater than at higher altitude. Hence, upwards curved propagation path results and the sound pressure is attenuated more than in neutral conditions. Headwind has a similar effect because wind speed increases as a function of the height. Negative temperature gradient and downwind have opposite effects and produce downwards curved propagation paths. The estimate for the maximum height of the refracted path due to the downwind is given by

$$H \approx \frac{r^2 k}{8c_0} \tag{11}$$

where r is the propagation path length, k = dc/dh is the constant gradient and c_0 is the initial speed of sound. The equation applies when $H << 2c_0/k$. For example, a path length of 1000 meters and a velocity gradient of 0.05 would result in approximately 18 meter maximum height of the refracted propagation path. (Lahti 1979)

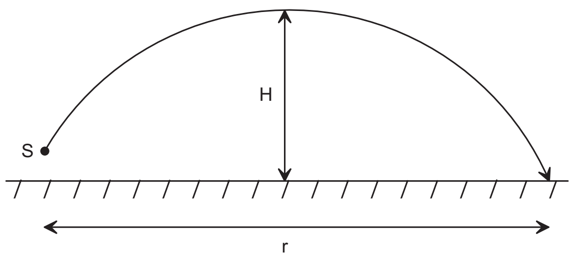

Figure 6. Illustration of refracted propagation path due to positive velocity gradient. H is the maximum height of the path and r the horizontal distance between the source and the receiver.

2.2.5 Turbulence

The turbulence is a phenomenon of local variations of wind close to the ground. In practice it occurs always in the atmosphere. Turbulence causes scattering and it affects the sound propagation direction and speed arbitrarily.

In a turbulent medium, some of the sound energy is absorbed and some is deflected to various directions from its original course. When the scattered sound waves merge in the observation at some distant point in space, they have travelled paths of different lengths. For short impulsive sounds this can be observed as the spreading and distortion of the waveform in time. For shooting noise, the effect can be perceived at a distance of few hundred meters already (see Sec. 7.3).

The phase and the amplitude of a sound wave can be randomized by turbulent regions until the amplitude deviation is 6 dB and the phase deviation is 90°. The distance of this saturation point is roughly 700 times the wavelength at the frequency range of 500 Hz to 5 kHz. (Lahti 1979)

The turbulence affects also the interference due to the ground reflection. The interference minima can be suppressed significantly due to the phase deviation.

In propagation models, though, turbulence is not usually taken into account. One reason for this is that scattering is noted not to affect the energy propagation significantly. Turbulence affects the propagation of sound wave when observed in a short period of time but when averaged over a longer period of time, no significant change in sound energy propagation takes place (McLeod et al. 2004).

2.2.6 Scattering

The proportion of the incident wave that scatters depends on the obstacle size and the wavelength. Common knowledge is that long waves scatter less than short waves as happens with light waves (Rossing et al. 2002). Thus, in average for high-frequency sounds, there are more propagation paths than for low-frequency sounds. On the other hand, if the obstacle size is close to the wavelength, a variety of interference phenomena may occur.

Such scattering obstacles can be, for example, tree trunks, rocks and other relatively large irregularities in the propagation path. There is no sense to model each of such small obstacles individually and therefore they are usually modelled in large units. Also only the attenuation of the total sound energy is usually modelled and effects in the time domain are ignored.

2.2.7 Diffraction

In propagation models, strongly diffracting barrier elements like buildings and hills are dealt with separately from foliage scattering. Diffraction is a special case of scattering where the obstacle size is substantial in relation to the wavelength. It depends on the Fresnel number N given by

$$N = \frac{2}{\lambda}(d_{\mathrm{dif}} - d_{\mathrm{dir}}) \tag{12}$$

where d_{dif} is the diffracted path length and d_{dir} the direct path length without the diffracting element. The relation of the Fresnel number N to the magnitude of attenuation is illustrated in Fig. 7 (Rossing et al. 2002).

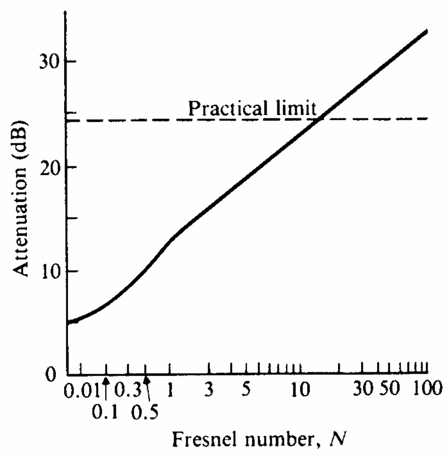

Figure 7. Attenuation due to diffraction as a function of the Fresnel number *N*. A practical limit of maximum attenuation is shown in dashed line. (Rossing et al. 2002).

The sound propagation path outdoors is often curved due to temperature and wind gradients. In downwind conditions the path is curved downwards and the path length difference decreases substantially from still weather conditions. Already a small change in the path length difference and in Fresnel number *N* affects the attenuation notably. This can result in big differences between measurements and theoretical calculations with shooting noise as in (Saunders 1990).

3 ASSESSMENT OF ANNOYANCE

Annoyance caused by noise is a broad subject. Aspects such as loudness, duration, roughness, tonality and impulsiveness are all parameters that describe annoyance to some degree. Also other psychological issues affect the annoyance. In order to map all these qualities to the desired parameter of annoyance, extensive listening tests and research would be needed. The problem with the listening tests is that they are very demanding, time-consuming and expensive to be held. They also apply only for that specific type of noise and environment and, thus, the reuse of existing data is difficult. (Karjalainen 2000)

Due to the complexity of the subject, simplifications need to be made to achieve a suitable parameter that describes the annoyance at least reasonably well. Most often this is done in noise measurements by assessing only the loudness and duration of the sound. In environmental noise measurements, A-weighted equivalent continuous sound pressure level L_{Aeq} is the most frequently used assessment parameter. A more accurate psychoacoustic model would need a considerable amount of work and research. Also the limitations of sound level meters (SLMs) favour the use of conventional noise parameters in practice. With conventional parameters, the mapping of loudness level to annoyance is made by finding a reference level that is used as the limit in regulations. Also an impulse correction is sometimes added to impulsive noise level in order for it to be comparable with other noise types.

A wide variety of different levels have been used in different countries and communities. An important question is: which ones of the existing levels are the most suitable for assessing human response to shooting noise of different weapon types. Time- and frequency weighting, duration of measurement, energy vs. maximum are the technical parameters that need to be considered. In addition, psychophysical issues must be taken into consideration. The risk of hearing impairment is a different subject and it is not discussed in this thesis in any way.

3.1 Equal-loudness-level contours

In order to comprehend the purpose of frequency weighting, one must first know some of the basics about the human sensation of loudness with respect to frequency. Normally, the loudness as a function of frequency is represented with a set of equal-loudness-level contours. The contours are acquired from several sets of psychoacoustic tests made for young adults (age 18 to 25) with normal hearing. Each contour represents a set of SPL-frequency pairs that are judged equally loud. The used test signal is a continuous tone listened binaurally. For the contour set, 1 kHz has been used as a reference frequency. The loudness quantity is a phon. ISO has standardized and revised contours in ISO

226:2003[1] and they are shown in Fig. 8.

From the contour set can be seen that lower frequencies need to incorporate more energy in order to be sensed equally loud as higher frequencies. It can also be noticed that the auditory system is most sensitive at a frequency range of 2-5 kHz. The first resonance of the ear canal is on the same frequency range. Not by chance, this is also the main frequency range of the speech. Another important property is that the contours are flatter at high total levels than at low total levels. This suggests that one frequency-weighting network for all sound levels is not sufficient. (Karjalainen 2000)

The first ISO standardized contours (in 1987) have been compared to contours acquired with the use of tone bursts of 20 ms instead of continuous tones in (Masaoka et al. 2001). The results show that below 6 kHz, the two contour sets were close to each other. Above 6 kHz 10 dB higher loudness was observed with bursts. This observation matches with the contours revised in 2003. Thus, the results suggest that equal-loudness-level contours are directly applicable with impulse noise.

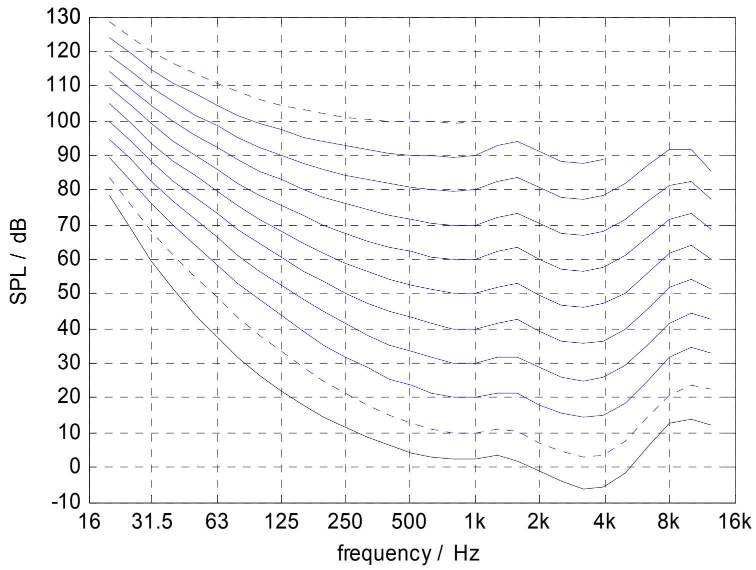

Figure 8. Equal-loudness-level contours according to (ISO 226:2003). Each line represents an equally loud SPL-frequency pair for a pure continuous tone. Blue lines are the models based on several independent sets of psychoacoustical laboratory tests made with young adults (age 18 to 25) with normal hearing. Black line is the absolute threshold of hearing and the dotted blue lines lack of test data.

3.2 Frequency weighting

The original purpose of the frequency weighting was to model the loudness response

[1] They were first standardized in (ISO 226:1987) and the revision in 2003 includes significant differences compared to the original both in the low- and high-frequency ranges.

of the human auditory system. With the use of equal-loudness-level contours, three different networks were introduced: A-, B- and C-networks. Each of the networks was intended to be used for modelling curves of different total level. Later also D- and E-networks were introduced. The latter two model the equal-loudness-level contours more accurately but they have not been widely adapted to practical use for historical reasons.

A-weighting is the most commonly used frequency weighting in noise measurements. It was originally intended to be used only for low-level noises but nowadays it is used in almost all kinds of noise measurements. It can be seen from Fig. 9 that with A-weighting frequencies below 1 kHz are weighted heavily. Therefore it correlates quite well with the loudness sensation at low SPL.

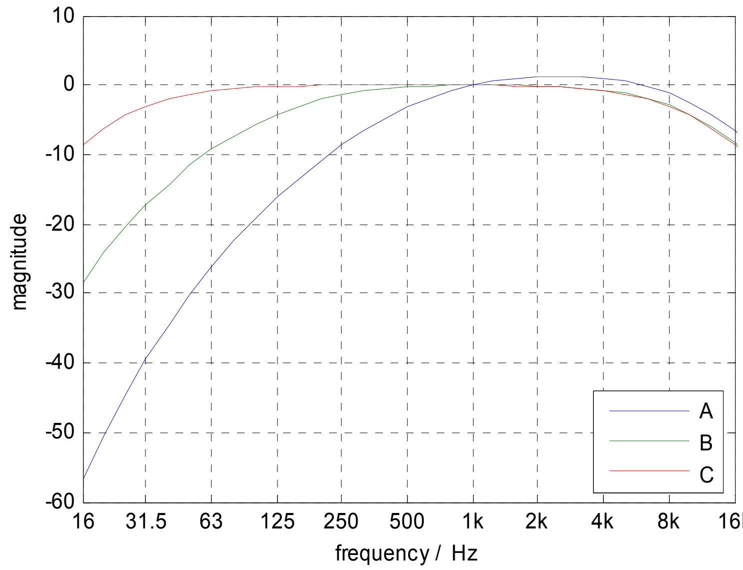

Figure 9. A-, B- and C-frequency-weighting magnitude responses according to (International Engineering Consortium [IEC] 61672-1 2002). A-network is the most accurate at low SPL and C-network is the most accurate at high SPL according to equal-loudness-level contours. Rarely used B-network is a network in between A- and C-networks.

Equal-loudness-level contours are relatively flat at high SPL and A-weighting is not an optimum choice anymore. For high SPLs, a more appropriate network is C-weighting which does not discard as much energy from the low frequencies as the A-weighing does. This is the reason why the C-weighting is quite commonly used in measuring shooting noise of heavy weapons, which incorporate most of the energy at low frequencies. Thus, C-weighting would seem to be an obvious choice to measure heavy weapon noise. Though, when the sound propagates long distances in the environment, it attenuates and the C-network does not necessary model the loudness well anymore.

The congruence of A-filtering and inverse of both 1987 and 2003 released equal-loudness-level contours are studied in (Vos and Geurtsen 2003). For different weapons and levels, the congruence is different. For example 155 mm howitzer at A-weighted sound exposure level L_{AE} = 60 dB matches well with the revised contours (2003) whereas at L_{AE} = 40 dB, A-filtering is 10 dB higher. With SCWs A-filtering seems to match equal-loudness-level contours within a few decibels. The results suggest that, if C-filtering would be used instead, the loudness would be significantly overestimated at low levels. At shorter distances (higher levels), the situation is different.

B-weighting is rarely used and it can be seen as a network in between the A- and C-networks. B-weighting is not in general use. Zero-weighting[1], as the name indicates, is no weighting at all. It leaves the frequency response intact. This is not preferred in loudness assessment because some frequency weighting occurs always in the human auditory system. It is useful only in finding out the peak level for measuring purposes or when measuring a spectral input for propagation models. From pure psychoacoustical view of loudness, the most correct method of frequency weighting would be dynamic filtering with the inverse of equal-loudness-level contours. This has been also suggested to be done with shooting noise by Schomer (2000).

Although the basic weighting networks are widely used in practice and implemented in the modern SLMs, a more accurate way of assessing loudness would be to use a loudness computation model based on psychoacoustics. One of the first loudness models was developed by Zwicker some fifty years ago. It is standardized in (ISO 532b:1975). Zwicker's model is three-staged:

- A fixed filter modelling the outer and middle ear acoustics
- Calculation of the excitation pattern that takes into account the spreading of the excitation in frequency domain
- Transformation of the excitation pattern to specific loudness

Later the model has been revised by Moore and Glasberg (1996). The revised model has modifications and extensions in every stage of the Zwicker's model. For example, it models more accurately the way the equal-loudness-level contours change with SPL and it is able to take into account partial masking. It also has an advantage of being based on analytical formulae rather than on fixed charts as in the Zwicker's model. (ISO 532b:1975, Moore and Glasberg 1996, Karjalainen 2000)

The use of C-weighting with heavy weapon noise in the literature is often justified by the resulting vibrations. The strong low-frequency content may put building structures, windows and interiors into vibrating motion and therefore increase the annoyance substantially. The A-weighting would discard this information and the rattle would not be taken into account. Even infrasonic sound that is not heard directly by people can produce such rattles and perturb actions. The rattles need to be concerned only with heavy weapon noise due to its low-frequency content. The sound pressure is not normally high enough to generate hazard to building structures, because the distances are long.

[1] Lin., linear-weighting

3.3 Time weighting

It has been long known that the sensation of loudness does not grow into full instantly. Increasing the duration of the sound signal by a factor of 10 increases the loudness roughly by 10 dB (Zwislocki 1969). The summation takes place somewhere in the central nervous system but the details of the mechanisms are not well known. The limit of the loudness saturation, or integration time, is about 100-200 ms. After the integration time perceived loudness does not increase anymore. The integration time is not constant but changes with absolute level. 100 ms is a close estimate at high and suprathreshold levels and 200 ms at levels near absolute threshold of hearing (Zwislocki 1969, Poulsen 1981). In (Zwislocki 1969), the theory is tested with both psychophysical and neurophysiological experiments. On the other hand, also longer and shorter integration times have been presented before (Garner 1949, Small et al. 1962). Florentine et al. (1996) came also in conclusion that integration time is shorter for higher SPL than for low SPL. In Fig. 10, temporal integration is illustrated for a pure tone and broadband noise. The integration time for broadband noise is longer than that for pure tone (Rossing et al. 2002).

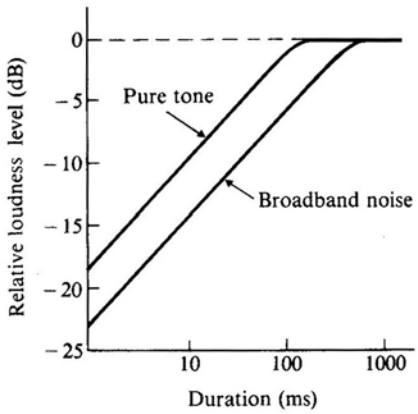

Figure 10. Rough approximative sketches of relative loudness levels as a function of duration for pure tones and broadband noise. The real integration time of broadband noise is about two times longer than the integration time of a pure tone. (Rossing et al. 2002)

The existence of temporal integration implicates that the mechanism should be incorporated in the noise measurements as well. Luckily temporal integration has been part of the SLMs from the beginning of their development. Temporal integration in the SLMs is called time weighting. Originally, though, time weightings were just limitations of the electronics and were not implemented for psychoacoustical reasons. Technically time weightings are just different time constants of the integration circuits. The longer the integration time the slower the detector reacts to the fluctuations in a signal and vice versa. In the modern SLMs four standardized time weightings are implemented: fast (F), slow (S), impulse (I) and peak. The corresponding time constants are presented in Table 1. (Lahti 1997)

Table 1. Time constants of the four standard time weightings. The constants equal to integration times with transient signals. Peak-weighting is the only weighting that does not integrate energy in time and the time constant is rather the maximum allowed rise time of the detector.

Id	weighting	time constant
F	fast	125 ms
S	slow	1000 ms
I	impulse	35 ms (rise time) and 1500 ms (decay time)
Peak	peak	< 50 µs

Originally the F time constant was the fastest possible response of the detectors of that time. It is pure luck that later research has showed that the fast time constant of 125 ms is actually fairly close to the temporal integration. Especially with high levels, 125 ms seems to be an accurate estimate. This supports the use of maximum F-weighted sound pressure level L_{Fmax}. In fact, several countries use it as the descriptor of annoyance.

In the conventional integrating SLMs the detectors reacted too fast to changes in the signal. It was impossible to read the levels from the detector manually when the sound was rapidly fluctuating. Slow time constant of 1000 ms was introduced as a remedy for this problem. The 1000 ms is significantly longer than 125 ms and therefore it was easier to read the level from the display. It does not however relate to human temporal integration in any way. In fact, it should be used only in the case of particular continuous sounds where it can be statistically more reliable than the F-weighting. (Lahti 1997)

I-weighting was an attempt to make a better correspondence between the measured level and the risk of hearing impairment in the case of impulsive noise. Still the rising time constant of 35 ms was later found out too slow to be able to react to shooting noise peak, which can be shorter than a millisecond. Another downside of I-weighting is its asymmetric integration which makes it impossible to measure equivalent or exposure levels with I-weighting. Therefore it cannot be used to combine sound events into one and it cannot be compared to other types of noise directly.

In the latest SLM standard of IEC (61672-1 2002), I-weighting is included only in its informative annex. In the standard is stated that: "...time-weighting I is not suitable for rating impulsive sounds with respect to their loudness. Time-weighting I is also not suitable for assessing the risk of hearing impairment, nor for determining the 'impulsiveness' of a sound."

Peak-weighting was introduced later to replace I-weighting and to indicate better the risk of hearing impairment. Time of Peak (50 µs) is actually not an integration constant but rather the fastest rise time of the meter. It does not integrate sound pressure in any way but is the maximum instantaneous value of sound pressure over the period of measurement. Therefore L_{peak} is a parameter describing only the waveform and should not be used in assessing loudness or annoyance. For measuring the risk of hearing impairment, the use of peak may be better justified. (Lahti 1997)

3.4 Long-term exposure

In addition to the maximum levels of different time weightings, sound levels can be measured by integrating sound pressure over a longer period of time. Equivalent continuous sound pressure level L_{eq} and other long-term levels are often used with other types of noise. The most common annoyance descriptor is L_{Aeq} which is used, for example, with traffic noise. Integrating level quantities take into account the longer time of exposure to noise and combine the effect of multiple noise sources and events. For example, consider hundred muzzle blasts versus one muzzle blast. When a maximum level would produce the same level in both cases, equivalent level would result in 20 dB higher level in the former case if the length of the measurement period was the same.

There are many different opinions about the use of equivalent levels. By measuring the noise dose from one shot, noise dose from N shots is often calculated by adding $10\log_{10}N$ to the one shot exposure level. The ten-based logarithmic rule has been discovered to match the increase in annoyance well in several studies (Smoorenburg 1981, Bullen and Hede 1985, Leatherwood et al. 2002, McCurdy et al. 2004). At the same time these studies support the use of L_{eq} because also the ten-based logarithmic rule is based on equal-energy principle. Also a research by Bullen et al. (1991) supports the use of equal-energy-based measures over others.

Sound exposure level L_E is also an equivalent level but normalized (compressed) to one second. L_E can be stated to be the quantity of a noise dose and it is a versatile quantity from technical point of view. It can be used to combine multiple noise sources or multiple events into one to obtain the total exposure.

3.5 Level quantities

There are quite a few published studies about the annoyance of impulsive noise and recommendations about which one of the many types of sound levels is the most applicable. Some recommend using more than one level. Often the SCW and LCW noises are separated and assessed using different types of sound levels.

Pesonen (2005) concludes his study's chapter on impulse noise by stating that maximum levels are not valid and generally applicable indicators for assessing the annoyance of impulse noise. Also in the new ISO shooting noise standard series (ISO 17201) only energy-based levels are used and maximum levels are ignored. The same applies for (ISO 1996-2.2:2005).

In a literature review of shooting noise assessment Jokitulppo et al. (2006) studied several publications about the subject. In the primary papers referred to, an apparent tendency was that L_{AE} correlates well with the experienced annoyance of SCWs, where as C-weighted sound exposure level L_{CE} correlates better with LCWs. Both of the levels describe only one event doses. Long-term equivalent level should be measured in addition to account for longer exposure times and multiple events and to be comparable with other noise types and existing noise limits.

Vibrations of building structures and induced rattles in interiors have been several times noted to increase the annoyance substantially. Also Jokitulppo et al. (2006) and Pesonen (2005) found out the same tendency in their literature studies and no controversial evidence was found. The strong low-frequency content does not generate only vibrations that are felt, but also indirectly sounds that are heard (Findeis and Peters 2004). The indirect sound means that the primary sounds are not necessarily heard but the secondary sounds from rattling artefacts are. Both of these affect the experienced annoyance substantially. Due to the low-frequency content of vibrations inducing vibrations, L_{CE} would seem to be a better option than L_{AE}.

In 1984, Schomer stated that L_{CE} is the best available parameter due to its property of taking low-frequency vibrations and rattles into account. Later in (Schomer and Averbuch 1989) it was found that neither A- nor C-weightings correlate well with the experienced annoyance when blast induced rattle is perceived. They also found that the lower the sound level is the more annoying the rattles are. A 13 dB increase in annoyance compared to noise without the rattle is perceived at low SPL and the increase lowers to about 6 dB when L_{peak} is about 112-122 dB.

L_{AE} is preferred in (Meloni and Rosenheck 1995), where outdoor and indoor levels are compared in order to match the shooting and traffic noise annoyances. An extra 5 dB penalty is proposed to LCW noise to compensate for the poor sound insulation of façades at low frequencies. The rattles were neglected in the study. In (Vos 2003) the effects of façade sound insulations on shooting noise annoyance have been studied. L_{AE} is stated to be the primary predictor and the product $(L_{CE}\text{-}L_{AE})L_{AE}$ the secondary predictor of the annoyance rated indoors when measured outdoors. In (Buchta 1990) L_{eq} is found to be a better descriptor than maximum I- or F-weighted sound pressure levels L_{Imax} or L_{Fmax}. Also in the two studies (Buchta 1996, Schomer 2000) it is stated that the exposure level with an impulse correction is a proper parameter for assessing annoyance. In some papers studied by Pesonen (2005) maximum F- and A-weighted sound pressure level L_{AFmax} and maximum S- and A-weighted sound pressure level L_{ASmax} are found to be equally good descriptors of annoyance as L_{AE}. In the same studies maximum I- and A-weighted sound pressure level L_{AImax} is stated to overrate the experienced annoyance.

Noise from shooting ranges in Finland has been stipulated in (Ympäristöministeriö [YM] 1999). It applies to SCWs only and uses L_{AImax} as the annoyance descriptor. Military shooting noise has not been studied in Finland extensively and the first guide for

LCW noise was published only in 2005 by FDF in (Jaloniemi et al.). In the guide three different quantities of measurement are used. L_{Cpeak} is used as the first indication of excessive noise. If L_{Cpeak} exceeds 115 dB at outdoors of a residential area, a more detailed survey is made using L_{CE} and A-weighted day-evening equivalent level L_{Ade}.

In (Miljøstyrelsen 1997), five different levels are used in parallel. L_{CE} is used for heavy weapon single event exposure and C-weighted day-evening-night equivalent level L_{Cden} for one-year-average exposure. The corresponding night-time penalty is 10 decibels and evening and weekend penalty 5 decibels. L_{AE} and A-weighted day-evening-night equivalent level L_{Aden} are used equally with SCWs excluding shooting ranges which are still assessed using L_{AImax} as in the rest of the Nordic countries.

The use of assessment descriptors is diverse between countries and no general agreement on the most appropriate level quantity exists. Level quantities used in some of the countries for SCWs are (Desamaulds et al. 1998, North Atlantic Treaty Organisation [NATO] 2000):

- L_{AImax} in the Nordic Countries, Austria, Netherlands and Australia (in Australia also L_{peak}).
- L_{AFmax} in Germany, Czech Republic.
- Peak sound pressure level L_{peak} and A-weighted sound exposure level L_{AE} in the U.S.

Quantities of measurement for LCW noise are levels (Desamaulds et al. 1998, NATO 2000):

- L_{CE} in Sweden, Germany, Denmark and the U.S.
- C-weighted day-night equivalent level L_{Cdn} in Norway.
- L_{peak} in Australia and Netherlands (also L_{AImax} in Netherlands).
- L_{AFmax} in Germany, the U.K. and Switzerland.
- L_{AE} in Czech Republic.

3.6 Impulse correction

Impulse noise is generally accepted to be more annoying than non-impulsive noise of the same sound level. Still it would be beneficial to be able to compare these noise types, especially because traffic noise quantities are something that people are used to and the limits are well regulated. In order to make this possible, a correction for impulse noise is often added. Impulse correction is a value added to the equivalent continuous sound pressure level L_{eq} of impulse noise in order for it to be directly comparable with other noise types (e.g. traffic noise). It is important to understand that impulsiveness is a different concept. Impulsiveness is a shape parameter that depicts the short, rapid and strong loudness of the shot and not the experienced increase in annoyance

In (ISO/DIS 1996-2.2:2005) it is stated that: "There is no generally accepted method to detect impulsive sound using objective measurements." Still Nordtest method (NT ACOU 112 2002) is a standardized way to do this. It uses the onset rate (dB/s) and the level difference of the F-weighted signal to estimate a prominence factor and further a correction factor. The model is tested to have less than 1 dB deviation from psychoacoustical tests held in a laboratory.

The determination of the value of the penalty is a hard task and a large amount of test subjects is needed. Nevertheless, there is a wide range of impulse corrections proposed for shooting noise. Different values of correction are often proposed for different types of weapons. Some of the stipulated or proposed impulse corrections in the literature are:

- 10 dB for SCWs (Sosiaali- ja terveysministeriö [STM] 2003).
- 9 dB to L_{Aeq} for LCWs (Jaloniemi et al. 2005).
- 10 and 5 dB for highly impulsive and impulsive noise, respectively. Highly impulsive noise can be for example SCWs with L_{AE} > 55-60 dB.[1] (Pesonen 2005)
- 13 dB for SCWs (Buchta 1990).
- 10 dB for SCWs and 15 dB for 25 mm cannon (Schomer and Wagner 1995).

Jokitulppo et al. (2006) found out that the penalty should not be a static number but rather it should depend on the distance since shooting noise looses its impulsiveness as a function of the distance. A method for this kind of dynamic correction has been presented in (Buchta 1996) for various weapon calibres. Dynamic impulse correction changing as a function of the distance can be a very difficult case to be solved in practice because numerous environmental aspects affect it.

3.7 Noise limits

The measured sound levels are not useful until compared to noise limits which describe percentage of people “highly annoyed” or like. Stipulated noise limits for shooting ranges are presented in the Table 2 (VNp 53/1997).

Table 2. Noise limits L_{AImax} / dB for shooting noise stipulated in (VNp 53/1997).

outdoors	
living area and educational institute	65
recreational area in a suburb, nursing institute, vacation and conservation area	60

In the FDF guide of heavy weapon noise (Jaloniemi et al. 2005) three different types of levels are used. L_{Cpeak} gives a first indication of the excess noise. If it exceeds 115 dB, a more precise investigation takes place using L_{CE} and L_{Ade}. The limits for the latter two

[1] A 20 dB correction for LCWs, explosions and sonic booms was presented in a draft version of the ISO 1996-2 standard but was not approved to the final version. A bigger penalty for LCWs would seem to have no factual background, because heavy weapon noise is usually less impulsive than SCW noise at significant distances (see Secs. 7.3 and 7.5).

are 100 dB and 55 dB, respectively. Both of these are outdoors levels and a 9 dB impulse correction is proposed to be added to L_{Ade}. Indoors noise limits stipulated in (VNp 993/1992) are used (see Table 3).

Table 3. Noise limits L_{Aeq} / dB for general noise stipulated in (VNp 993/1992).

outdoors / area	**day**	**night**
living-, recreation- in suburb, nursing and educational institute	55	50[1]
vacation-, camping, recreation- and conservation-	45	40
indoors / room, facility		
residential-, sickroom, accommodation	35	30
educational-, recreational-	35	-
business and office premises	45	-

Specific limits of shooting noise have been investigated in Denmark by several interviews (Miljøstyrelsen 1997). The presented noise limits are:

- L_{Cden}= 55 dB for LCWs
- L_{Aden}= 45 dB for SCWs in scattered practices (e.g. military practice in a forest)
- L_{AImax} = 55-70 dB for fixed shooting ranges depending on the utilization rate

The first two limits were acquired by interviewing people living near practice and shooting areas. 7191 and 2000 interviews were made for acquiring L_{Cden} and L_{Aden}, respectively. The limits are based on 10 % fractile of interviewees "strongly annoyed" by the noise. Note that the shooting range noise is separated from the scattered SCW noise.

In Norway the shooting noise limits L_{AImax} range from 60 to 70 dB depending on the amount of shots fired per year. 65 dB is used when less than 65000 shots are fired and 70 dB when less than 20000 shots are fired. The limits apply between 0700 and 2300 hours. (Statens förurensningstilsyn 2005)

In Sweden 65-70 dB limit of L_{AImax} is used in new residential and vacation areas. Normal 5 and 10 dB penalties are used for evening- and night-time activities. (Naturvårdsverket 2005)

[1] 45 for new areas.

4 MEASUREMENT METHODS

For the propagation models to produce accurate results, emission levels need to be reliable. The first Nordic method for emission measurement was so called Kilde's model presented in 1984. Although not officially published in Finland, it was in use before the newer methods. NT ACOU 099 includes an improved version of the method and it is directly adapted to Finnish guide of shooting range noise (YM 1999) as well. The new method ISO/FDIS 17201-1:2005 is intended for the same purpose but it has different means. These differences are one of the key problems studied later in the thesis. All the preceding methods are intended for SCW emission only.

In the FDF heavy weapon guide (Jaloniemi et al. 2005) emission level measurement method is taken directly from Danish guide (Miljøstyrelsen 1997). FDF have also made immission measurements but no extensive modelling of noise areas has been done before the last year. Alongside with this thesis, there is a literary study in progress concerning also emission method issues (Eurasto 2005).

In this section the emission measurement methods are critically reviewed on the basis of conclusions of Secs. 2. and 3. Also some general technical aspects of measurements are discussed.

4.1 Emission

Emission measurements of weapons introduce new problems compared to general emission measurements. High levels, strong directivity and projectile noise are new issues that need to be considered a priori. In the case of LCWs, L_{peak} can be over 160 dB even at the distance of 100 m. This is relatively close to the static pressure (196 dB) and nonlinear propagation needs to be taken into consideration. Directivity is significant with most weapon types. For instance, 45° difference in azimuth angle can affect the measured SPL by almost 20 dB for some LCWs (Pääkkönen et al. 2001).

General emission measurements have been standardized by ISO. In standard measurement of any point sound source an imaginary symmetrical area is drawn around the centre of the source. Hemisphere and box are the preferred shapes. On this area SPL measurements are made at several points. The emission of the source L_{W} is achieved from the measured SPLs L_p by

$$L_{\text{W}} = L_p + 10\log_{10} S \tag{13}$$

where S is the measurement area and L_p is the average of the measured equivalent SPLs. The equation applies only to continuous sound sources. (Lahti 1997)

Since shooting noise is not continuous and it is strongly directive, the same method cannot be directly used with it. Instead of measuring L_{eq}, L_{E} can be measured to obtain source sound energy level L_E[1]. The strong directivity means that the source energy cannot be described using only one parameter but the directivity pattern needs to be included. Directivity is usually indicated with relative differences of exposure levels at different directions.

4.1.1 Nordtest ACOU 099

The first Nordic shooting range emission measurement method was presented in by Kilde Akustikk AS from Norway in 1984. In the method weapon is placed horizontally at the height of 1.5 m and microphones are placed between 45° angles at maximum 2 cm height from a reflecting panel of 1 x 1 m lying on the ground. The distance from the weapon to the microphones is 10 m so that measurement positions form a circle around the weapon. The ground reflection is assumed to be in coherence with the direct sound and the measured levels are adjusted by -6 dB to obtain free-field values. The measured level quantity is L_{AImax}.

Later the method was updated and published as a Nordtest method NT ACOU 099 2002. The new version differs in a couple of ways from the old one but the principles are the same. The guide of Ympäristöministeriö (YM 1999) includes the exactly same emission measurement method.

The method is defined by the following rules:

1. The measurement site is level and no other reflections than from the ground are included in the measurement period.
2. The weapon is placed horizontally at the height of 1.5 m from the ground.
3. The microphones are positioned 10 m from the muzzle in a semi-circle around the source with 45° spacing. The microphones are placed on a reflecting board (size at least 1 x 1.5 m) on hard ground at least 0.1 m from the edges of the board. The microphone capsule is placed at maximum 0.7 cm above the surface of the board to ensure that the ground reflection is coherent with the direct sound. The microphone axis is perpendicular to the direction to the muzzle[2].
4. The weather conditions shall be dry and wind speed less than 2 m/s at 2 m height.
5. The measurements are analyzed in octave bands from 63 Hz (or 31.5 Hz for LCWs) to 8 kHz. For each octave in all directions L_{Imax} is determined.
6. For octaves below 250 Hz a correction due to I-weighting needs to be done.
7. A correction for nonlinearity is done according to the curve in Fig. 11.
8. The measurement results are arithmetical averages of 10 shots.

---

[1] E in this case stands for energy and not for exposure.

[2] The axis should be the calibrated axis, which is not necessarily the physical axis. E.g. pressure microphones should be placed at 90° angle.

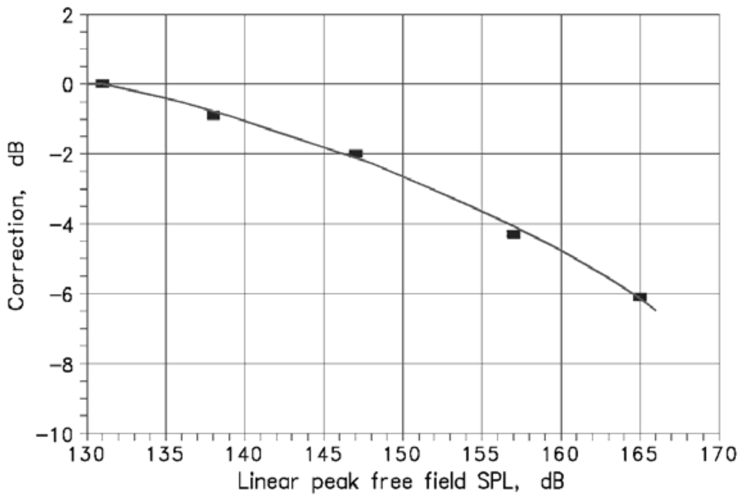

Figure 11. Correction for nonlinear propagation as a function of L_{peak} according to (NT ACOU 099 2002). Curve is a result from faster attenuation of nonlinear propagation of sound pressure compared to what linear propagation predicts.

In the method, fully coherent ground reflection is sought. When the direct sound and reflection are in coherence, a -6 dB correction can be made to all levels. For this to be justified ground impedance needs to be high enough on all frequencies and the phase response must be zero. As was discussed in Sec. 2.2.3, these conditions are not met on porous ground. On porous ground, underestimation of the emission level may occur. The function of the panel is to prevent this.

The function of the sixth rule is to compensate for the short integration time of the I-weighting. The compensation is proposed to be done by first adding silence of 200 ms around the actual waveform. Then the octave filtering can be done so that the whole response of the filter fits into the window. For this window linear equivalent level is measured. Finally L_{Imax} octave level is acquired by adding $10\log_{10}(200/36.4)$ to the equivalent level. This is a rather odd way of making this compensation. A more simple way would be to measure exposure levels in octave bands and add $10\log_{10}(1000/35)$ to obtain L_{Imax}. There is also no explanation why 36.4 ms is used instead of 35 ms (time constant of I-weighting). Though, the difference is only 0.17 dB.

The seventh rule of nonlinear correction is for compensating the faster attenuation of nonlinear propagation compared to linear propagation. The method is following. First, the maximum octave f_0 is found. Second, the amount of correction is read from Fig. 11 for corresponding L_{peak}. Third, the (negative) correction value is added in full to octaves above f_0 and half of the correction value is subtracted from the octaves below f_0. Hence, high frequencies are lowered and low frequencies raised. Unfortunately the original reference of the correction was not available and the correction cannot be assessed.

The method cannot be directly used with LCWs. 10 meter distance is too short since the low frequencies have not developed yet and the sound pressures are in the nonlinear range. The increasing of the distance to 100 meters would solve these problems. However, it would also introduce another problem. Are such big sites with hard reflecting ground available and is the ground hard on the whole frequency range? In the case of SCWs the main frequency range is roughly above 200 Hz but in the case of LCWs it is often below it. It is very optimistic to suggest that such sites were available.

4.1.2 ISO 17201-1

The new shooting noise standard series' first part (ISO/FDIS 17201-1:2005) includes a method for emission measurement of SCWs. The method differs from the Nordtest method in three profound ways:

- Microphone height is 1.5 m from the ground.
- Distance from the muzzle is 10 to 50 m so that peak pressure is below 1 kPa (154 dB).
- L_E is the used level quantity instead of L_{Imax}.

The raised microphone affects the coherence of the direct sound and the ground reflection. The path length difference with raised microphone at 10 m is 0.44 m and the time difference is approximately 1.3 ms. The increased time difference means that the reflection is not coherent and thus -6 dB rule cannot be applied. What results from the out-of-phase reflection is interference. At some frequencies the two waves are constructive but at some frequencies destructive as stated by the superposition rule of waves. In frequency response this can be seen as a comb-filter effect (see Fig. 5).

In the standard, two ways of removing the ground reflection are proposed: gating the reflection or by measuring the ground impedance and removing reflection contribution from the measured levels. Unfortunately, accurate measurement of complex (magnitude and phase) ground impedance is a difficult task especially for incident angles different from 0° as discussed earlier in Sec. 2.2.3. Without an accurate estimate of ground impedance, the interference cannot be accurately modelled and reliable results cannot be obtained. Unfortunately the reflection also arrives so close to the direct sound that it cannot be windowed. If the reflection is violently removed from the signal, low-frequency information is lost too. Thus the reflection is both too far and too close to the direct sound for either of the removal methods to work. If the ISO method is adapted to LCWs by increasing the measurement distance, the ground effect is even more difficult to remove.

The limit of 154 dB is proposed to eliminate the effect of nonlinear attenuation from the measured levels. The limit is contradictory to the correction used in Nordtest method, which is done for sound with L_{peak} already above 130 dB.

4.1.3 Danish method for heavy weapons

A Danish method presented in (Miljøstyrelsen 1997) is intended for LCW emission measurements only. The same method is almost directly adopted in the FDF guide (Jaloniemi et al. 2005). The method is described by the following rules:

1. Measurement site of 300 x 300 m is level and free of obstacles.
2. Microphones are placed at a distance of 100 m from the weapon at 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° angles.
3. Microphone is placed at the height of 1.5 m.
4. Measurement equipment frequency response needs to be within ± 1 dB from 10 Hz to 10 kHz.
5. Weather is dry and wind speed is less than 10 m/s at 2 m height.
6. L_{Cpeak} must not exceed 165 dB and measurement distance must be at least 2-3 times the wavelength of the lowest frequency of interest.
7. L_{peak} is measured in addition to octave-band linear exposure levels L_E from 16 Hz to 8 kHz. The final results are averages of five shots.
8. A reference explosion of TNT is used to compensate for meteorological and ground shape unidealities.
9. Projectile noise levels are measured separately at 3 m height 100 m from the source line. The propagation is calculated according to the theory in G.B. Witham's "The flow pattern of supersonic projectile."

The method has one major deficiency. Sites as big as proposed are rarely ideally reflective on the whole frequency range. The measurement results therefore include the ground effect, which has to be calculated off backwards before source energy level can be achieved. Unfortunately, no better method has been presented for LCWs.

4.2 Immission

Immission measurements are often made alongside with the modelling to verify the results. It is important to note that immission measurement results, although represent the real exposure, are true only in the conditions of the measurement. Normally, the measurements are made in favourable weather in order not to underestimate the situation. Also, propagation models ISO 9613-2 and Nordic General Prediction Method (NGPM) are tweaked for downwind conditions.

Since shooting noise can travel over long distances due to the high emission levels, major differences in measurement results are expected in different weather conditions.

The number of shots that need to be measured depend on the deviation of the single results. No strict limit can be stated but the number should be assessed in situ.

5 PROPAGATION MODELS

This section covers some of the most widely used propagation models that were available during the making of the thesis. The generalized models NGPM and ISO 9613-2 are used in general environmental noise modelling but are applied to shooting noise as well. The more shooting noise specific models are NT ACOU 099, which is designed for propagation of SCW shooting noise with L_{AImax}, Danish FOFTlyd for both SCW and LCW and German WinLARM which is a LCW noise model used by Bundeswehr. In addition one of the most interesting new models is the European Harmonoise. The last three models are summarized only briefly because they were not available for testing.

5.1 Nordic general prediction method

One of the most important and widely used noise propagation models in Finland is the Nordic General Prediction Method (Kragh et al. 1982). The method was published by the Danish Acoustical Laboratory. It was originally designed to be used for industrial noise but later it has been successfully used with other types of noise as well.

The methods used in the model are based on both empirical and theoretical knowledge. The aim has been to match the model with measurements and therefore equations are made to match the empirical observations. NGPM is originally meant to be used with distances of less than 1 km. The limit does not mean that it cannot be used for longer distances but that it has not been tweaked and tested for such situations. At longer than 1 km the accuracy can be less satisfying. The model is an octave band model with centre frequencies from 63 Hz to 8 kHz. Later it has been expanded to 31.5 Hz octave.

In NGPM each source is represented by an equivalent monopole point source with some sound power level. In addition the source can have horizontal directivity. Vertical directivity is assumed to be zero. NGPM is a point-to-point prediction method meaning that each source-receiver pair transmission path is calculated separately. The path attenuation is approximated with six components: divergence, air absorption, reflections, screening, vegetation and ground effect. All the correction terms are added together to get the total attenuation. Total attenuation is finally subtracted from the source power level to get the approximation of the immission point SPL

$$L_p = L_{\mathrm{W}}(\phi) + \Delta L_{\mathrm{d}} + \Delta L_{\mathrm{a}} + \Delta L_{\mathrm{r}} + \Delta L_{\mathrm{s}} + \Delta L_{\mathrm{v}} + \Delta L_{\mathrm{g}} \qquad (14)$$

where L_p is the SPL in the immission point, $L_{\mathrm{W}}(\phi)$ is the source power level as a function of the azimuth angle ϕ, ΔL_{d} is the correction term for divergence, ΔL_{a} for air absorption, ΔL_{r} for lateral reflections, ΔL_{s} for screening, ΔL_{v} for vegetation and ΔL_{g} for ground effect.

In NGPM only one meteorological condition is modelled. The method is fitted to meet the measurement results when there is a moderate downwind (about 3 m/s) or slight temperature inversion. Also, the moderate downwind is always directing away from the source. I.e. a noise map describes a situation that cannot be true at different locations at the same time. Because sound propagates well on such conditions, the estimate is close to "worst-case" situation.

Attenuation due to geometrical spreading is calculated directly according to Eq. (8) and air absorption according to the same coefficients as presented in (ISO 9613-1:1993). Correction for vegetation is of empirical nature. For vegetation to be considered, the top of the dense vegetation needs to be at least 1 m above the curved transmission path. Vegetation is considered dense, if it is impossible to see through. Vegetation is treated in groups and in the case of dense forest, each 50 m of the forest is one group. Maximum number of groups is four (200 m of forest). ΔL_v is given by

$$\Delta L_a = -n_V \alpha_V \qquad (15)$$

where n_v is the number of groups and α_v is the attenuation coefficient. The coefficients are acquired from empirical data and the model predicts the overall attenuation due to both absorption and scattering. It does not, however, model the spreading in time but only the attenuation of sound energy.

In the method lateral reflections are treated using simple mirror image considerations. Reflection from an obstacle is calculated using a mirror source image with the same or different transmission path as the direct path. If different, mirror image transmission path is calculated equally as the direct transmission path expect that it is weighted by an (energy) reflection coefficient of the surface of the reflecting obstacle. If the transmission paths are assumed to be equal, the reflection amplification ΔL_r is given by

$$\Delta L_r = 10 \log_{10}(1+\rho) \qquad (16)$$

where ρ is the reflection coefficient. The reflection correction does not model interference or scattering in any way and frequency-dependence of reflection coefficient is also ignored.

In NGPM, ground reflection is modelled separately from other reflections. In the method ground is treated as hard, porous or partly porous. The ground is divided into three parts: source, receiver and middle part. For each part, ground effect is calculated separately using equations that are fitted to meet the immission measurements made on flat terrain. Adaptation to hilly terrain is also included in the method but it has not been verified by measurements by the developers. The method simplifies the interference effect strongly and it is impossible to say without testing whether it models it reasonably well or not.

Screening due to noise barriers, buildings and terrain profile is estimated using both empirical and theoretical methods. Each screen is represented using one or at maximum two regular-shaped thin screens. The conditions for the barrier that need to be fulfilled before the screening effect is taken into account are:

- The mass should exceed 10 kg/m^2.
- There should be no holes or openings.

- Horizontal dimension component should be greater than the wavelength.

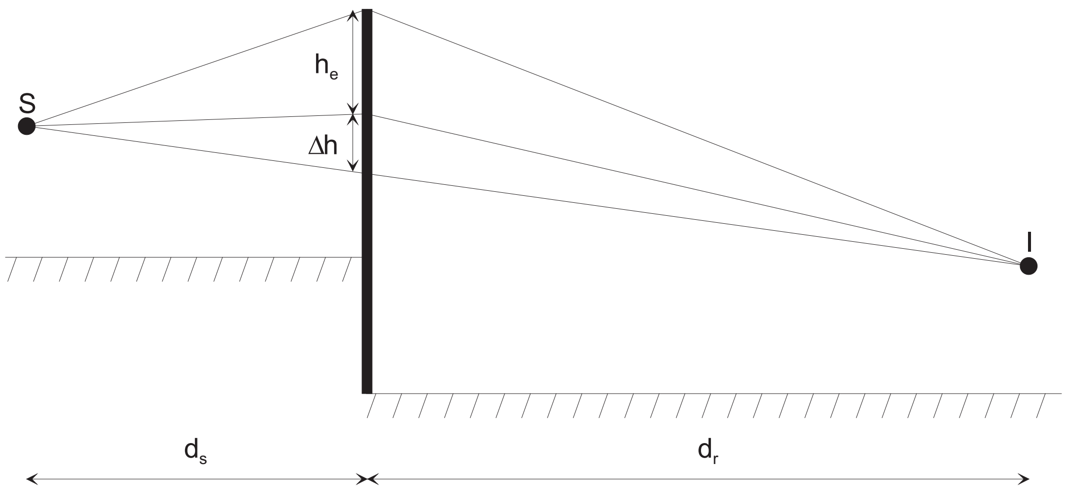

Figure 12. Effective height of a barrier due to refracted propagation path in downwind and/or positive temperature gradient conditions. S is the source point, I is the immission point, h_e is the effective height of the barrier, Δh is the height difference of direct and curved propagation paths and d_s and d_r are the distances of the source and immission point to the barrier in horizontal plane, respectively.

In NGPM the effective height of the screen h_e, the distance to the source d_s and to the receiver d_r are used to calculate the magnitude of the screening. It is important to note that the effective height of the screen is affected due to the assumed downwind conditions (see Fig. 12). The favourable conditions make the sound propagation path curved. In NGPM the curved path height at the barrier is approximated using

$$\Delta h = \frac{d_s d_r}{16 \cdot d} \tag{17}$$

where d is d_s+d_r.

The effective height of the screen is the screen height from the curved path height in the cross-section of the screen. With the use of effective height, difference of the transmission path lengths of the screened and direct sound can be estimated. The magnitude of diffraction can finally be estimated from the path difference as a function of frequency. Diffraction is calculated using Fresnel numbers (see Sec. 2.2.6). Also horizontal diffraction is estimated using the same algorithms. Lateral and horizontal diffraction are summed on energy basis to get the final correction term ΔL_s.

For more than one screen, a choice of the two most effective single screens takes place. In short terms, first chosen screen is the one having steepest elevation angle from the source and the second from the immission point of view. For the chosen screens, the normal one-screen attenuation is calculated assuming it to be the only screen present. For the second screen, though, source height is assumed to be the height of the first screen. The two terms are summed to get the total attenuation. The case of multiple screens is of speculative nature and its validity has not been verified by measurements.

As can be summarized from the different corrections, NGPM is designed to estimate the propagation of energy mean values, L_{eq} to be specific. Scattering and other physical phenomena affecting the signal in the time domain are ignored and only propagation of energy is modelled. Therefore scattering cannot be estimated with the model. In the model signal energy is treated as a unity. Also coherence and interference are modelled only partially in the correction terms, in ground effect to be precise.

The precision of the model should be in the order of 5 to 10 dB for a single source close to the ground radiating narrowband noise. For groups of broadband sources at distances less than 500 m, the precision should be 1 to 3 dB. High values are expected for immission points close to the ground and far from the source.

5.2 ISO 9613-2

In ISO 9613-2:1996 the attenuation coefficients are very similar to the NGPM. The ISO model is also a point-to-point model where source power level L_W, directivity and attenuation are considered to obtain the level at the receiver point. It has also the same frequency range and resolution octave bands with nominal centre frequencies from 63 Hz to 8 kHz. Meteorological conditions for which the model is fitted are at least 45° downwind of 1-5 m/s at height 3-11 m above the ground or moderate temperature inversion.

The ISO model incorporates generally the same correction terms as the NGPM. Terms for divergence, ground effect and reflections are equal. Atmospheric absorption is also equal with one exception. The absorption coefficients (which are tabled in one-third-octave bands) for particular octave band is chosen by the centre one-third-octave band instead of the lowest one-third-octave band of the octave. By contrast in the NGPM the lowest one-third-octave band is chosen. Correction for vegetation is also empirical in the ISO model but the coefficients are somewhat bigger and the correction is per meter rather than per group as is in NGPM.

The ISO model differs from the NGPM mainly in the screening correction estimation. For one screen the amount of diffraction is calculated using the same principles. Where ISO differs from NGPM are the calculations of the effective height. Where as in NGPM a curved propagation path is considered in calculation of the path length difference, in ISO it is treated as a different correction factor K_{met}. The text in ISO is ambiguous and background for certain terms is not explained. In the case of multiple screens, calculations are also done for only the two most effective screens as in NGPM. In ISO model the screen correction removes the ground effect.

In addition to corrections in NGPM, ISO incorporates meteorological correction for long-term average levels and housing correction for areas with many buildings. The latter correction tries to estimate the extensive reflections and screens that cannot be estimated with screening and reflection corrections but are rather complex.

The precision of the ISO model is stated to be ± 3 dB for distances up to 1 km. For this accuracy, optimum meteorological conditions are assumed. Accuracy at further than 1 km is not discussed in the standard. Such distances are still very important in shooting noise, or at least with heavy weapons.

5.3 Nordtest ACOU 099

The first Nordic shooting noise prediction model was published in 1984 by Kilde Akustikk AS. The propagation part is based on NGPM. The calculation is done using spectral terms and not real spectra. The method was tested by Valtion Teknillinen Tutkimuskeskus (VTT) in 1984 and noted to be fairly inaccurate (Saario 1984). In 1995 the shooting noise model was revised by Delta Acoustics & Vibration. The revision was published in 2002 as a Nordtest method (NT ACOU 099 2002). The method is designed for SCWs and shooting ranges.

The NT method has only few differences to NGPM. In the NT method downwind and summer conditions are assumed and calculations are made in octave bands as in NGPM. The frequency range is from 31.5 Hz to 8 kHz. The main difference is that the NT method is adjusted for predicting L_{AImax} and not L_{Aeq}. Because the maximum level attenuates more rapidly than energy level due to scattering, new correction has been included in the model. In the NT method the difference to NGPM is included in the correction of vegetation ΔL_{V}. It is calculated with

$$\Delta L_{\mathrm{v}} = -d_{\mathrm{v}} \frac{(4\alpha_{\mathrm{v}} + 5)}{200} \tag{18}$$

where d_{v} is the length that the curved propagation path penetrates the vegetation. The maximum value for d_{v} is 200. It seems like Eq. (18) is adjusted so that the calculations would match the measurements. Although scattering happens also due to turbulence and other objects, only scattering due to vegetation is taken into account. Also the maximum amount of vegetation, 200 m, does not seem to have any factual background.

Other differences to NGPM are the empirical shooting hall and firing shed corrections and the choice in multiple screen situations. In the NT method two or more terrain screens are not normally considered as multiple screens but the most effective ones as the single one. Only if one screen is less than 50 m from the source and the most effective terrain screen is further away, the screen attenuations are summed as in NGPM. In other multiple screen scenarios only one screen is included in the screening correction term.

Another big difference to NGPM is the inclusion of bullet noise. It is treated as a separate component of shooting noise and the source level is calculated based on the physical theories presented in (Pierce 1981). The attenuation is estimated using the same algorithms as for muzzle with the exception of divergence which is

$$\Delta L_{\mathrm{d}} = -10\log_{10}(4\pi r^{5/4}) \tag{19}$$

This means that sonic boom of a bullet attenuates slower than a point source but faster than a line source. As discussed in Sec. 2.1.2, $r^{5/4}$ is the attenuation term for projectile noise energy.

In NT ACOU 099 the maximum of muzzle, bullet noise and reflections is chosen as the final result. In the method, when significant screening or vegetation is on the propagation path, 5-6 dB bigger values to measurements are expected. This accuracy applies for measurements made on relatively short distances.

5.4 ISO 17201-3

In the new ISO standard draft (ISO/CD 17201-3:2003) for shooting noise, propagation is advised to be calculated according to (ISO 9613-2:1996). The model is simply applied to shooting noise by substituting the source power level L_{W} with the source energy level L_{Q}.

Only two adjustments to the model are advised. Ground effect should be calculated according to an alternative method presented in the ISO 9613-2 model, which applies to the following conditions:

- "only the A-weighted SPL at the receiver position is of interest
- the sound propagation occurs over porous ground or mixed ground most of which is porous
- the sound is not a pure tone."

There are no references or justifications for the alternative calculation.

The ISO model is based on night-time measurements, which is a favourable condition for sound propagation. In the draft is emphasized that the ISO model leads to an underestimation of the barrier effect because of the overestimated propagation path curvature.

5.5 Harmonoise

The new Harmonoise model (Nota et al. 2005) is an attempt to unify noise modelling and mapping in Europe. The model is a generic model with source and propagation separated. Though, it has been designed to be used with traffic and railroad noise. The validation to other industrial and aviation noise is made by project Imagine but the project has not concluded yet.

Harmonoise is based on the Nord2000 traffic noise model. Harmonoise incorporates two different models: reference and engineering method. Reference method is aimed at geometrically simple but physically complex situations, e.g. nonlinear wind speed profile near a barrier edge. The reference method is designed for validating the engineering method. The engineering method does not model the details as accurately but rather can be used for larger areas due to the decreased complexity and faster calculations. The engineering method is one-third-octave band model from 25 Hz to 10 kHz.

One of the main priorities of Harmonoise has been the implementation of a broad range of meteorological classes. In the final version, 25 combinations of wind speed and stability classes are included. Also the different correction terms are more detailed compared with older models and they have been validated with 1500 measurements. The precision should be 5 dB for distances up to 2000 m although only measurements up to 1200 m were made in the validation process. The limited distance is clearly a shortcoming in modelling LCW shooting noise as in the Nordic and ISO models.

5.6 Other models

In addition to the models above, few not so well-known models seem to be interesting as well. One of them is WinLARM, which has been designed by Institut für Lärmschutz for the use by Bundeswehr. It uses L_{CE} measured at 250 m as the input data and it is intended for LCWs (Pääkkönen et al. 2001). Unfortunately not much information of the model is freely available and no report of validation could be found.

FOFTlyd is a Danish octave band model based on NGPM. In the model, 16 and 31.5 Hz octaves have been added. Also a linear 0.8 dB/km correction term and projectile noise have been included to match the measurement results better. It is used for both LCW and SCW noise. (Andersen 1998)

6 SIMULATIONS

In this section, the most important aspects of emission measurement and propagation are simulated using a piece of software that calculates theoretical transfer functions of the environment. Simulations are made in order to point out the things that need to be considered when methods are applied in practice. The section begins by a brief description how the direct sound used as an input signal for the transfer functions was acquired.

6.1 Estimation of the direct sound

In the simulations, recordings of muzzle blasts of 7.62 mm assault rifle are used (see Appendix A for complete measurement description). An example of one such a waveform measured using ISO/FDIS 17201-1:2005 method is presented in Fig. 13. The measurement direction was 90°. From the waveform can be seen that the duration of the first positive phase is less than 0.5 ms and that the reflection arrives less than 2 ms after the direct sound. Although both waveforms are distinctive, direct sound cannot be windowed without losing low-frequency information.

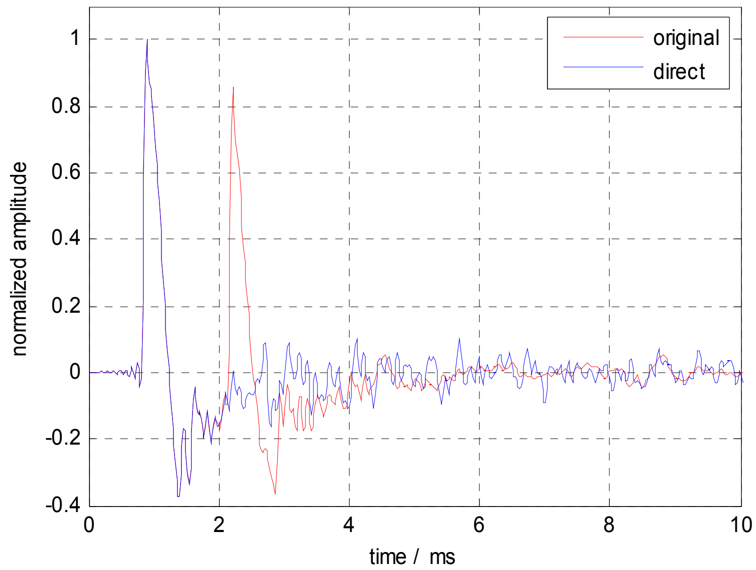

Figure 13. Measured waveform of 7.62 mm assault rifle muzzle blast at 90° azimuth angle at height 1.5 m (red line). The blue line is the direct sound acquired from the original signal by deconvolution. From 0 to 2 ms the waves are identical.

For simulation purposes, direct sound unaffected by the environment is needed. Unfortunately, no such measurement data is available and therefore a different approach is taken. If the surface is assumed to be ideally hard and the reflection to have zero phase shift, the reflection can be removed using deconvolution. Deconvolution is the inverse operation of convolution given by

$$y(t) = h(t) \otimes x(t) \qquad (20)$$

In this case, *y(t)* is the measured signal, *h(t)* the impulse response (IR) of the system and *x(t)* the wanted source signal. By deconvolving system's theoretical impulse response (IR) from the measured signal, approximation of the direct sound is acquired. In this case, the direct sound was acquired by deconvolving a sequence from the measured signal. The deconvolved sequence was a vector of +1, 62 zeros and +0.85. The first digit represents the direct sound, the zeros represent the time difference of arrival of the reflection and the last represent the somewhat attenuated reflection.

Equal attempt was made with LCW measurements made at 100 m distance on soft ground (see Fig. 14 as an example). Unfortunately, the environment could not be made as ideal as in the case of SCW measurements. The longer distance and the unideal ground make the deconvolution method too unreliable. Therefore, LCW emission measurement properties are simulated without an input signal. The different scenarios are simulated using only the magnitude responses of the environment.

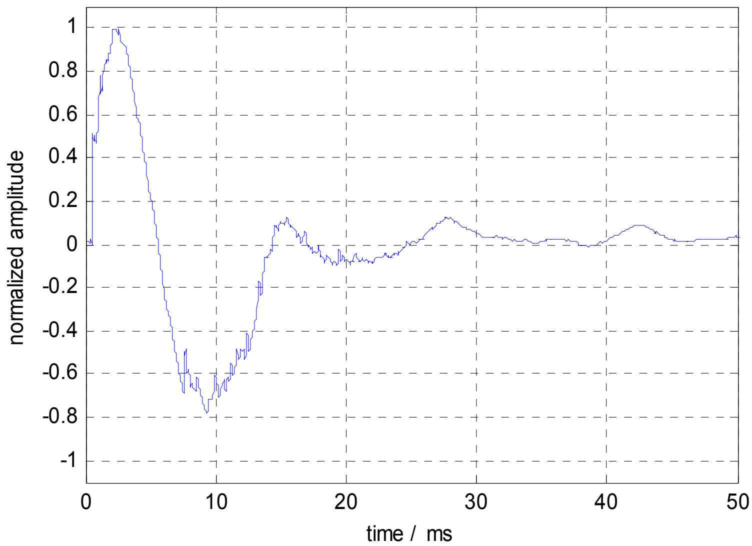

Figure 14. Measured waveform of 122 mm howitzer muzzle blast at 100 m on porous ground. The waveform comprises direct sound and reflection with a time difference of about 0.4 ms but they are not distinguished.

6.2 Emission measurement methods

6.2.1 Small-calibre weapons

Emission measurements of SCWs are simulated using four different configurations, which correspond to NT ACOU 099 and ISO/FDIS 17201-1:2005 methods on two different grounds. The ground effect is simulated using a computer program presented in (Lahti 2001). The program is designed to calculate theoretical complex transfer functions for different ground and weather types. For SCW simulations, wind speed, turbulence and air absorption are neglected. They were tested to not have notable influence on the results at 10 m distance.

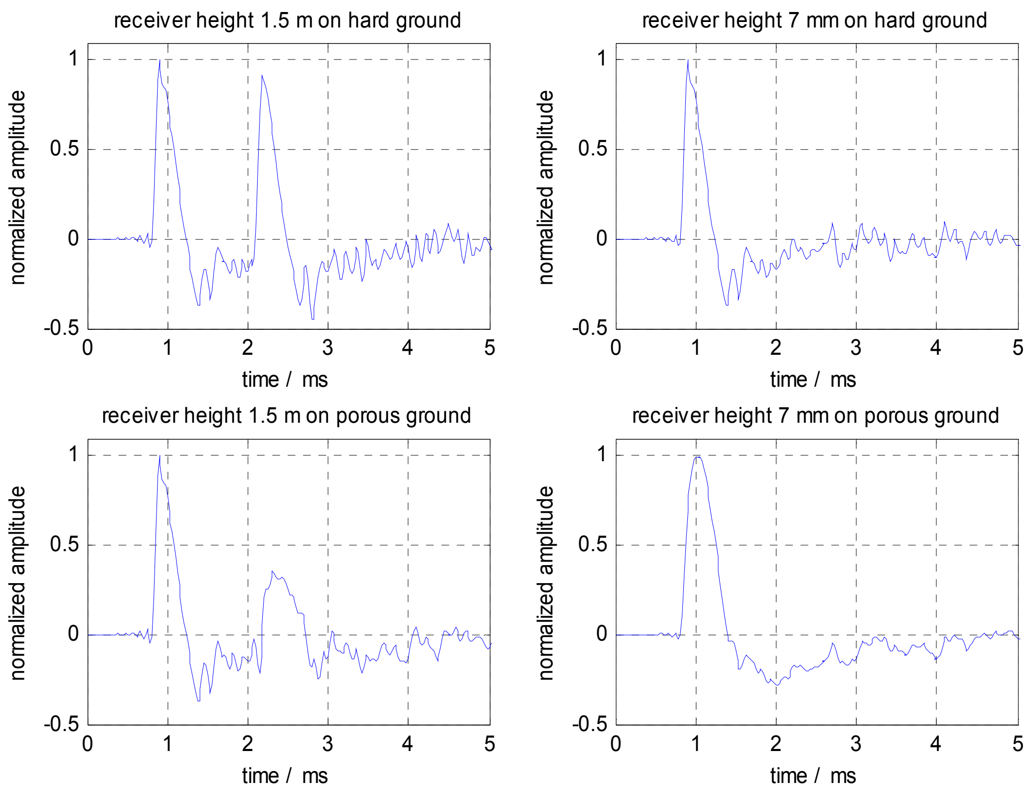

Figure 15. Simulated waveforms of 7.62 mm assault rifle muzzle blasts at 10 m distances at receiver heights of 1.5 m and 7 mm on hard and porous grounds. The source height is 1.5 m in all the cases. The 1.5 m and 7 mm receiver heights correspond to NT ACOU 099 and ISO/FDIS 17021-1:2005 methods, respectively.

The simulation results are presented as waveforms in Fig. 15. Three interesting observations from the waveforms can be made:

- At receiver height of 1.5 m, the direct sound is not attenuated to zero before the arrival of the reflection. The low-frequency information of the direct sound overlaps the beginning of the reflection.

- On hard ground at receiver height of 7 mm, the reflection is well in coherence with the direct sound.
- On porous ground, the reflection is spread and attenuated at both receiver heights. It is a result from non-zero phase response of the porous ground.

The spectra of ground attenuation are presented in Fig. 16 in one-third-octave bands. Observations from the spectra are:

- At receiver height of 1.5 m, the interference minima and maxima are shifted to lower frequencies on porous ground compared to hard ground. Also the interferences are not as predominating as on the hard ground.
- At receiver height of 7 mm, the difference between the hard and porous ground smoothly increases as a function of the frequency.

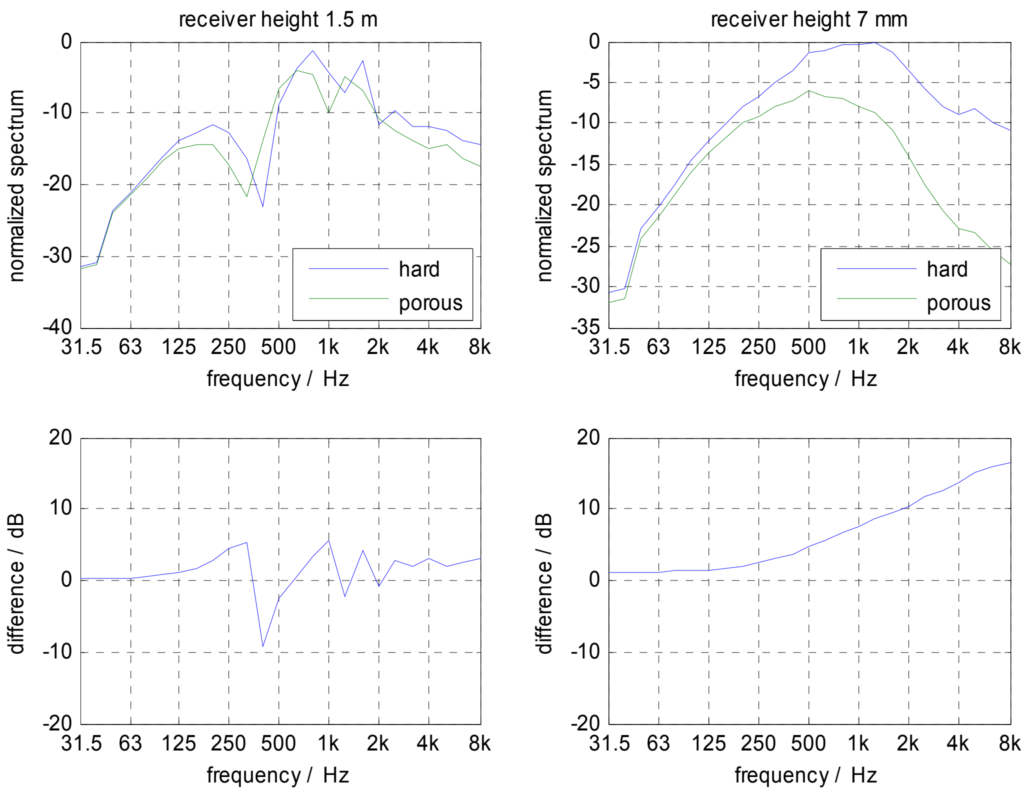

Figure 16. Simulated spectra of muzzle blasts at 10 m at receiver heights of 1.5 m and 7 mm on hard and porous grounds. All the spectra are normalized to the maximum one-third-octave level of all the spectra. The bottom subfigures are the corresponding differences of the ground types. The spectra are calculated in one-third-octave bands.

Note that all the grounds are assumed to be homogeneous. This means that a reflecting board required in (NT ACOU 099 2002) is not included in the simulation results. The effectiveness of the panel is tested in Sec. 7.2 using measurement data.

6.2.2 Large-calibre weapons

In the case of LCWs, the longer measurement distance inflicts new problems to the measurement. The shortened time difference between the direct sound and the reflection makes it impossible to window them. Also, such a large area with ideal hard ground on the whole frequency range is not feasible. Therefore the measurements need to be made on porous ground. In all the following simulations, porous ground and 2.5 m source height are used. In addition air absorption according to (ISO 9613-1:1993) is included.

In Fig. 17, the effect of receiver height on frequency response is presented. At 2 m receiver height, the first interference minimum is centred at 350 Hz and it is several one-third-octaves wide. By upraising the receiver height to 5 and 10 m, interference minima narrow and shift to lower frequencies. Unfortunately, even 10 m receiver height does not solve the problem fully. The upraising of the source would help in this but normally this is not feasible. Shortening of the measurement distance would also have the same result. The downside of this is the risk of closing to the nonlinear propagation zone. Still, the interference is unwanted, when free-field level is sought.

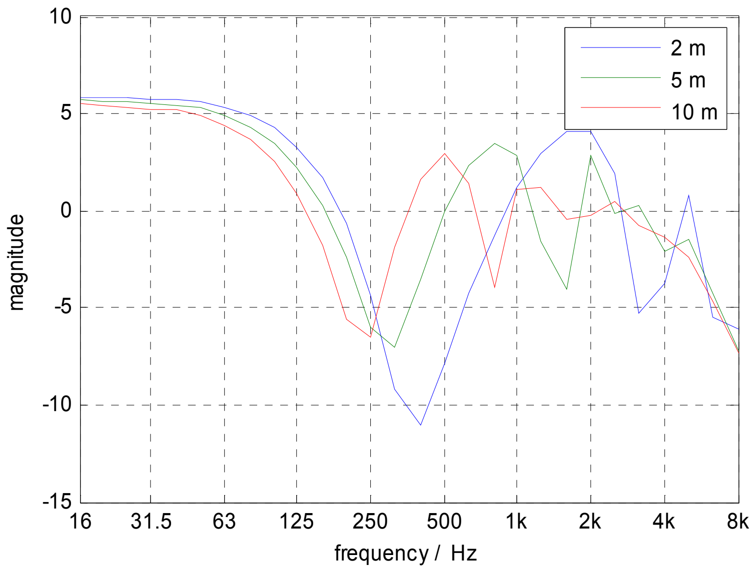

Figure 17. Simulated effect of receiver height on magnitude response at 100 m on porous ground calculated in one-third-octave bands. Source height is 2.5 m in all cases. Increment of receiver height narrows and shifts the interference minima.

With 100 m distance, the wind begins to have some influence on the travelling sound. From Fig. 18**Figure 17** can be seen that downwind has a minor effect on the ground magnitude response. The first interference minimum at about 400 Hz does not change considerably. This is because the downwind refracts the sound propagation path downwards and the ground effect stays as it was without wind. Headwind has a different effect. It refracts the path upwards and inflicts smaller incident angle toward ground. This flattens the magnitude response and the comb-filter effect weakens. The program has been noted to overestimate the effects of wind gradient compared to measurements. Therefore the simulation results should be interpreted only as rough estimates demonstrating the general effects.

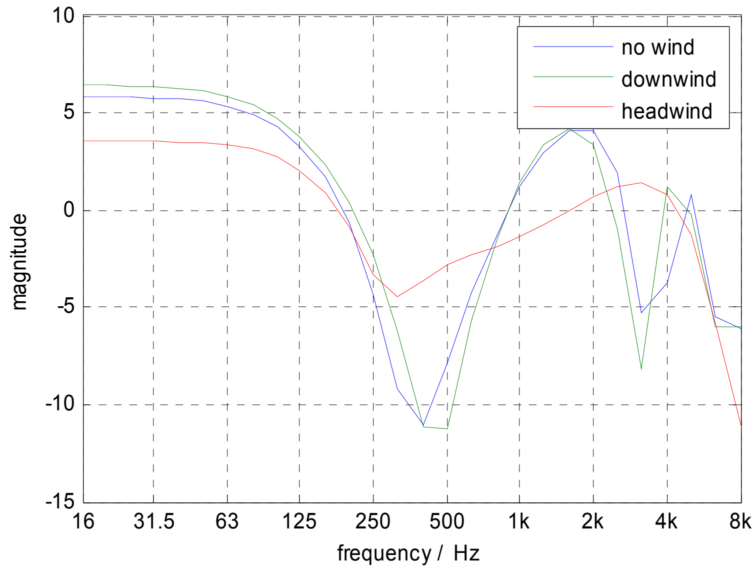

Figure 18. Simulated effect of wind on frequency response at 100 m on porous ground calculated in one-third-octave bands. Source height is 2.5 m. Downwind does not affect the results significantly but headwind flattens the magnitude response.

6.3 Propagation effects

Distance affects the ground effect substantially. In Fig. 19, SCW muzzle blast propagation over porous ground is simulated at three distances. At 10 m, the reflection is still distinctive and in-phase with the direct sound. At 100 m as the time difference shortens, the reflection begins to overlap with the direct sound. The ground also has non-constant phase response that almost shifts the low-frequency phase by 180°. This can be seen as a negative pulse arriving after the positive phase.

At 500 m, the time difference begins to be so short that it looks like the direct sound would shorten in time. This is because the negative reflection pulse overlaps the positive direct pulse. In reality, scattering predominates over this effect by randomizing phases and amplitudes. Therefore the 500 m distance simulation result is not obtainable by a measurement. In contradiction the scattering affects the pulse by spreading it in time.

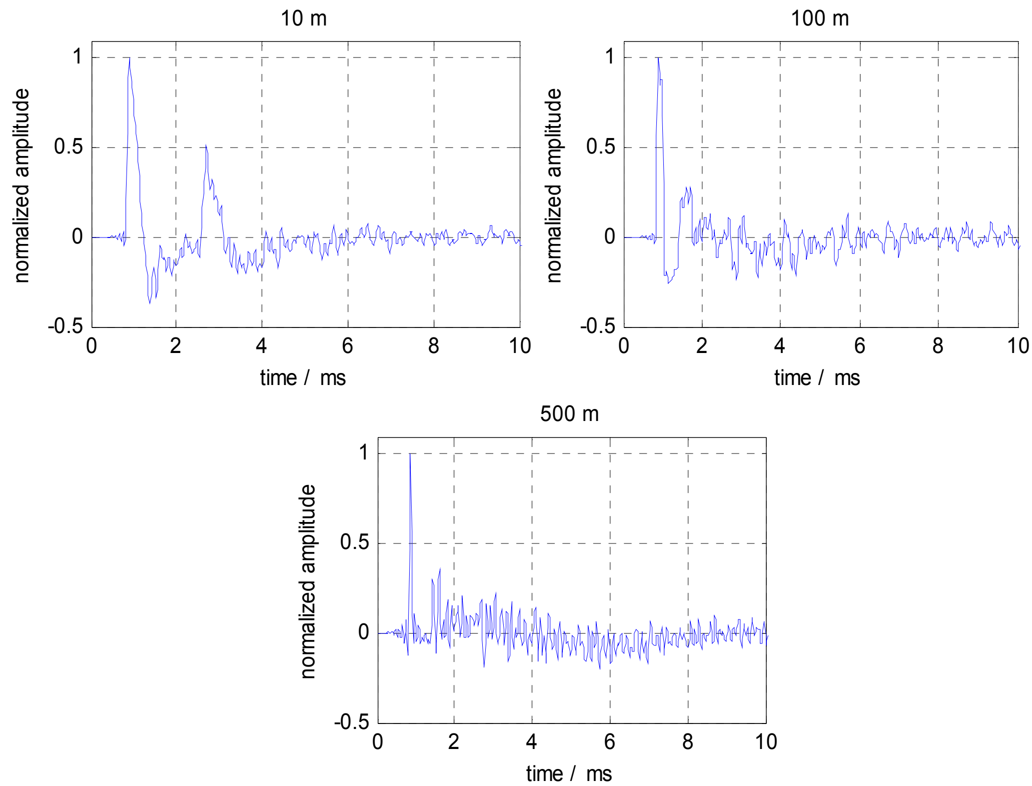

Figure 19. Simulated waveforms of 7.62 mm assault rifle muzzle blast on porous ground at 10 m, 100 m and 500 m distances. Source height is 1.5 m and receiver height 2 m. The differences result from phase-shifted ground reflections.

In Fig. 20, spectra of the above configurations are presented. At 500 m, the ground effect is strong at low frequencies. Approximately 40 dB attenuation at 400 Hz would be even more significant for LCW noise. Air absorption attenuates the spectra above 2 kHz.

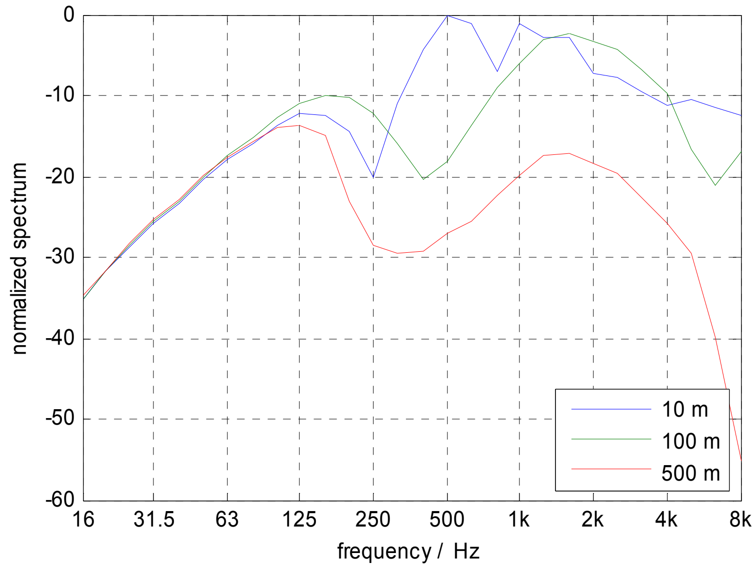

Figure 20. Simulated spectra of 7.62 mm assault rifle muzzle blast on porous ground at 10 m, 100 m and 500 m distances calculated in one-third-octave bands. Source height is 1.5 m and receiver height 2 m.

Since shooting noise can propagate longer distances than other noise types, it is beneficial to see what happens when the terrain shape changes. Hills etc. can be even the most important effect on propagation. This applies in both modelling and practice situations. In propagation models multiple hills and barriers are simplified by taking only the two most prominent screens into account. Therefore it is of interest to test what happens with propagation models in long distances.

The terrain shape effect is simulated using NGPM and the ISO 9613-2 propagation model. The two models were tested to produce almost the same results without a barrier. The only difference without barrier is in the calculation of air absorption. NGPM calculates the air absorption using the value of the lowest one-third-octave band where as ISO calculates using the middle one-third-octave band as a substitute for the octave-band value.

The configurations of the simulations of barriers imitating terrain shape are kept simple. Terrain shape is simulated with one and two thin parallel barriers on otherwise flat ground. Both of the cases are simulated at four distances. The barrier height is increased together with the distance. The results for attenuation due to one barrier in the middle (e.g. a hill in the middle) are plotted in Fig. 21 and for two barriers (two hills) in Fig. 22. The following observations can be made from the figures:

- The spectrum shapes are similar between the two models, but the magnitudes are rather different. At maximum 20 dB differences are found. The differences are substantial already at relatively short distances.
- With two barriers, NGPM results in about 5-10 dB stronger attenuation than

ISO on the whole frequency range.

- NGPM takes into account the ground effect above 125 Hz in all configurations. The octaves above are on average 3 dB more attenuated on porous ground compared to hard ground.
- ISO does not model the difference in porous and hard grounds with existing barrier. In only one case such a difference was observed.

In conclusion, it is very hard to say which of the methods models the barrier effect more accurately since no real situation measurement results were available. The differences between the models in the presence of one or more barriers are not totally consistent and many different properties seem to affect the results. The most important reason is probably in the calculation of the refracted path height.

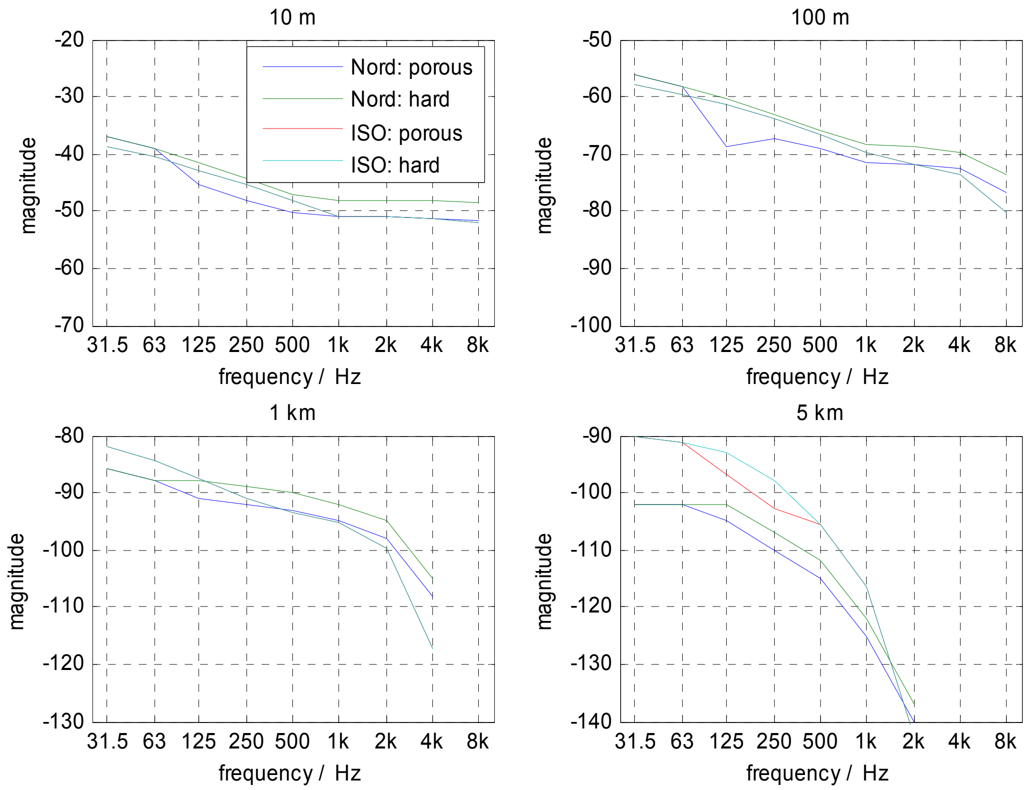

Figure 21. Simulated attenuation due to diffraction from one barrier using NGPM and ISO 9613-2 propagation model at 10 m, 100 m, 1 km and 5 km distances. ISO model on porous ground (the red line) is equal to ISO model on hard ground where red line does not exist. The barriers were situated in the middle of the source and receiver locations and their heights were 3, 10, 100 and 500 m, respectively.

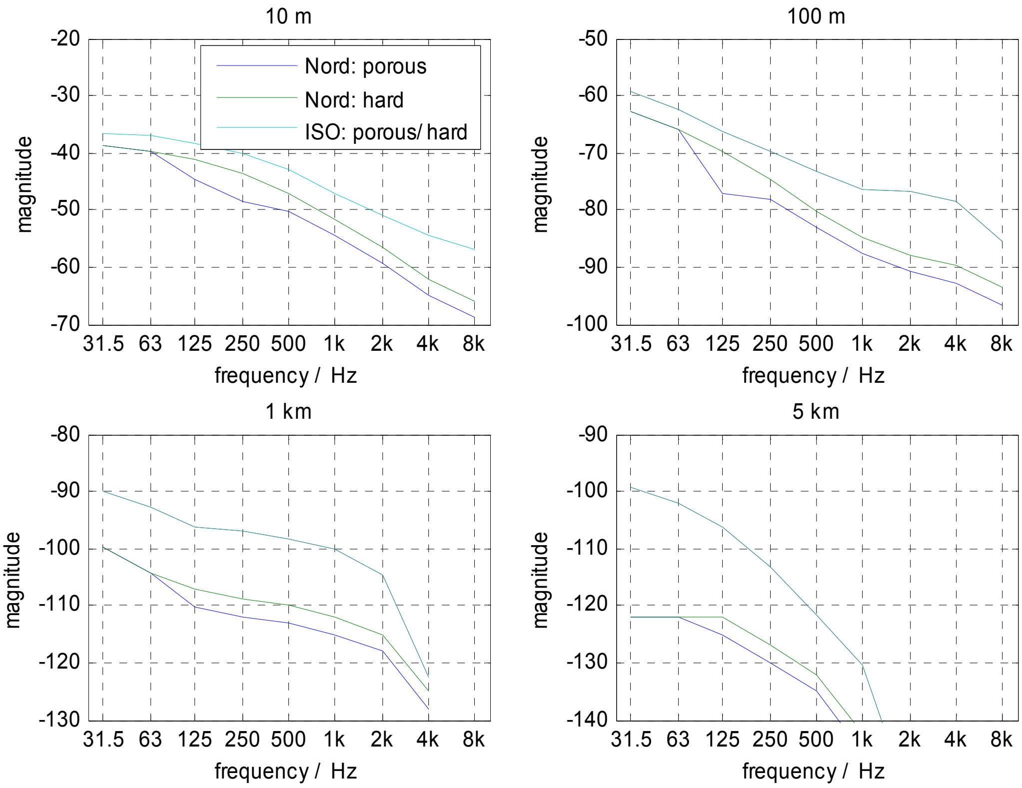

Figure 22. Simulated attenuation due to diffraction from two barriers using NGPM and ISO 9613-2 propagation model at 10 m, 100 m, 1 km and 5 km distances. ISO model on porous ground is equal to ISO model on hard ground and thus only one data line is plotted. The barriers were situated in one/thirds of the distances and their heights were 3, 10, 100 and 500 m, respectively.

6.4 Discussion

In the case of SCWs, the simulations showed that the ISO/FDIS 17201-2:2005 emission measurement method is not reliable due to the uncontrolled ground reflection and resulting interference. The Nordtest method is a more accurate method because a fully coherent reflection is obtained on a hard ground when the microphone is placed on the ground. However, the method cannot be applied accurately on a porous surface because it does not produce coherent reflections in the whole frequency range. On a hard ground a -6 dB adjustment can be made to obtain a free-field value.

With LCWs the measurement distance needs to be increased. A new difficulty compared to SCWs is that no hard reflecting grounds over such large areas are to be found which would produce coherent reflection in the whole frequency range. Therefore, the method of placing a microphone close to the ground cannot be applied in practice. Because the relative time difference is even shorter with increasing distance, the interference cannot be avoided. By somewhat increasing the microphone height a weaker interference can be achieved, though.

A mild wind does not affect the measurements made at the 10 m distance but it does affect at 100 m. Downwind does not affect the comb-filter effect much but headwind flattens the spectrum.

When the distance is increased (to simulate propagation to an immission position), the ground reflection with more or less inverse phase arrives almost at the same time with the direct sound. In theory this means that the measured pulse is shorter. In practice, other effects prevail and such ideal situations do not occur. The increased distance also increases the magnitude of the ground effect which can be seen from the spectra.

The attenuation effect of a barrier (e.g. terrain shape, building, noise barrier etc.) was tested using the ISO 9613-2 and Nordic propagation models. The two models produce propagation responses with similar shapes but with different magnitudes. The differences are hard to explain as they do not vary consistently. It is even harder to give any opinions about which of the models predict the attenuation more accurately since no measurement results were available.

7 MEASUREMENTS

In this section, field measurement data of four different FDF shooting ranges and areas is used for investigating both measurement and modelling functionalities. Emission measurement methods and bullet noise are investigated based on the measurements made at a test shooting site. The used SCW emission measurements are described in full in Appendix A. The main focus is on the emission measurement methods and on the propagation model applicability. The section begins with a test of the octave filtering effects on different level quantities.

7.1 Spectral analysis in octave bands

In the case of shooting noise, it is beneficial to examine the effects of octave filtering on the waveform. Because the signal is very short and impulsive, it is not clear how the waveform and different level values are affected by the filtering. The effects are studied using measured muzzle blasts of a 7.62 mm assault rifle as an input to analogue octave filter set[1]. The input waveform example is presented in Fig. 23. Its first positive phase length is about 0.5 ms.

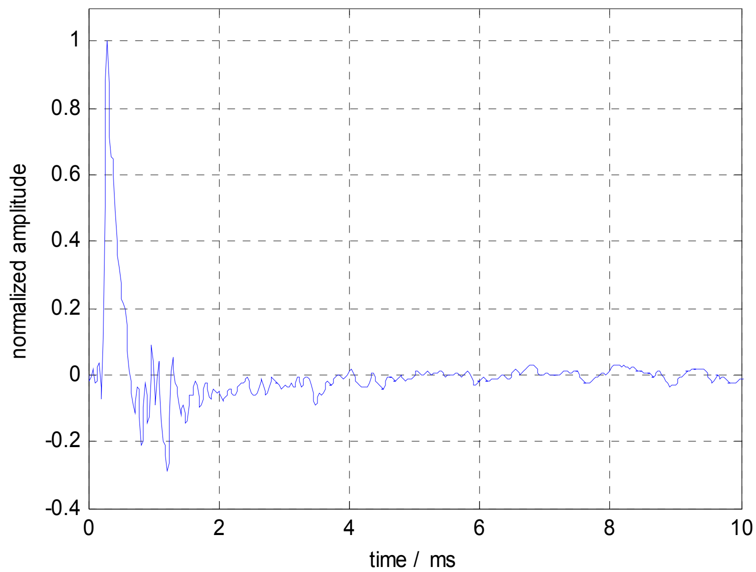

Figure 23. Measured muzzle blast waveform of a 7.62 mm assault rifle at 10 m distance. The signal is used as an input signal for the octave filter analysis.

Two of the filtered waveforms are presented in Fig. 24. The output of a 31.5 Hz

[1] Bruel & Kjær (B&K) type 1624 octave filter

octave filter is almost equal to that of the IR of the filter itself because filter's IR is significantly longer than the input signal itself. Thus, the input signal acts as an almost ideal Dirac delta function exciting the filter and convolution produces a signal almost the same as the filter's IR.

By filtering the same shot with a 4 kHz octave filter, the output waveform is different. The IR of the filter is shorter than the shot's first pulse. As a result, the input signal is long enough to produce several smaller but similar shaped waveforms to the output. Hence, the strongest peak of the input leaks into several smaller peaks.

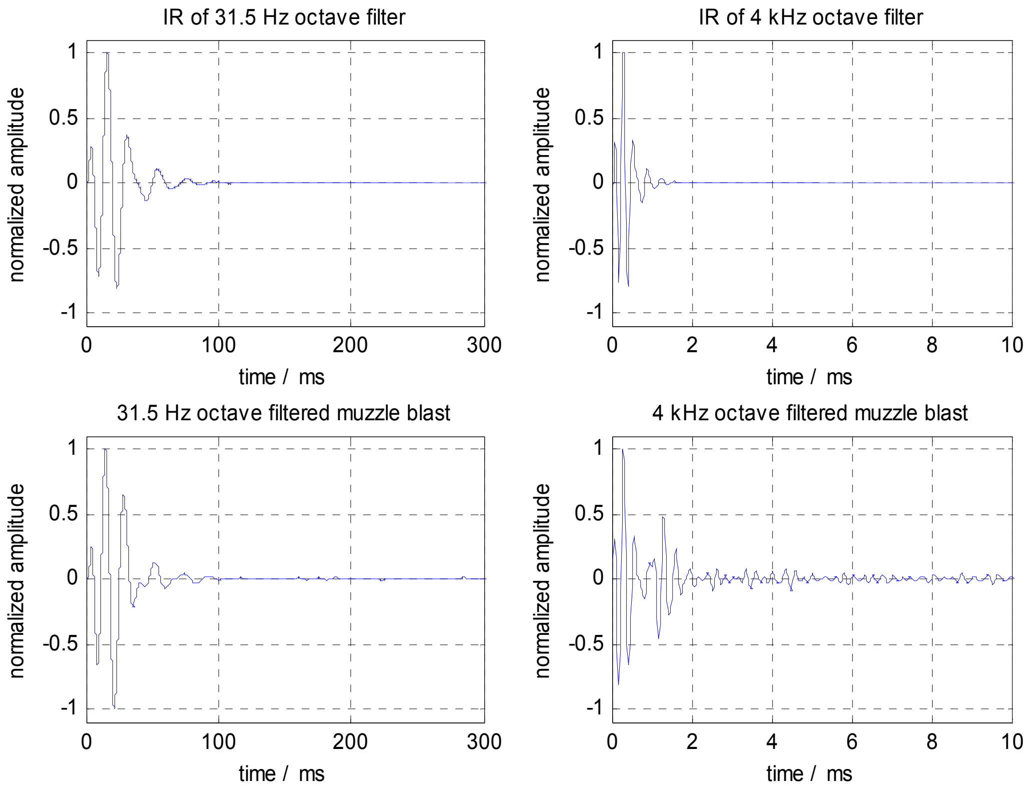

Figure 24. Impulse responses of 31.5 Hz (top left) and 4 kHz (top right) octave filters and corresponding outputs (bottom) for muzzle blast of a 7.62 mm assault rifle muzzle blast (see Fig. 23).

When filtering is done with octave filters from 31.5 Hz to 8 kHz, interesting results occur. In Fig. 25, the spectrum of peak octave levels is presented together with exposure levels and I-weighted maximum levels. All the spectra are individually normalized to 0 dB in order to emphasize the spectral differences in relation to each other. From the figure can be noted that peak spectrum shape is rather different to those of exposure and I-weighted spectra shapes. Peak levels at high frequencies are much lower. This is due to the leakage presented in Fig 23. No such leakage occurs with L_E, which integrates over a longer period of time. Also I-weighting integration time of 35 ms is long enough to not produce leakage at high-frequency range.

One problem with I-weighting is that at 250 Hz and below I-weighting's integration time, 35 ms, is not long enough to integrate all the energy of the filtered signal. This problem can be corrected using L_E as an intermediate level for acquiring L_{Imax}. At low frequencies, L_{Imax} octave levels can be calculated by adding $10\log_{10}(1000/35) = 14.6$ dB to the L_E. The signal needs to be shorter than 35 ms. The correction was tested to be accurate enough on the whole frequency range (less than 1.5 dB difference). The presented results are uncorrected.

One observation of the measurements was that L_E and L_{Imax} do not have as big deviation between single events as L_{peak}. Though, not enough data was available to make true statistical analysis.

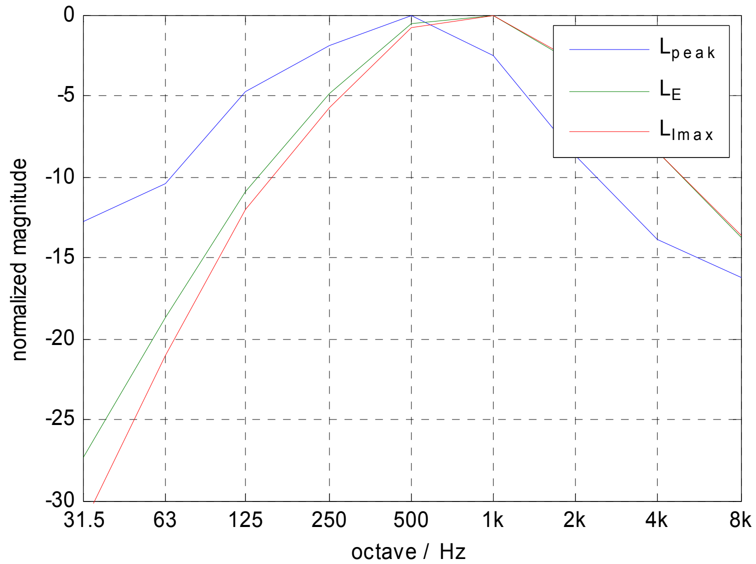

Figure 25. Octave filtered levels L_{peak}, L_E and L_{Imax} of a 7.62 mm assault rifle muzzle blast at 90° direction at 10 m distance. Each of the spectra is normalized to 0 dB individually to point out the differences in spectral shapes. L_{Imax} octaves are uncorrected. L_{peak} low-frequency levels are not stronger compared to other level quantities, but rather high-frequency attenuation occurs already above the first couple of octaves.

7.2 Small-calibre weapon emission measurement

Emission measurements of rifle calibre weapons were made according to both the NT ACOU 099 and ISO/FDIS 17201-1:2005 methods (see Appendix A). The Nordtest method was used on two grounds: hard asphalt and porous sand. The ISO method was used only on asphalt. As discussed in Sec. 4.1.2, the main difference between the two methods is the microphone height. In the Nordtest method, the microphone was attached to a 1 m^2 wooden panel lying on the ground. Microphone capsule was closer than 0.7 cm from the surface of the panel. In the ISO method, the microphone was attached to a stand at 1.5 m height from the ground.

The ISO method's main difficulty was the uncontrolled reflection. Even at only 10 m distance, ground reflection could not be windowed without removing information of the direct sound at the same time. The other reflection removal method proposed in the standard besides the windowing is the measurement of ground impedance. No such measurements could be made here. An example of a waveform at 45° direction measured with the ISO method is presented in Fig. 26.

Another difficulty was the bullet noise. Using both methods at 45° direction, bullet noise arrived at almost the same time as the muzzle blast to the measurement position. Approximately 0.5 ms time difference was observed. Calculations according to Eqs. (4), (5) and (6) predict a time difference very close to that. Because bullet noise cannot be reliably removed from the muzzle blast, all 45° direction measurements of the rifle include bullet noise. From 0° direction bullet noise is removed. With other weapons and bullet velocities, the bullet noise difficulty occurs in different positions. E.g. a pistol with 400 m/s bullet initial velocity, the bullet noise occurs roughly at the same time with muzzle noise at 0° angle.

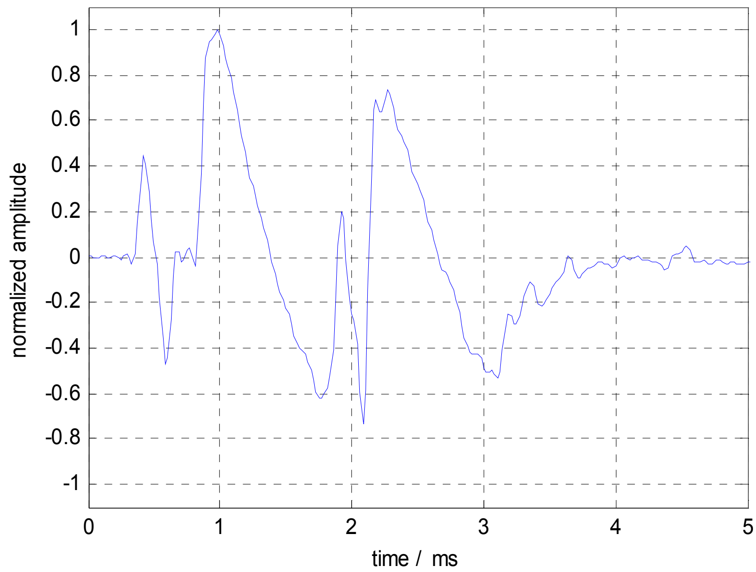

Figure 26. Measured waveform of bullet noise, muzzle blast and their reflections at 45° direction of 7.62 mm assault rifle. Measurement distance is 10 m and receiver and source heights 1.5 m. Bullet noise N-wave is at 0.5 ms and muzzle noise peak at 1 ms. The latter two distinctive peaks are reflections of both bullet and muzzle noise from the asphalt.

In Fig. 27, the difference of the Nordtest method on the two different ground types is plotted. Because fully coherent reflection is sought, higher levels mean more accurate estimates of the emission. If the reflection is not in coherence with the direct sound on all frequencies, resulting emission levels on those frequencies are underestimated. From the figure can be seen that at the frequency range 250-1000 Hz the reflection is not coherent when measured on porous ground. This is true provided that on hard ground the reflection is close to ideal. A plywood board of 1 m^2 under the microphone helps in frequency-range above 2 kHz but not below. The results support the simulation results of Sec. 6.2.1.

For the reasons stated above, an asphalt surface should be preferred when full -6 dB correction is sought. Unfortunately no measurement data was available to made similar ground type comparison with the ISO method. Though, this is not important either since reflection is unwanted in any case.

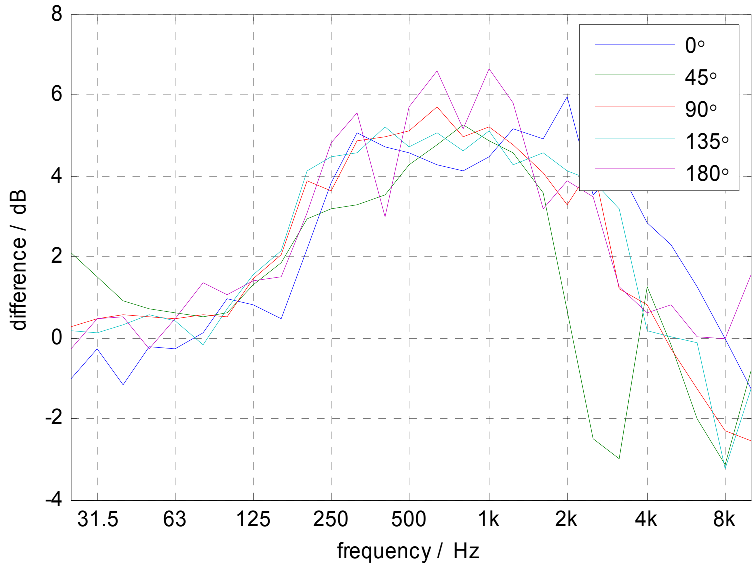

Figure 27. Difference of measurements made according to NT ACOU 099 on two types of ground, asphalt and porous sand (calculated in one-third-octave bands). Positive difference means that asphalt surface gave higher value than the sand surface. 45° angle results are not comparable between 1.6 and 4 kHz due to the inclusion of the bullet noise.

In Fig. 28, narrowband spectra of the Nordtest and ISO methods are presented. It can be clearly seen that the ISO method suffers from the interference effect when reflection cannot be removed. The comb-filter effect is evident at the whole frequency range. The first minimum is at 350 Hz. With the Nordtest method interference occurs only above 2 kHz and in smaller degree. With the ISO method, interference needs to be modelled and compensated accurately. As mentioned earlier, this is a very difficult task to be done reliably. By increasing the source and receiver height or by shortening the distance, time difference could be made longer and reflection could be more easily windowed.

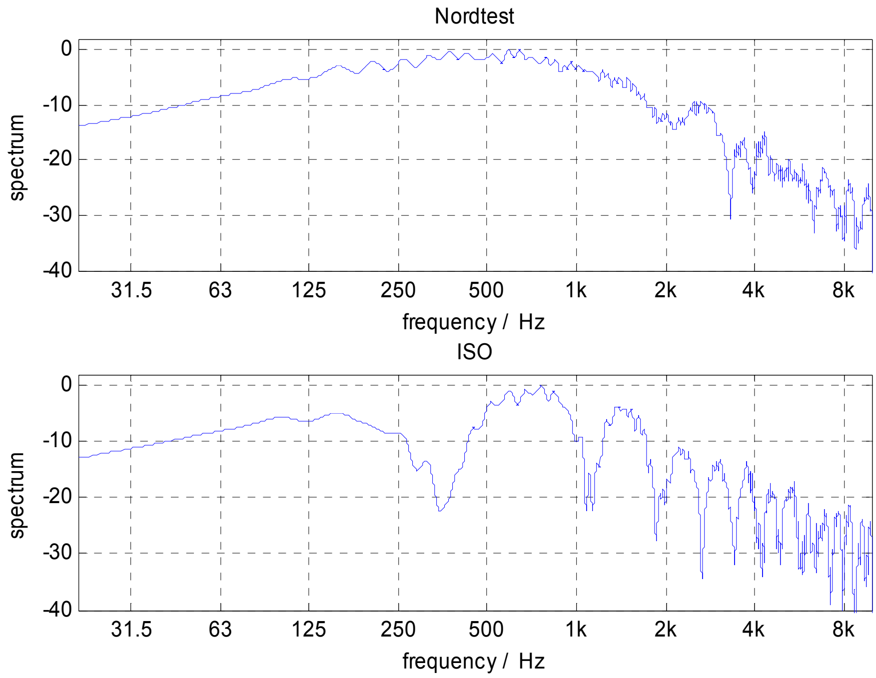

Figure 28. Narrowband spectra of Nordtest (above) and ISO (below) methods. In Nordtest method the interference occurs only above 2 kHz and in ISO method on the whole frequency range.

The interference is presented as one-third-octave band differences between the Nordtest and ISO methods in Fig. 29. Both of the measurements were made on asphalt. The magnitude of the first interference minimum at about 350 Hz with the ISO method is undisputable. The dip is almost two octave bands wide and 17 dB deep. Because it belongs to the main frequency range of the muzzle blast, the dip is unacceptable.

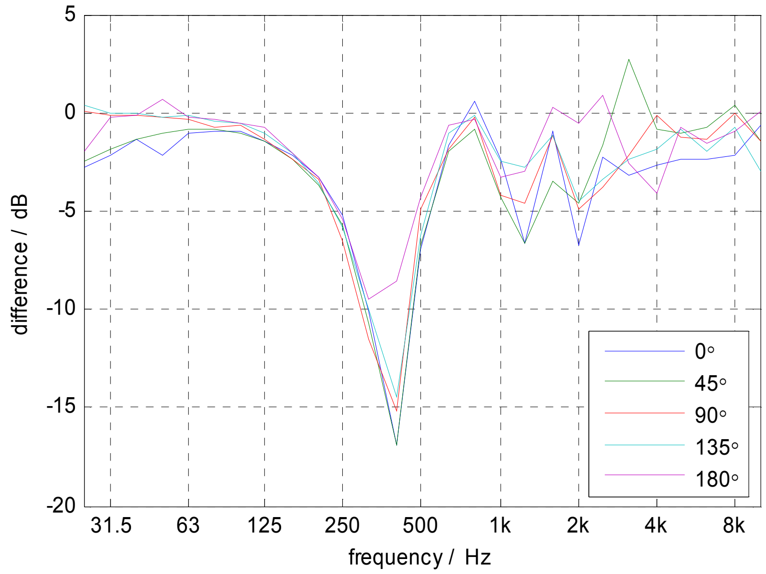

Figure 29. Difference of the Nordtest and the ISO methods calculated in one-third-octave bands on hard ground. Negative difference means smaller value of the ISO method compared to the Nordtest method.

7.3 Propagation in time- and frequency-domain

In Sec. 6.3, propagation of a rifle shot was simulated. The simulation results are valid only in an ideal environment with flat terrain of constant impedance and without scattering objects. In real situation, things are never as simple. Two cases of real measured waveforms and spectra are considered in this section. The first case is an example of typical SCW noise and the second case of LCW noise.

In the first case at 10 m distance the waveform is clean (see Fig. 30). There is one predominant pulse that includes most of the energy of the signal. The signal is attenuated to below -40 dB fast, after just 30 ms, and no significant "reverberation" occurs. The main frequency range is about 250 Hz – 8 kHz. When the shot has propagated 640 m distance in a forested environment, the wave has spread in time. There is no longer one predominant pulse including most of the energy but rather the energy is spread in time and can be heard as "reverberation" of the forest. The shot is not fully attenuated even after 500 ms and should be windowed using a longer time window.

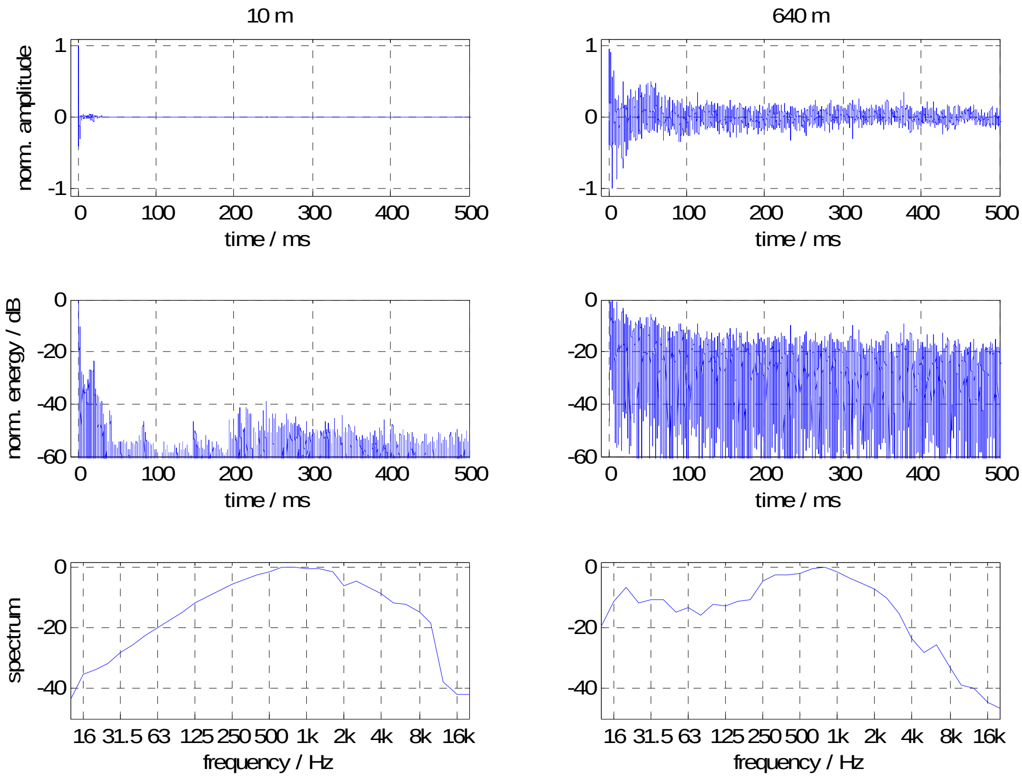

Figure 30. Muzzle blasts of 7.62 mm assault rifle at 10 m and 640 m distances and the corresponding energy-time curves and spectra. All the plots are normalized individually to point out the differences in waveforms, energy-time curves and spectral shapes. At 640 meters the levels of the frequencies below about 100 Hz result from the wind and do not represent the shooting noise itself.

Similar examination is made with LCW noise in Fig. 31. The weapon used in the example is 122 mm armoured howitzer measured in hilly forested terrain. The first peak is predominant in this case too but also a ground reflection with inverse phase can be distinguished. The sound energy is centred around 80 Hz.

Surprisingly after 1600 m propagation, two distinct waveforms can be seen. The first one is the direct sound but the second is a reflection from a boundary. The separation of low frequencies is a subject of wave acoustics and cannot be explained with ray-acoustics theory. The reverberation has significant low-frequency energy similarly as in the first case. Due to scattering, air absorption and diffraction, the main sound energy is shifted to a lower frequency-range. The trough around 100 Hz is a result of the finite ground impedance and frequencies above 500 Hz are attenuated due to air absorption. Diffraction of the hilly terrain shape is hard to observe from the spectrum.

The differences in close and long-distance measurement results show that sound energy and peak pressure propagations differ. Propagated shot's peak pressure is attenuated faster than the sound energy. This is also one reason why models designed for sound energy propagation cannot be used directly for peak and maximum level calculations.

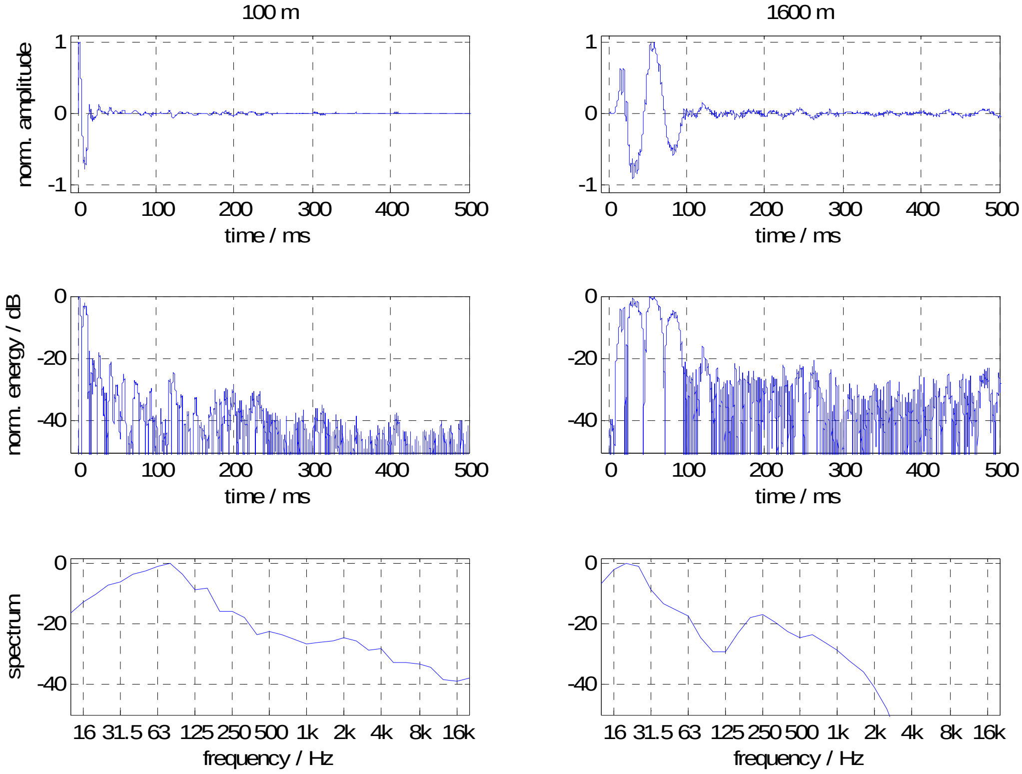

Figure 31. Muzzle blast of 122 mm armoured howitzer at 100 m and 1600 m distances and the corresponding energy-time curves and spectra. All the plots are normalized individually to point out the differences in waveforms, energy-time curves and spectral shapes. At 1600 meters the levels of the frequencies below about 100 Hz result from the wind and do not represent the shooting noise itself.

7.4 Comparison of modelling and measurement results

In Finland, noise from shooting ranges is assessed with L_{AImax}. For LCWs L_{CE} is the primary level indicator and L_{AE} is used as an intermediate level to acquire L_{Ade}. In the selection of the most suitable level quantity, reliability issues concerning both measurements and noise propagation modelling need to be taken into account. In practice, an equal-area noise map is often the final document from which the results are read, often by non-professionals.

In Fig. 32 immission measurement results from two FDF shooting ranges of SCW are compared to calculated levels. The levels L_{AE} and L_{AImax} are plotted as logarithmic functions of the distance. In the figure, positive difference indicates higher calculated levels compared to measurement results. The modelling was made using the NGPM without correction for vegetation. Maximum measurement distance was 710 m. Each measurement result is an energy-basis average of 5-10 shots.

Calculations and measurements are relatively close to each other for L_{AE}. The differences are less than 5 dB at all the distances. A regression model of the rather limited measurement data is almost straight. For L_{AImax} the differences are bigger. Already at short distances NGPM overestimates the levels. The NT ACOU 099 propagation model which is intended for L_{AImax} prediction differs from NGPM in the correction for vegetation. The calculations could be closer to measurements if this was included.

The deviation of the measurement results is bigger with L_{AImax} than with L_{AE}. Unfortunately, proper statistical analysis could not be made due to the limited amount of measurement data. The figures are plotted to just give first indication of the accuracy of the model. What is notable in the figure, is the relation of L_{AE} and L_{AImax} at each point. There is not much correlation between the two levels. When L_{AE} difference is negative, L_{AImax} difference is not necessarily negative and the other way.

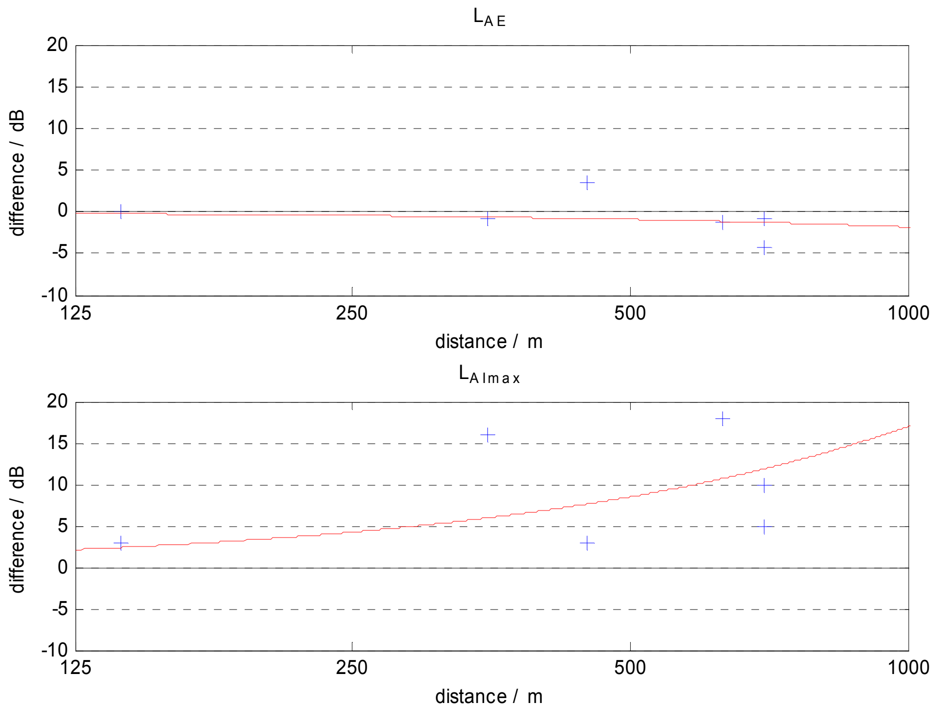

Figure 32. L_{AE} and L_{AImax} as a function of the distance for two FDF pistol and rifle shooting ranges normalized to modelling results of NGPM. Positive difference indicates higher modelling results compared to measurement results. Measurements were made on favourable weather conditions. Blue crosses are the measured averages of 5-10 shots and the red line is the first order linear regression model.

Similar analysis is made for LCWs at shooting areas but with longer distances. L_{AE} and L_{CE} are the investigated level quantities. Due to the increased amount of measurement data, the results are divided into three rough categories of meteorological conditions: favourable, neutral and unfavourable weather. The differences of L_{AE} of measurement and modelling results are presented in Fig. 33 and the differences of L_{CE} in Fig. 34. Each measurement result is an energy-basis average of 5-50 consecutive shots. It is not surprising to discover that neutral and unfavourable conditions affect the measurements significantly. Deviation of measurement results in favourable conditions is far smaller. Because NGPM is calibrated for favourable conditions, not only deviation is smaller but also absolute levels are closer to modelling results.

L_{CE} seems to be statistically a bit more unreliable than L_{AE}. The larger amount of information conveyed in L_{CE} is an explanation for this. Low-frequency content that is heavily weighted with A-network is included in C-weighted levels and therefore there is also more information to deviate. Still the correlation between the levels is far better than previously with L_{AE} and L_{AImax}.

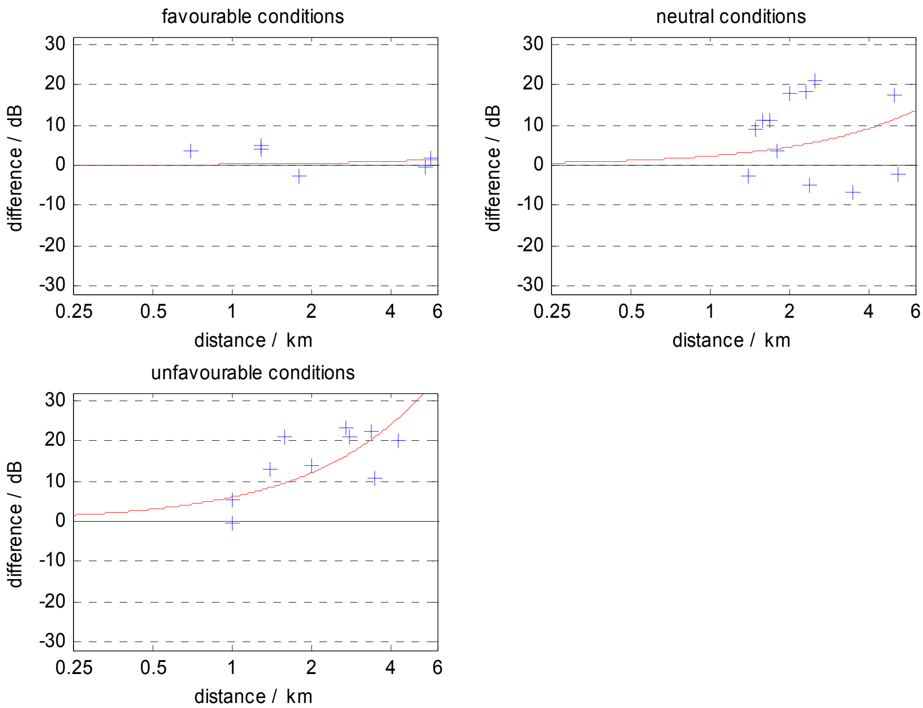

Figure 33. L_{AE} as a function of the distance for two shooting areas of the FDF normalized to modelling results of NGPM. Positive difference indicates higher modelling results compared to measurements. Measurements are divided to roughly favourable, neutral and unfavourable conditions. Blue crosses are the measured averages of 5-50 shots and red line is the first order linear regression model.

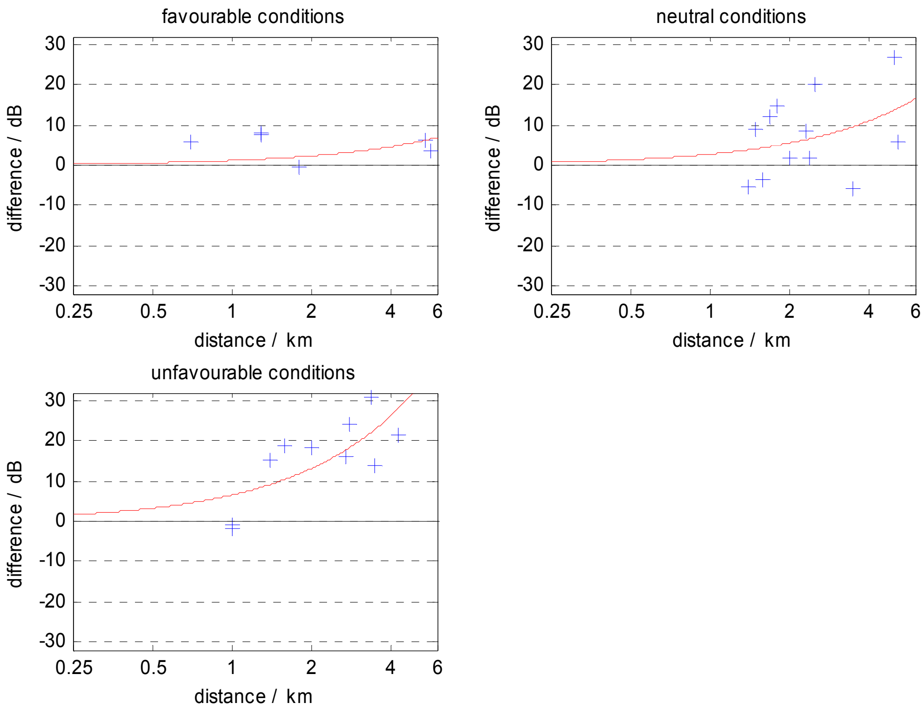

Figure 34. L_{CE} as a function of the distance for two shooting areas of the FDF normalized to modelling results of NGPM. Positive difference indicates higher modelling results compared to measurements. Measurements are divided to roughly favourable, neutral and unfavourable conditions. Blue crosses are the measured averages of 5-50 shots and red line is the first order linear regression model.

7.5 Level differences

Quite often in shooting noise literature, a conversion from one level quantity to another is used. There can be several needs for doing this; comparison to other types of environmental noise, assessment of impulsiveness, reuse of existing data etc. Although conversion is an easy way to jump from one level quantity to another, it is only a rough estimate of the level that would be acquired with measurements. Conversion should be avoided, if precise levels are needed. New measurement or analysis for the wanted levels should be made in such situations.

Propagation models are often designed to be used only in estimation of one particular level quantity. Especially models designed for propagation of sound energy are not valid for propagation of maximum sound level. Figures 35 and 36 show how some level differences behave in the case of SCW and LCW, respectively. All the level difference types in the figures are taken from the literature where they have been used in characterizing impulsiveness of shooting noise. The measurement results were acquired from the same measurement as in Sec. 7.4[1].

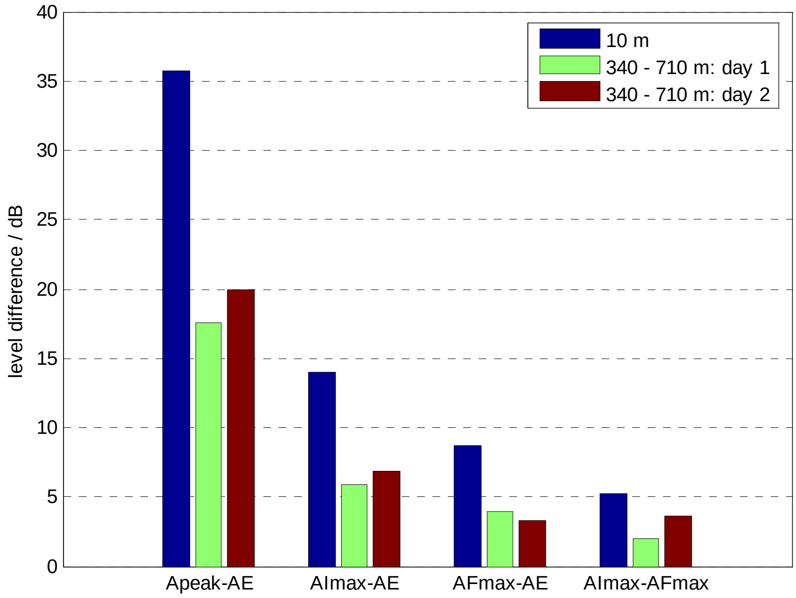

Figure 35. Level differences of small-calibre weapon muzzle blast at close and at long-distance in two different weathers at two shooting ranges of the FDF.

The general tendency in the results is that the level differences decrease by increasing distance. Scattering seems to affect the level differences already at relatively short distances of few hundred meters. Though, not all of the level differences behave in the same manner. Some of the results are rather random and the reasons cannot be explicitly stated. The differences between the results in the two weathers in Fig. 35 are surprisingly low. One possible explanation for this is that weather affects all the levels rather equally and thus does not affect impulsiveness.

[1] Measurements were made in 2005 in two FDF heavy weapon shooting areas.

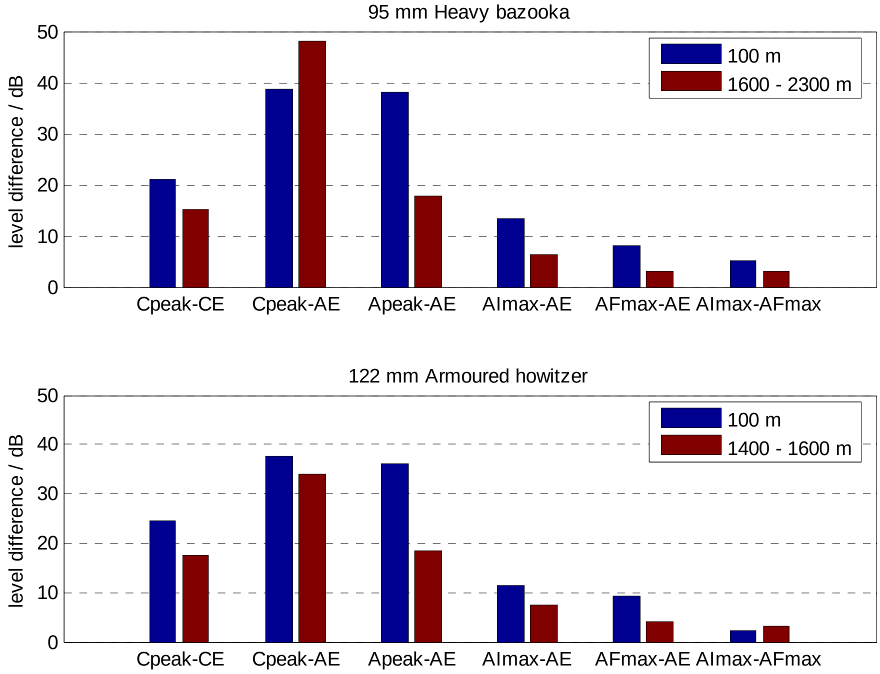

Figure 36. Level differences of large-calibre weapon muzzle blasts at close and at long-distance in a forested shooting area of the FDF.

In Table 4 measured level differences are compared to conversions recommended in (ISO/CD 17201-3:2003). The measured differences are very close to the ISO recommended differences at close with SCWs. At longer distances (340 – 710 m) the ISO presented differences do not apply anymore. For LCWs the differences presented by ISO do not apply even at close.

Table 4. Comparison of measured and recommended level differences in (ISO/CD 17201-3:2003).

Small-calibre weapons	**10 m**	**300 - 700 m**	**ISO 17201-3**
L_{Fmax}-L_E	8.7	6.1	9.03
L_{Imax}-L_E	14.0	10.1	14.56
L_{Imax}-L_{Fmax}	5.3	4.0	5.5
Heavy weapons	**100 m**	**700 - 5700 m**	**ISO 17201-3**
L_{Fmax}-L_E	8.8	3.7	9.03
L_{Imax}-L_E	12.5	6.9	14.56
L_{Imax}-L_{Fmax}	3.7	3.2	5.5

7.6 Projectile noise

Projectile noise is a case of nonlinear acoustics. Sonic boom resulted from clustered pressured waves affects also the muzzle blast emission measurement. At certain angle, depending on the bullet velocity and the distance, projectile noise may arrive at the same time as the muzzle blast. It can also be a relevant source of noise overstepping the muzzle blast in absolute level. This is strongly weapon and environment dependent. In this section, theoretical calculations and measurements of bullet noise peak pressure and duration are compared. In addition, muzzle blast propagation is compared to bullet noise propagation of 7.62 mm assault rifle in simplified manners. The bullet is described in Appendix A.

Measurements of bullet noise were made at three distances from the bullet flight path: 1, 10 and 20 meters. Examples of measured waveforms and spectra are presented in Fig. 37. The initial velocity of the projectile is 709 m/s. The N-wave spreads in time with increasing distance, since the velocity is a function of the pressure as discussed in Sec. 2.1.2. In the frequency domain the same phenomenon can be seen as a shift of energy to lower frequencies. From 20 m measurements, ground reflection could not be windowed out and it is not therefore directly comparable with the other distances.

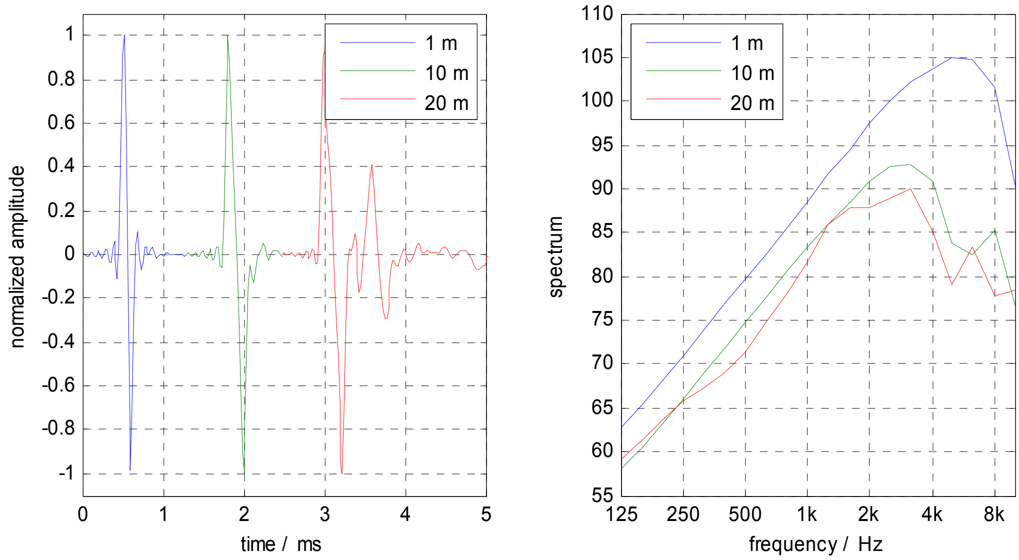

Figure 37. Bullet noise waveforms and spectra. 20 m results include ground reflection that could not be windowed. The N-wave spreads in time as the distance increases and the energy shifts to lower frequencies. The spectra are calculated in one-third-octave bands.

Theory enables to predict theoretical projectile peak levels L_{peak} and N-wave durations at any distance. In Table 5 theoretical L_{peak} values are compared with the measured levels. Projectile form factor K = 0.6 was used in the calculation. Static pressure during the measurement was 99.8 kPa and temperature 13° C.

Table 5. Comparison of calculated and measured bullet noise peak levels L_{peak} / dB. Calculations were made according to (Pierce 1981). $K = 0.6$.

	1 m	**10 m**	**20 m**
Theory	156.2	141.2	136.7
Measurement	151.8	137.9	134.5

The theory seems to predict L_{peak} surprisingly accurately. The tendency is that predicted levels are few decibels higher than the measured ones. The difference is about 5 dB at 1 m and 2 dB at 20 m. Some of the difference might come from the form factor approximation $K = 0.6$. The value was not an obvious choice but rather taken from (NT ACOU 099 2002). A change of 0.1 in K affects the levels approximately ± 1.5 dB at all the distances.

The measured L_{peak} is attenuated 14 dB from 1 to 10 meters and 3.5 dB from 10 to 20 meters. The theory says that at ten times the distance L_{peak} should be attenuated 15 dB and at double the distance by 4.5 dB. Thus, the measurements show a bit slower attenuation than the theory.

N-wave total durations are underestimated by the theory as can be seen from Table 6. 0.06 ms shorter waves were predicted by the theory at all the distances. A ± 0.1 change in form factor K affects the duration by ± 0.05 ms. Because peak SPLs are overestimated and durations underestimated, the predicted exposure levels are fairly well in balance with the measurements.

Table 6. Comparison of calculated and measured bullet noise N-wave total durations t / ms. Calculations were made according to (Pierce 1981). $K = 0.6$.

	1 m	**10 m**	**20 m**
Theory	0.15	0.27	0.32
Measurement	0.21	0.33	0.38

In the case of 7.62 mm assault rifle, bullet noise and muzzle blast levels are close. The levels are compared as a function of distance in Fig. 38. In addition to divergence, air absorption is taken into account because the two spectra are very different. Both 45° and 90° muzzle blast directions are compared to bullet noise propagation due to the strong directivity.

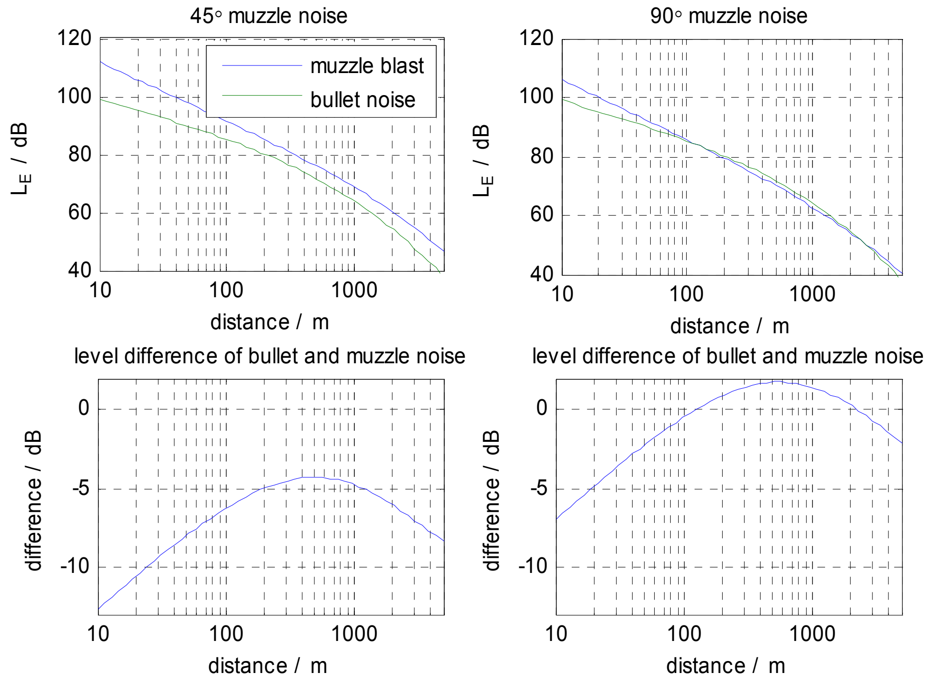

Figure 38. Comparison of bullet noise and muzzle blast L_E of both 45° and 90° directions. The bottom subfigures are the corresponding differences of muzzle blast and bullet noise levels. The spectra are calculated in one-third-octave bands.

In comparison with the 45° direction, bullet noise L_E is lower than the muzzle blast at all the distances. From the curves can be noted that air absorption starts to make difference at approximately 1 km. After that, bullet noise is attenuated faster than the muzzle blast due to the higher-frequency spectrum where air absorption works better. At 90° direction bullet noise is more important. Between 100 and 2000 meters, bullet noise level is a few decibels over the muzzle blast.

In a real situation, the region of bullet noise and its relation to muzzle blast azimuth angle is not as simple as demonstrated above. 0° direction could be a more accurate estimate for muzzle blast in parts of the bullet noise region. However, it would not bring anything new to the comparison because the emission to that direction is even higher than to 45° direction.

7.7 Discussion

The octave analysis of shooting noise shows that the IR of the filter itself affects the values when measured using I-weighting and especially when measuring L_{peak}. The octave levels of peak sound pressure are underestimated with higher frequencies because the signal energy "leaks" over a longer period of time. The I-weighting does not work with low frequencies because the whole signal does not fit into the time window of 35 ms. These problems do not concern the exposure level which works correctly despite of the length of the filter's IR.

The measurement results obtained with the Nordtest and the ISO SCW emission measurement methods support the findings of the simulations. The ISO method suffers from the interference because the ground reflection cannot be windowed out without losing low-frequency energy of the direct sound. The first interference minimum is located at the same frequency of about 350 Hz as the simulation suggested.

The results of the Nordtest method are better. Only minor interference occurs above 2 kHz. However, the method works only on a hard ground. The use of a hard reflecting board on a porous ground does not produce a coherent reflection in the frequency range approximately from 250 Hz to 2 kHz.

The examples of immission measurements make it clear that the impulse spreads in time and loses some of its impulsiveness. The reflections and scattering add "reverberation" to the impulse and make the originally short impulse much longer. This happens with both LCWs and SCWs. At the same time the spectrum is flattened except for the ground attenuation dip. With LCWs also significant transferring of energy to lower-frequencies was observed. A significant change in the shape of the spectra was also observed. Due to the increased attenuation of high frequencies at longer distances, the spectra got a more predominant low-frequency character.

The previous results mean also that the maximum level quantities cannot be directly modelled with energy-based prediction methods. This was observed with modelling the propagation of L_{Imax}. The level quantity differences further support the statement: impulsiveness is lowered with increasing distance. So no direct correction value can be used to jump from one quantity to another. The only situation where this can be done is at close distance (10 m) where the deviation was found to be very small.

When the exposure level modelling results were compared to measurement results, NGPM was found to work poorly in other than favourable weather conditions. This was in line with the expectations as the model is tweaked to predict worst-case situations. The weather did not seem to affect the impulsiveness.

As a final analysis, the bullet noise measurements were compared to theory. They seem to be fairly close to each other (difference < 5 dB) at short distances. Simulating the propagation of bullet noise and comparing it to muzzle blast propagation predict that the bullet noise can be an important part of shooting noise at some distances and in some directions.

8 CONCLUSIONS

In this thesis, the noise from shooting with small- and large-calibre weapons was treated in three ways. The propagation of shooting noise was studied mainly using simulations but also by comparing the results given by current calculation methods. The measurement of the emission of shooting noise was investigated using both simulations and comparisons of actual measurement results, obtained with various procedures proposed or in use. The assessment of the annoyance of shooting noise was treated based on the literature. The emission and projectile noise measurement data was obtained from the FDF but analyses were made by the author. Other measurement and modelling data was acquired by own experiments.

It is concluded here that the best existing annoyance descriptors for a single-event exposure seem to be the sound exposure levels L_{AE} and L_{CE} for small- and large-calibre weapons, respectively. This conclusion is supported by both psychoacoustical studies and technical aspects. The maximum level quantities do not correlate well with the experienced annoyance over longer periods of time and with multiple events. However, if a maximum level quantity is used, the time weighting F correlates best with the perceived loudness. C is the preferred choice of frequency weighting network with LCWs because it does not discard the low-frequency content which may induce vibrations and result in rattles in interior spaces.

In this thesis it was found that the noise emission of the SCWs is most accurately measured with microphones placed on the ground on a reflecting board according to the Nordtest method. Preferably, the ground should be acoustically hard. The ISO method with a raised microphone produces interference which cannot be windowed out without losing low-frequency information at the same time, or without degradation in accuracy.

It was also found that the emission of the LCWs should be measured with microphones placed as high as possible because in practice they cannot be placed on the ground. The comb-filter effect still affects the measurement results and it needs to be calculated off using backwards calculation with a prediction model or other similar method.

The comparisons of measurement and modelling results in this thesis show that the propagation of shooting noise can be modelled with the current energy-based propagation models. However, larger differences to the measurement results are expected due to the longer distances compared with other environmental noise types. The ground impedance is the most important factor of propagation at the emission measurement distances. At larger distances the refraction in the atmosphere due to weather and the barrier effect are more important factors and they overcome the ground effect. Third important effect is the scattering which spreads the impulse energy in time. Therefore, the maximum level quantities cannot be predicted with conventional energy-based propagation models. Further, the difficulties found with the maximum levels and their octave filtering support the use energy-based levels.

The measurements and tests of bullet noise show that the bullet noise of SCWs needs to be taken into account in addition to the muzzle blast. The bullet noise can be estimated with theoretical calculations but measurements are advised to further verify the accuracy of the theory.

Although, in this thesis, the measurements and simulations were made for military weapons, the confluences to recreational shooting noise are clear.

8.1 Future work

Four different questions arose while preparing this thesis, and future work needs to be done to solve these problems:

- What is the best value (or best compromise) for an impulse correction?
- How well do the modern propagation models work, for instance Harmonoise?
- What is the pressure limit where nonlinear effects are no longer significant?
- Do the theoretical calculations of the bullet noise match the measurement results at long distances?

REFERENCES

Andersen, J. 1998. Item 12. Danish Defence Research Establishment (DDRE). *International sound and vibration digest.* (online). [Referred 27.4.2006]. Available: http://www.auburn.edu/isvd/v4n1apr98.txt.

Buchta, E. 1990. A field survey on annoyance caused by sounds from small firearms. *Journal of the Acoustical Society of America (JASA).* 88(3). p. 1459-1467.

Buchta, E. 1996. Annoyance caused by shooting noise – determination of the penalty for various weapon calibres. *Proceedings of the Internoise 96.* Liverpool, United Kingdom, July 1996. p. 2495-2500.

Bullen, R., Hede, A. 1985. Community reaction for isolated impulsive sounds. *Proceedings of the Internoise 85*. p. 937-940.

Bullen, R., Hede, A., Job, R. 1991. Community reaction to noise from an artillery range. *Noise Control Engineering Journal.* 3(37). p. 115-124.

Desamaulds, V., Monay, G., Favarger, D. 1998. Shooting noise regulation review of various national practices. *Proceedings of the Internoise 98*. Christchurch, New Zealand, November 1998.

Eurasto, R. 2005. *Ampumaratamelun laskentamallien lähtöarvojen määrittäminen*. Draft 20.12.2005. Rakennus- ja yhdyskuntatekniikka, VTT. 16 p.

Findeis, H., Peters, E. 2004. Disturbing effects of low frequency sound immissions and vibrations in residential buildings. *Noise & Health.* 6(23). p. 29-35.

Florentine, M., Buus, S., Poulsen, T. 1996. Temporal integration of loudness as a function of level. *JASA.* 99(3). p. 1633-1644.

Garner, W. 1949. The loudness and loudness matching of short tones. *JASA.* 21(4). p. 398-403.

IEC 61672-1. 2002. *Electroacoustics - Sound level meters - Part 1: Specifications*. Geneva, Switzerland. International Electrotechnical Commission. 85 p.

ISO 226:1987. *Normal equal-loudness-level contours*. International Organization for Standardization. 8 p.

ISO 226:2003. *Normal equal-loudness-level contours.* 2nd ed. International Organization for Standardization. 18 p.

ISO 532b:1975. Method for calculating loudness level: method B. International Organization for Standardization. p. 473-485.

ISO/DIS 1996-2.2:2005. *Description and measurement of environmental noise - Part 2: determination of environmental noise levels.* International Organization for Standardization. 37 p.

ISO 9613-1:1993. *Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere.* International Organization for Standardization. 26 p.

ISO 9613-2:1996. *Attenuation of sound during propagation outdoors. – Part 2: General method of calculation.* International Organization for Standardization. 18 p.

ISO/FDIS 17201-1:2005. *Noise from shooting ranges – Part 1: Determination of muzzle blast by measurements.* International Organization for Standardization. 41 p.

ISO/CD 17201-3:2003. *Noise from shooting ranges – Part 3: Guidelines for sound propagation*. International Organization for Standardization. 6 p.

ISO/DIS 17201-4:2004. *Noise from shooting ranges – Part 4: Prediction of projectile noise.* International Organization for Standardization. 16 p.

Jaloniemi, R., Pääkkönen, R., Parri, A. 2005. *Raskaiden aseiden ja räjähteiden aiheuttaman ympäristömelun arviointi*. Hamina, Pääesikunta, Puolustusvoimat. 47 p. Puolustusvoimien ohje.

Jokitulppo, J., Lahti, T., Markula, T. 2006. *Ampumamelun aiheuttama häiritsevyys ja altistumisen arviointi.* Draft. Insinööritoimisto Akukon Oy, Helsinki.

Karjalainen, M. 2000. *Kommunikaatioakustiikka.* Revised 1st pre-ed. Espoo, Finland. Laboratory of Acoustics and Audio Signal Processing, Department of Electrical and Communications Engineering, Helsinki University of Technology. 237 p. Report no 51.

Kragh, J., Andersen, B., Jakobsen, J. 1982. *Environmental noise from industrial plants. general prediction method.* Danish Acoustical Laboratory, The Danish Academy of Technical Sciences. 89 p.

Lahti, T. 1979. *Äänen eteneminen maanpinnalla*. Otaniemi, Finland. Acoustics laboratory, Helsinki University of Technology. 70 p. Report 16.

Lahti, T. 1997. *Akustinen mittaustekniikka.* 2nd ed. Espoo, Finland. Laboratory of Acoustics and Audio Signal Processing, Department of Electrical Engineering, Helsinki University of Technology. 152 p. Report 38.

Lahti, T. 2001. Äänen eteneminen ulkona. *Akustiikkapäivät*. Acoustical Society of Finland. Espoo, 8.-9.10.2001. p. 115-118.

Leatherwood, J., Sullivan, B., Shepherd, K., McCurdy, D., Brown, S. 2002. Summary of recent NASA studies of human response to sonic booms. *JASA.* 111(1). p. 586-598.

Masaoka, K., Ono, K., Komiyama, S. 2001. A measurement of equal-loudness-level contours for tone bursts. *Acoustical science and technology*. 22(1). p. 35-39.

McCurdy, D., Brown, S., Hilliard, R. 2004. Subjective response of people to simulated sonic booms in their homes. *JASA.* 116(3). p. 1573-1584.

McLeod, I., Don, C., Swenson, G. 2004. Acoustic pulse propagation in an outdoor turbulent atmosphere. *JASA.* 116(5). p. 2855-2863.

Meloni, T., Rosenheck, A. 1995. Choice of frequency weighting for the evaluation of weapon noise. *JASA.* 97(6). p. 3636-3641.

Miljøstyrelsen. 1997. *Beregning af støjkonsekvensområder omkring forsvarets øvelsområder.* Miljø- og Energiministeriet, Miljøstyrelsen. 36p. Vejledning nr. 8 1997.

Moore, B., Glasberg, B. 1996. A revision of Zwicker's loudness model. *Acta Acustica.* 82(1996). p. 335-345.

Morse, P., Ingard, K. 1968. *Theoretical acoustics.* McGraw-Hill Book Company. 927 p.

NATO. 2000. *The effects of noise from weapons and sonic booms, and the impact on humans, wildlife, domestic animals and structures.* Committee on the challenges of modern society, NATO. 136 p. Report 241.

Naturvårdsverket. 2005. *Naturvårdsverkets allmänna råd om buller från skjutbanor.* Naturvårdsverket författningssamling NFS 2005:15. 6 p.

Nota, R., Barelds, R., van Maercke, D. 2005. *Harmonoise WP 3 Engineering method for road traffic and railway noise after validation and fine-tuning*. (online). [Referred 27.4.2006]. Available: http://www.imagine-project.org/bestanden/D18_WP3_HAR32 TR-040922-DGMR20.pdf. 53 p. Harmonoise deliverable 18.

NT ACOU 099. 2002. *Shooting ranges: prediction of noise.* Nordtest. 17 p. Nordtest method.

NT ACOU 112. 2002. *Acoustics: prominence of impulsive sounds and for adjustment of* L_{Aeq}. Nordtest. 5 p. Nordtest method.

Pesonen, K. 2005. *Ympäristömelun haittojen arvioinnin perusteita.* Helsinki. Sosiaali- ja terveysministeriö. 174 p. Disquisition 2005: 14.

Pierce, A. 1981. Acoustics. *An introduction to its physical principles and applications.* 1st ed. McGraw-Hill Book Company. 642 p.

Poulsen, T. 1981. Loudness of tone pulses in a free field. *JASA.* 69(6). p. 1786-1790.

Pääkkönen, R., Parri, A., Tiili, J. 2001. Low-frequency noise emission of Finnish large-calibre weapons. *Journal of low frequency noise, vibration and active control.* 20(2). p. 85-92.

Rossing, T., Moore, F., Wheeler, P. 2002. *The science of sound.* 3rd ed. Addison Wesley. 783 p.

Saario, H. 1984. *Ampumaratamelumalli.* VTT. Espoo. 20 p.

Saunders, D. 1990. Attenuation of explosive noise by natural barriers. *Applied Acoustics.* 29(1990). p. 229-239.

Schomer, P. 1984. Assessment of community response to impulsive noise. *JASA.* 77(2). p. 520-535.

Schomer, P., Averbuch, A. 1989. Indoor human response to blast sounds that generate rattles. *JASA.* 86(2). p. 665-673.

Schomer, P., Wagner, L. 1995. Human and community response t military sounds – Part 2: Results from field-laboratory tests of sounds of small arms, 25-mm cannons, helicopters and blasts. *Noise Control Engineering Journal.* 43(1). p. 1-13.

Schomer, P. 2000. Loudness-level weighting for environmental noise assessment. *Acta Acustica*. 86(2000). p. 49-61.

Small, A., Brandt, J., Cox, P. 1962. Loudness as a function of signal duration. *JASA.* 34(4). p. 513-4.

Smoorenburg, G. Evaluation of impulse noise, in particular shooting noise, with regard annoyance. *Proceedings of the Internoise 81*. p. 779-782.

Sosiaali- ja terveysministeriö. 2003. *Asumisterveysohje.* Guide 2003:1. 93 p.

Statens forurensningstilsyn. 2005. *Veileder til Miljøverndepartementets retningslinje for behandling av støy i arealplanlegging (støyretninsglinjen).* p. 188.

Valtioneuvoston päätös 53/1997. *Valtioneuvoston päätös ampumaratojen aiheuttaman melutason ohjearvoista*. Helsinki. 16.1.1997.

Valtioneuvoston päätös 993/1992. *Valtioneuvoston päätös melutason ohje-arvoista.* Helsinki. 29.10.1992.

Vos, J. 2003. A- and C-weighted sound levels as predictors of the annoyance caused by shooting sounds, for various façade attenuation types. *JASA.* 113(1). p. 336-347.

Vos, J., Geurtsen, F. 2003. On the assessment of shooting sounds: Loudness-level weightings versus A- and C-weighted sound exposure levels (*L*). *JASA.* 114(4). p. 1729–1732.

Ympäristöministeriö. 1999. *Ampumaratamelun mittaaminen.* Helsinki. Ympäristönsuojelu. 41 p. Ympäristöopas 61.

Zwislocki, J. 1969. Temporal summation of loudness: an analysis. *JASA.* 46(2B). p. 431-441.

APPENDIX A. SMALL-CALIBRE WEAPON EMISSION MEASUREMENTS

Measurements
Niinisalon koeampuma-asema, the Finnish Defence Forces
Made by Rauno Pääkkönen and Asko Parri
17 August, 2005

Weapon
7.62 mm assault rifle (7.62 Rk 62) with JVA0316 ammo (bullet weight 8.0 g, bullet initial velocity 709 m/s and gun powder weight 1.65 g)

Configurations
1. Microphones on a 1.5 x 1.5 m hardboard (< 0.7 cm). Sandy ground.
2. Microphones on a 1.5 x 1.5 m plywood board (< 0.7 cm). Sandy ground.
3. Microphones on a 1.5 x 1.5 m plywood board (< 0.7 cm). Asphalt.
4. Microphones at 1.5 m height. Asphalt.

Microphones were placed at 10 m distance in 45° spacing from 0° to 170°.
Gun was placed horizontally at 1.5 m height.

Measurement equipment

0°	B&K 2209	¼” B&K 4136
45°	B&K 2260	½” B&K 4189 and 20dB passive attenuator
90°	B&K 2260	½” B&K 4189 and 20dB passive attenuator
135°	B&K 2260	½” B&K 4189 and 20dB passive attenuator
170°	B&K 2209	¼” B&K 4136

Recording device: 8-channel digital audio tape (DAT) recorder Sony PC208Ax.
Calibration was made before and after the measurements by recording 1 minute of reference signal (1 kHz, 94 dB).

Weather

1.-2.	Static pressure: 99.6 kPa
	Temperature: 14-16° C
	Humidity: 85 %
	Wind: <2 m/s from direction 145-190° (south)
3.-4.	Static pressure: 99.8 kPa
	Temperature: 13° C
	Humidity: 65 %
	Wind: 2-3 m/s from direction 300° (west)

Analysis
The analyzed levels are energy-basis averages of 10 consecutive shots.
Bullet noise was windowed from all but 45° direction.

Bullet noise measurement configuration and equipment

1. 50 m in front of the gun, 1 m side from the line of fire
   B&K 2209 ¼" B&K 4136
2. 50 m in front of the gun, 10 m side from the line of fire
   B&K 2260 ½" B&K 4189 and 20dB passive attenuator
3. 50 m in front of the gun, 20 m side from the line of fire
   B&K 2260 ½" B&K 4189 and 20dB passive attenuator
4. 40 m in front of the gun, 20 m side from the line of fire 135°
   B&K 2260 ½" B&K 4189 and 20dB passive attenuator