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Acoustics — Framework for calculating a distribution of sound exposure levels for impulsive sound events for the purposes of environmental noise assessment

Acoustique — Cadre pour le calcul d'une distribution des niveaux d'exposition sonore pour les sons impulsionnels pour les besoins de l'évaluation du bruit environnemental

Reference number
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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 13474 was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 1, *Noise*.

It cancels and replaces ISO/TS 13474:2003, which has been technically revised.

Introduction

The aim of this International Standard is to provide a framework for the evaluation of descriptor quantities for use in environmental noise assessment. Part of this framework includes an engineering method for calculating a statistical distribution of event sound exposure levels at locations which are some distance from high-energy impulsive sound sources. It is specifically intended for environmental noise assessment and not for the assessment of the risk of damage to buildings or the risk of injury to animals or people.

In ISO 9613-2, the immission level from sources such as traffic and industry is calculated for a so-called “downwind” condition. The long-term average level is estimated using a correction factor, C_{met}. This concept holds for distances where sound from such sources is assessed as environmental noise. ISO 9613-2 excludes impulses in its scope and holds only for A-weighting, for near-ground sources and receivers and for distances up to about 1 000 m. For high-energy impulsive sound sources, the impulsive sound event duration is short, and low frequencies are more prominent than for traffic and industrial sound sources. Lower-frequency sounds are generally less attenuated over a given distance in the atmosphere than higher frequencies and, as a consequence, the level-influencing effects of propagation over much larger distances need to be taken into account.

A general outline is given of a method that takes into account ground reflection, shielding by topography and the meteorological effects of refraction and turbulence. Starting from the source strength, this method calculates a distribution of immission levels for a set of replica atmospheres, each replica being a specific combination of atmospheric-absorption class and excess-attenuation class. To carry out practical calculations using the procedure, it is useful to exploit the statistical contribution of the meteorological and ground surface conditions. In particular, histograms of the frequencies of occurrence of the wind velocity, wind direction, temperature, humidity and atmospheric stability can be used to describe the classes. From the distribution of the immission levels, a number of assessment metrics can be obtained. For instance, the long-term averaged immission level can be calculated as a weighted average. The weighting factors are determined by the probability of occurrence of each replica atmosphere during the relevant time period for the location of interest.

INTERNATIONAL STANDARD **ISO 13474:2009(E)**

Acoustics — Framework for calculating a distribution of sound exposure levels for impulsive sound events for the purposes of environmental noise assessment

1 Scope

This International Standard specifies the framework of an engineering method for calculating a statistical distribution of sound exposure levels for impulsive sound events for the purposes of environmental noise assessment. This International Standard is applicable to impulse sounds propagating over large distances (e.g. 0,5 km to 30 km) from sources such as mine blasting, artillery fire and bomb explosions, using conventional explosives of moderate charge mass (e.g. 0,05 kg to 1 000 kg of TNT equivalent). The effects of meteorological conditions and terrain upon sound propagation are considered.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1996-1, *Acoustics — Description, measurement and assessment of environmental noise — Part 1: Basic quantities and assessment procedures*

ISO 3534-1, *Statistics — Vocabulary and symbols — Part 1: General statistical terms and terms used in probability*

ISO 9613-1, *Acoustics — Attenuation of sound during propagation outdoors — Part 1: Calculation of the absorption of sound by the atmosphere*

ISO 9613-2, *Acoustics — Attenuation of sound during propagation outdoors — Part 2: General method of calculation*

ISO 17201-1, *Acoustics — Noise from shooting ranges — Part 1: Determination of muzzle blast by measurement*

ISO 17201-2, *Acoustics — Noise from shooting ranges — Part 2: Estimation of muzzle blast and projectile sound by calculation*

ISO 17201-4, *Acoustics — Noise from shooting ranges — Part 4: Prediction of projectile sound*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

VDI MSR 8/559, *Standard Method to Measure the Sound Exposure Emissions and Immissions from Large Weapons (Standardmethode zur Messung der Geräuschemissionen und -immissionen von schweren Waffen)*, Edmund Buchta (ed.), in *Meß-, Steuerungs- und Regelungstechnik*, No. 8/559, Fortschritt-Berichte, VDI Verlag, Düsseldorf, 1996 (in English and German)

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1

atmospheric absorption

attenuation of sound by air, resulting from viscous molecular processes, molecular rotation and molecular vibration

3.2

atmospheric-absorption class

range of meteorological parameters yielding approximately the same attenuation of sound by air, all within a specified uncertainty

NOTE See also atmospheric absorption.

3.3

atmospheric stability

tendency of the atmosphere to reduce or enhance vertical motion of the air

NOTE Enhanced (or reduced) vertical motion of the air usually implies enhanced (or reduced) atmospheric turbulence.

3.4

atmospheric-stability class

subset formed from partitioning the set of atmospheres according to stability

NOTE See also atmospheric stability.

3.5

direct path

position displacement vector, in metres, originating at the source and describing a straight trajectory terminating at the receiver

NOTE The direct path may intercept objects such as buildings or terrain.

3.6

directed sound speed

algebraic sum of the adiabatic sound speed and the horizontal component of the wind velocity along the direct path

NOTE Directed sound speed is expressed in metres per second.

3.7

directed sound speed profile

sound speed along the direct path, expressed as a function of height

NOTE See directed sound speed.

3.8

event

single short burst, or rapid sequence of bursts, associated with a sound source

NOTE A single activity, such as firing a gun, could produce multiple sound events. In the case of firing an explosive projectile from a high-velocity gun, sound events are associated with each of the following sound sources: the muzzle blast, the ballistic shock and the projectile impact.

3.9
event duration
T
time interval starting just before immission, at time t_1, and ending just after immission, at time t_2, to encompass all significant sound of a single short blast or rapid sequence of blasts

NOTE The time interval $t_2 - t_1$ is expressed in seconds.

3.10
exceedance level
sound level of a stated type, in decibels, exceeded by no more and no less than a stated percentage of samples

NOTE The sampling set shall be identified, e.g. percentage of times during a stated time interval or percentage of firing events from an exercise.

3.11
excess attenuation
that part of sound attenuation not included when accounting for geometric divergence (from a small sound source in non-refracting and non-moving air), atmospheric absorption of sound waves along the direct path from source to receiver and attenuation of screens and/or barriers

NOTE Excess attenuation is expressed in decibels.

3.12
excess-attenuation class
range of combined directed sound speed profiles and ground types yielding approximately the same attenuations, all within a specified uncertainty

3.13
ground condition
sound reflection and absorption properties of outdoor surface(s) along the sound path(s) between source and receiver

3.14
impulsive sound event
occurrence of a single short blast or series of blasts of sound in which the pressure-time history, close to the source, includes a rapid rise to the peak sound pressure followed by decay of the pressure

3.15
sound pressure
p
difference between instantaneous total pressure and static pressure

[ISO 80000-8:2007, 8-9.2]

NOTE 1 Sound pressure is expressed in pascals.

NOTE 2 The symbol p is often used without modification to represent a root-mean-square sound pressure. However, root-mean-square values should preferably be indicated by the subscript “eff”.

[ISO/TR 25417:2007, 2.1]

3.16
open-air explosion
blast, taking place out-of-doors, in which no part of the exploding material or gaseous products is limited by a container or any other obstructing surface

3.17
peak sound pressure

p_{peak}

greatest absolute sound pressure during a certain time interval

NOTE 1 Peak sound pressure is expressed in pascals.

NOTE 2 A peak sound pressure may arise from a positive or negative sound pressure.

[ISO/TR 25417:2007, 2.4]

NOTE 3 This definition is technically in accordance with ISO 10843.

3.18
peak sound pressure level

$L_{p,\,\mathrm{peak}}$

ten times the logarithm to the base 10 of the ratio of the square of the peak sound pressure, p_{peak}, to the square of a reference value, p_0, expressed in decibels

$$L_{p,\mathrm{peak}} = 10 \lg \frac{p_{\mathrm{peak}}^2}{p_0^2} \mathrm{dB}$$

where the reference value, p_0, is 20 µPa

NOTE Because of practical limitations of the measuring instruments, p_{peak}^2 is always understood to denote the square of a frequency-weighted or frequency-band-limited peak sound pressure. If a specific frequency weighting as specified in IEC 61672-1 is applied, this should be indicated by appropriate subscripts; e.g. $L_{p,\,\mathrm{C\ peak}}$ denotes the C-weighted peak sound pressure level.

[ISO/TR 25417:2007, 2.5]

3.19
receiver height

h_{r}

distance, in metres, of the sound receiver above the local ground surface

NOTE This definition is technically in accordance with ISO 9613-2.

3.20
replica atmosphere

conditions representing the atmosphere corresponding to a stated excess-attenuation class and a stated atmospheric-absorption class

3.21
roughness height

distance above local ground level to the elevation where the time-average horizontal wind velocity becomes non-zero

NOTE 1 The roughness height is expressed in metres.

NOTE 2 The time interval over which the wind velocity is averaged is 300 s.

3.22
sound exposure

E_T

integral of the square of the sound pressure, p, over a stated time interval or event duration T (starting at t_1 and ending at t_2) (see 3.9)

$$E_T = \int_{t_1}^{t_2} p^2(t)\,\mathrm{d}t$$

NOTE 1 Sound exposure is expressed in pascals squared seconds, $\mathrm{Pa}^2 \cdot \mathrm{s}$.

NOTE 2 Because of practical limitations of the measuring instruments, p^2 is always understood to denote the square of a frequency-weighted and frequency-band-limited sound pressure. If a specific frequency weighting as specified in IEC 61672-1 is applied, this should be indicated by appropriate subscripts; e.g. $E_{\mathrm{A,1\,h}}$ denotes the A-weighted sound exposure over 1 h.

NOTE 3 When applied to a single event of impulsive or intermittent sound, the quantity is called "single-event sound exposure" and the symbol E is used without a subscript.

NOTE 4 This definition is technically in accordance with ISO 80000-8:2007, 8-18.

[ISO/TR 25417:2007, 2.6]

3.23
sound exposure level

$L_{E,T}$

ten times the logarithm to the base 10 of the ratio of the sound exposure, E_T, to a reference value, E_0, expressed in decibels

$$L_{E,T} = 10 \lg \frac{E_T}{E_0} \mathrm{dB}$$

where the reference value, E_0, is $4 \times 10^{-10}\ \mathrm{Pa}^2 \cdot \mathrm{s}$

NOTE 1 If a specific frequency weighting as specified in IEC 61672-1 is applied, this should be indicated by appropriate subscripts; e.g. $L_{E,\mathrm{A,1\,h}}$ denotes the A-weighted sound exposure level over 1 h.

NOTE 2 When applied to a single event, the quantity is called "single-event sound exposure level" and the symbol L_E is used without further subscript.

NOTE 3 This definition is technically in accordance with ISO 80000-8:2007, 8-24.

[ISO/TR 25417:2007, 2.7]

3.24
source height

h_s

distance of the sound source above the local ground surface

NOTE 1 The source height is expressed in metres.

NOTE 2 This definition is technically in accordance with ISO 9613-2.

3.25
source forward direction

horizontal and vertical rotation angles assigned as references in the source-directivity coordinate system

3.26

adiabatic sound speed

c

speed of sound in the absence of ambient flow

NOTE The speed is expressed in metres per second.

4 Basic equations

4.1 General

ISO 1996-1 suggests a number of descriptors for environmental noise, some of which can be calculated from a statistically weighted summation of single-event sound exposures. Other descriptors can be evaluated by using order statistics derived from the distribution.

The single-event sound exposure level is subject to variation, in large part due to the effects of weather on the propagation to the receiver. In sound propagation measurements, it has been observed, for example, that the received sound level of a steady source can vary by several decibels from moment to moment, as well as from day to day or from season to season. Because the atmospheric temperature and wind can vary from point to point and from time to time, it is impractical to measure these values at all points during each event. It would also be equally impractical to employ so many measurements within a detailed calculation for making a routine noise assessment.

As a practical approach, the detailed atmosphere is described by several replica atmospheres, each being the (short term) average state of the atmosphere for various atmospheric conditions and ground conditions. Computations can be performed to estimate the single-event sound exposure level for the prevailing conditions for each replica atmosphere. For practical computations, only a limited number of representative situations can be managed. Therefore, the atmosphere is subject to classification in which each replica atmosphere is representative of its class. Histograms of the frequencies of occurrence of the wind velocity, wind direction, temperature, humidity and atmospheric stability are used to describe the different classes.

In this International Standard, two different classifications are used: atmospheric-absorption classes and excess-attenuation classes. Each replica atmosphere represents a combination of an atmospheric-absorption class with an excess-attenuation class. Using the calculated values of the short-term single-event sound exposure level, combined with the frequencies of occurrence of the various classes, as shown in this International Standard, it is feasible to calculate the sound exposure level as well as the exceedance level for a long-term interval.

4.2 Probability of occurrence

Consider a continuous random variable X. For any particular x, one can consider the likelihood that $X \leqslant x$. Accordingly, the cumulative distribution function is defined as:

$$F(x) = \mathrm{P_r}\left(X \leqslant x\right) \tag{1}$$

where

X is a random variable (possibly with dimensional units);

x is any value (with the dimensional units of X).

The cumulative distribution function is a monotonically increasing one and ranges in value from 0 to 1, as x ranges from $-\infty$ to $+\infty$.

Here and below, the role of the random variable can be taken by any of several types of quantity. The role includes, for example, such things as atmospheric parameters, sound exposure levels or sound attenuations. Two examples follow.

EXAMPLE 1 A measurement is performed to evaluate the probability distribution of the weather by atmospheric stability (see 8.4). In this case, the Monin-Obukhov length (see 8.3) is the random variable. The sample space is the list of all possible values of the Monin-Obukhov length.

EXAMPLE 2 The experiment is conducted to measure the probability distribution of the Z-weighted (unweighted) event sound exposure level of cannon fire measured at the receiver, for a specified type of cannon, ammunition, direction and elevation of fire, firing position and receiver position. In this case, the random variable is L_E. The sample space is the set of all values of the event sound exposure level.

For practical use, it is convenient to segment the range of a continuous distribution into several intervals. To this end, the following bin is defined:

$$\left\{ x : x_i - \delta_i < x \leqslant x_i + \delta_i \right\} \tag{2}$$

and the discrete probability:

$$\wp_i(x) = \mathrm{P_r}\left(x_i - \delta_i < x \leqslant x_i + \delta_i \right) = F(x_i + \delta_i) - F(x_i - \delta_i) \tag{3}$$

where

$\wp_i$ is the probability (dimensionless) of obtaining an outcome in the ith bin;

x_i is the central value of the ith bin (possibly with dimensional units);

δ_i is the bin half-width (with the dimensional units of x_i);

i is the index of the bin.

NOTE For simplicity, the probability bins are chosen to be equally spaced and contiguous, so that the sum of the probability of occurrence over the discrete domain is equal to one.

4.3 Band sound exposure level

The band sound exposure level, in decibels, from an impulse sound source shall be calculated by:

$$L_{E,k,l}(j) = S_{\phi,\theta}(j) - \left[A_{\mathrm{div}} + A_{\mathrm{atm},k}(j) + A_{\mathrm{rec}}(j) + A_{\mathrm{diff}}(j) + A_{\mathrm{exc},l}(j) \right] \tag{4}$$

where

$L_{E,k,l}(j)$ is the band sound exposure level, in decibels, under the conditions described by the kth atmospheric-absorption class and the lth excess-attenuation class;

j is the frequency band index;

$S_{\phi,\theta}(j)$ is the direction-dependent source band sound exposure level, in decibels, using a reference distance of one metre (see Clause 9);

ϕ is the (azimuth, yaw) angle, in degrees, between the source forward direction and the direct-path direction when all angles are projected onto the horizontal plane;

θ is the (elevation, pitch) angle, in degrees, between the source forward direction and the horizontal plane;

A_{div} is the attenuation, in decibels, due to geometric divergence (see 6.2);

$A_{\mathrm{atm},k}(j)$ is the band attenuation, in decibels, due to atmospheric absorption under conditions described by the kth atmospheric-absorption class (see 6.3);

$A_{\mathrm{rec}}(j)$ is the band attenuation, in decibels, due to the presence of barriers that can affect propagation (e.g. walls, berms or sound-attenuating screens) not already included in the source description (see 6.4);

$A_{\mathrm{diff}}(j)$ is the band attenuation, in decibels, due to shielding by terrain (see 6.5);

$A_{\mathrm{exc},l}(j)$ is the band excess attenuation, in decibels, under conditions described by the lth excess-attenuation class (see 6.6).

NOTE 1 For complex cases, the source sound exposure may include the combined effects of the source and sound-absorbing or -reflecting screens or barriers near to the source that affect propagation. The diffraction insertion loss of barriers or screens may be affected by meteorological conditions, requiring this to be accounted for separately.

NOTE 2 For omni-directional sources, such as open-air explosions, the source sound exposure is constant with respect to angles θ and ϕ.

4.4 Frequency-weighted sound exposure level

The frequency-weighted sound exposure level, $L_{E,\mathrm{w}}$, in decibels, shall be calculated by summation over bands, in accordance with

$$L_{E,\mathrm{w}} = 10 \lg \left[\sum_{j=N_{\mathrm{min}}}^{N_{\mathrm{max}}} 10^{0{,}1\left[L_E(j)+\mathrm{w}(j)\right]} \right] \mathrm{dB} \tag{5}$$

where

$L_E(j)$ is the band sound exposure level, in decibels, for the jth frequency band;

w is the type of frequency weighting (A-weighting or C-weighting, for example);

$\mathrm{w}(j)$ is the frequency weighting, in decibels, for the jth frequency band;

N_{min} is the lower band index;

N_{max} is the upper band index.

Bandwidths equal to one-third of an octave are preferred.

Contributions to the summation above from bands having values of $L_E(j) + \mathrm{w}(j)$ within twenty decibels of the maximum value of $L_E(j) + \mathrm{w}(j)$ for bands extending from band index 0 (1 Hz) to band index 40 (10 kHz) are considered significant and are required in the summation.

4.5 Long-term average single-event sound exposure level

For a single event with all source and receiver properties held constant, only the atmospheric absorption and excess attenuation can be subject to change. Using this fact, the probability of occurrence is the joint probability of the kth atmospheric-absorption class and the lth excess-attenuation class:

$$\wp\left(L_{E,\mathrm{w}} = x\right) = \sum_{\left\{(k,l) \mid L_{E,\mathrm{w},k,l}=x\right\}} \wp_{\mathrm{atm},k} \times \wp_{\mathrm{exc},l} \tag{6}$$

where

$\wp(L_{E,\mathrm{w}} = x)$ is the probability of occurrence of the equality $L_{E,\mathrm{w}} = x$ (see ISO 3534-1 for notation);

$L_{E,\mathrm{w}}$ is the frequency-weighted single-event sound exposure level for all combinations of excess-attenuation class and atmospheric-absorption class considered;

x	is a variable parameter, in decibels;
$\wp_{\mathrm{atm},k}$	is the probability of occurrence of the kth atmospheric-absorption class;
$\wp_{\mathrm{exc},l}$	is the probability of occurrence of the lth excess-attenuation class.

NOTE 1 It is implicit in Equation (6) that the joint probabilities of the atmospheric-absorption classes and the excess-attenuation classes are mutually independent, so that they appear only as multiplicands within the sum.

NOTE 2 The summation is performed as indicated by including those combinations, (k,l), which cause the frequency-weighted single-event sound exposure level to be equal to x.

The long-term average single-event sound exposure level, in decibels, can be found from the expectation value:

$$\langle L_{E,\mathrm{w}}\rangle_{\mathrm{LT}} = 10\ \lg\left[\sum_{k=1}^{N_{\mathrm{atm}}}\sum_{l=1}^{N_{\mathrm{exc}}} \wp_{\mathrm{atm},k}\wp_{\mathrm{exc},l}\ 10^{0{,}1L_{E,\mathrm{w},k,l}}\right]\ \mathrm{dB} \tag{7}$$

Alternatively, the long-term average single-event sound exposure rating level, in decibels, is

$$\langle L_{\mathrm{r}}\rangle_{\mathrm{LT}} = 10\ \lg\left[\sum_{k=1}^{N_{\mathrm{atm}}}\sum_{l=1}^{N_{\mathrm{exc}}} \wp_{\mathrm{atm},k}\wp_{\mathrm{exc},l}\ 10^{0{,}1\left(L_{E,\mathrm{w},k,l}+K\right)}\right]\ \mathrm{dB} \tag{8}$$

where

$\langle\ \rangle_{\mathrm{LT}}$	indicates the long-term average;
K	is the rating level adjustment for highly impulsive sounds, if applicable (see ISO 1996-1);
$\wp_{\mathrm{atm},k}$	is the probability of occurrence of the kth atmospheric-absorption class;
$\wp_{\mathrm{exc},l}$	is the probability of occurrence of the lth excess-attenuation class;
L_{r}	is the single-event sound exposure rating level, in decibels;
$L_{E,\mathrm{w},k,l}$	is the frequency-weighted sound exposure level, in decibels, under the conditions described by the kth atmospheric-absorption class and the lth excess-attenuation class;
w	is the type of frequency weighting, e.g. A-weighting or C-weighting;
N_{atm}	is the number of atmospheric-absorption classes;
N_{exc}	is the number of excess-attenuation classes.

The calculations in Equations (7) and (8) satisfy a key objective of this International Standard. The quantity $\langle L_{\mathrm{r}}\rangle_{\mathrm{LT}}$ is suitable for use in ISO 1996-1 as a frequency-weighted (and adjusted) single-event sound exposure level.

NOTE The method given above covers a unique single event, i.e. a single source, operated in the same mode, at the same location, in the same orientation, with the same intervening path to the receiver, etc. The only aspects allowed to vary are the atmospheric and ground parameters.

If a rating level is required (such as the day-evening-night level), this quantity shall take into account the penalties for the various assessment periods.

4.6 Equivalent level from multiple events

For the case of calculating the equivalent level from multiple events, the summation runs through the list of events, as follows:

$$L_{\mathrm{w,eq},T} = 10\,\mathrm{lg}\left[\frac{t_0}{T}\sum_{v=1}^{N_{\mathrm{evt}}} 10^{0{,}1\langle L_{E,\mathrm{w},v}\rangle_{\mathrm{LT}}}\right]\ \mathrm{dB} \tag{9}$$

where

$L_{\mathrm{w,eq},T}$ is the frequency-weighted equivalent level;

t_0 is the reference time period, in seconds, and is equal to 1 s;

T is the assessment time period, in seconds;

$\langle L_{E,\mathrm{w},v}\rangle_{\mathrm{LT}}$ is the long-term average frequency-weighted single-event sound exposure level;

N_{evt} is the number of events within the assessment time period;

v is the event index.

If a rating level is required (such as the day-evening-night level), this quantity shall take into account the penalties for the various assessment periods.

5 Calculation of a statistical distribution

To estimate a statistical distribution of the frequency-weighted sound exposure levels, all combinations of k and l shall be placed in sorted order with increasing values of level:

$$L_{E,\mathrm{w},m-1} < L_{E,\mathrm{w},m}, \quad \text{with } m = 2,\ldots,M \tag{10}$$

where

M is the number of combinations ($M = N_{\mathrm{atm}} \times N_{\mathrm{exc}}$);

N_{atm} is the number of atmospheric-absorption classes;

N_{exc} is the number of excess-attenuation classes.

This can be seen as a new classification of the sound exposure levels with M classes, in which each class is a unique combination of the kth atmospheric-absorption class and lth excess-attenuation class. The class width is chosen in such a way that there are no gaps between adjacent classes. The lower and upper boundaries, $g_{\mathrm{L},m}$ and $g_{\mathrm{U},m}$, between adjoining classes are chosen to lie half-way between consecutive values:

$$g_{\mathrm{L},m} = g_{\mathrm{U},m-1} = \left(\frac{L_{E,\mathrm{w},m-1} + L_{E,\mathrm{w},m}}{2}\right) \quad \text{for } m = 2,\ldots,M \tag{11}$$

The extreme lower and upper boundaries shall be chosen such that

$$g_{\mathrm{L},1} = L_{E,\mathrm{w},1} - (g_{\mathrm{U},1} - L_{E,\mathrm{w},1}) \tag{12}$$

and

$$g_{\mathrm{U},M} = L_{E,\mathrm{w},M} + (L_{E,\mathrm{w},M} - g_{\mathrm{L},M}) \tag{13}$$

The probability of occurrence of each class, m, is calculated by

$$\wp_m = \mathrm{P_r}\left\{g_{\mathrm{L},m} < L_{E,\mathrm{w},m} < g_{\mathrm{U},m}\right\} = \wp_{\mathrm{atm},k}\wp_{\mathrm{exc},l} \tag{14}$$

where

$\wp_m$ is the probability of occurrence for the interval m [of combination (k,l)];

$\wp_{\mathrm{atm},k}$ is the probability of occurrence of atmospheric-absorption class k;

$\wp_{\mathrm{exc},l}$ is the probability of occurrence of excess-attenuation class l.

A probability density function $\rho_m(x)$ can then be defined:

$$\rho_m(x) = \begin{cases} \dfrac{\wp_m}{g_{\mathrm{U},m} - g_{\mathrm{L},m}} & \text{for} \quad g_{\mathrm{L},m} < x < g_{\mathrm{U},m} \\ 0 & \text{elsewhere} \end{cases} \tag{15}$$

In the rare case that $L_{E,\mathrm{w},m-1} = L_{E,\mathrm{w},m} = L_{E,\mathrm{w},m+1}$, the probability function $\rho_m(x)$ is not defined. In this case, classes with the same level shall be combined.

The overall probability density function, $\rho(x)$, is defined as

$$\rho(x) = \sum_{m=1}^{M} \rho_m(x) \tag{16}$$

so $\rho(x) \times \delta x$ is the probability that the level is within the interval between $x - \frac{1}{2}\delta x$ and $x + \frac{1}{2}\delta x$. As a consequence of the method used [Equation (16)], the function $\rho(x)$ has discontinuities at the class boundaries, $g_{\mathrm{L},m}$ and $g_{\mathrm{U},m}$ (see Figure 1).

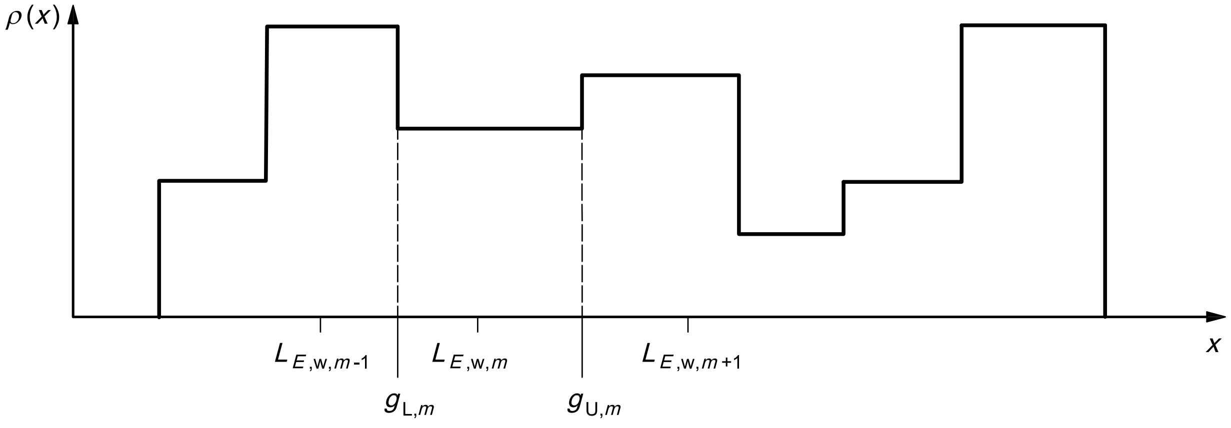
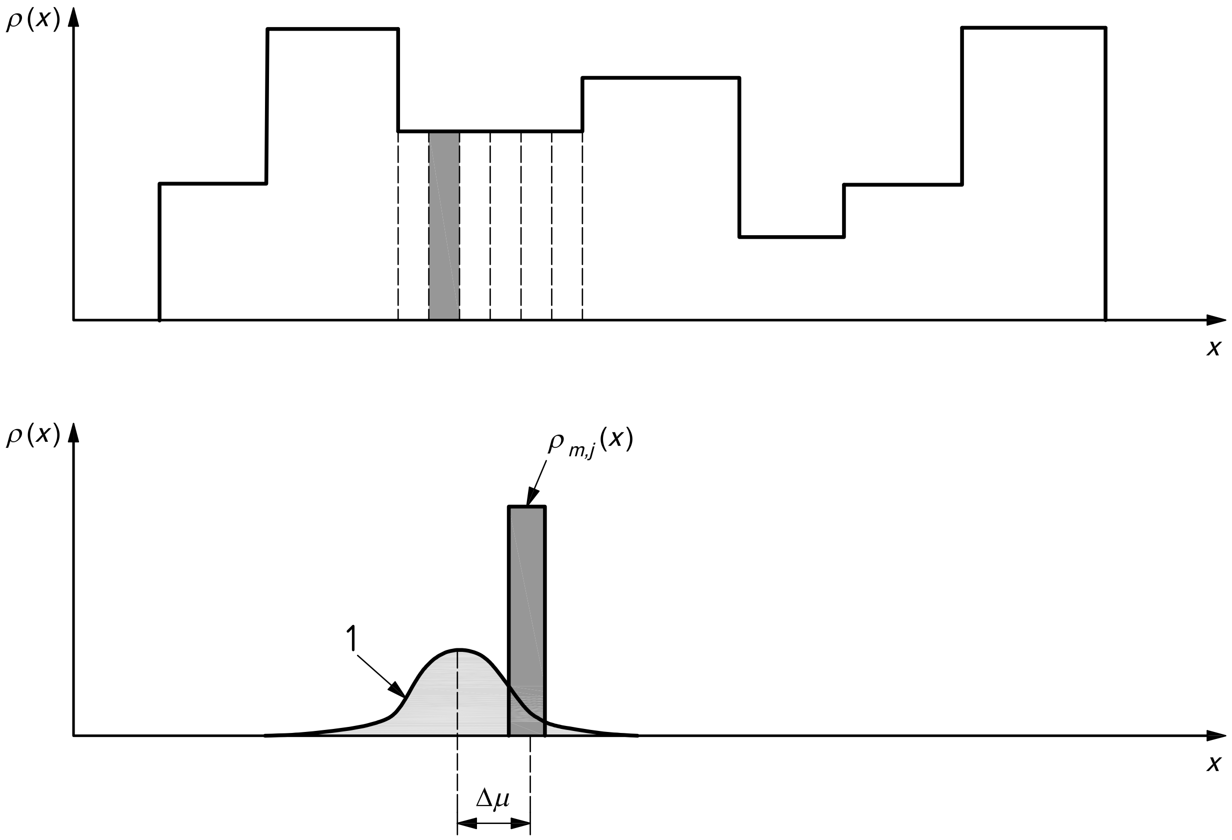


Figure 1 — Probability density function, $\rho(x)$, with constant values within classes m

In practice, the number of classes, M, is limited to a value of, typically, 10 to 100. Each class therefore represents a range of atmospheric conditions which are assumed to have an equal probability of occurrence in that class. The discontinuities in the function $\rho(x)$ cause discontinuities in calculated statistical distributions of the sound exposure level.

To obtain the final statistical distribution, the following has to be taken into account. The calculations are performed without taking into account the random perturbations of the sound speed profile (turbulence). Therefore, the different classes represent sample values from within a small range of different atmospheric and ground conditions. Field measurements indicate that the spread in levels due to turbulence can be described by a normal distribution with a standard deviation equal to 5 dB. However, depending on the local situation, other distributions may be more appropriate. If more information is available about the distribution of levels, this should be taken into account.

NOTE The purpose of the distribution is to quantify the spreading of the levels due to turbulence, which can occur in a particular combination of one atmospheric-absorption class and one excess-attenuation class. What must be considered is spreading of the levels over a short time interval, typically shorter than 15 minutes. The distribution is not meant to describe the spreading of levels due to changing weather conditions.



Key

1 Gaussian function

Figure 2 — Probability density function, with each class, m, divided into N_{sub} subclasses (top) and with subclass $\{m, j\}$ replaced by a continuous Gaussian function (bottom)

This spreading of levels due to turbulence will be taken into account by a convolution of the function $\rho(x)$ with a normal distribution having a standard deviation of 5 dB (the value typically used). This operation is carried out in two steps (see Figure 2):

First, each class, m, is divided into N_{sub} equal, contiguous subclasses labelled by an index, j (= 1,...,N_{sub}). Subclass $\{m, j\}$ runs from $x = \mu_{m,j} - \frac{1}{2} b_m$ to $x = \mu_{m,j} + \frac{1}{2} b_m$, where b_m is the width of each subclass and is given by

$$b_m = \frac{g_{\mathrm{U},m} - g_{\mathrm{L},m}}{N_{\mathrm{sub}}} \tag{17}$$

and $\mu_{m,j}$ is the centre of the subclass and is given by

$$\mu_{m,j} = g_{\mathrm{L},m} + (j - \tfrac{1}{2}) b_m \tag{18}$$

Each subclass corresponds to a probability density given by

$$\rho_{m,j}(x) = \begin{cases} \rho_m(x) & \text{for} \quad \mu_{m,j} - \tfrac{1}{2} b_{m,j} < x < \mu_{m,j} + \tfrac{1}{2} b_{m,j} \\ 0 & \text{elsewhere} \end{cases} \tag{19}$$

The total probability density function is therefore given by

$$\rho(x) = \sum_{m=1}^{M} \sum_{j=1}^{N_{\mathrm{sub}}} \rho_{m,j}(x) \tag{20}$$

Next, the discontinuous probability density functions, $\rho_{m,j}(x)$, are replaced by continuous normalized Gaussian functions to give

$$\rho^{*}_{m,j}(x) = b_m \rho_{m,j}(\mu_{m,j}) \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{ -\frac{\left[x - (\mu_{m,j} - \Delta\mu) \right]^2}{2\sigma^2} \right\} \tag{21}$$

where σ is the standard deviation, for which a value of 5 dB is typically used.

The shift $\Delta\mu$ is introduced to ensure that the energetically averaged level remains at the value $\mu_{m,j}$. The value of $\Delta\mu$ can be obtained using Equation (22):

$$\Delta\mu = 10\,\lg\left[\frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\infty} 10^{0{,}1x} \exp\left(-\frac{x^2}{2\sigma^2} \right) \mathrm{d}x \right] \text{ dB} \tag{22}$$

The continuous overall probability density function is defined as

$$\rho^{*}(x) = \sum_{m=1}^{M} \sum_{j=1}^{N_{\mathrm{sub}}} \rho^{*}_{m,j}(x) \tag{23}$$

From the continuous function $\rho^{*}(x)$, various types of statistical quantities or functions can be derived. For example, the cumulative probability that the frequency-weighted sound exposure level is higher than a value of x dB is given by

$$\mathrm{P_r}(L_{E,\mathrm{w}} > x) = \int_{x}^{\infty} \rho^{*}(x') \mathrm{d}x' \tag{24}$$

where x' is an integration variable.

An n-percent exceedance level, $L_{E,\mathrm{w},n}$ (for instance, $L_{E,\mathrm{A},95}$), can be obtained by solving Equation (25) for x:

$$\mathrm{P_{95}}(L_{E,\mathrm{A}} > x) = \int_{x}^{\infty} \rho^{*}(x') \mathrm{d}x' = 0{,}95 \tag{25}$$

where

n is the percentage of values that exceed x [in Equation (25) above, $n = 95$];

x is the exceedance level, in decibels.

6 Calculation of attenuation

6.1 General

Attenuation of sound during propagation is the result of several effects. Geometric divergence of sound away from a compact source is discussed in 6.2, atmospheric absorption in 6.3, insertion loss by receiver site screening objects in 6.4 and shielding by terrain in 6.5. It is common to include all other effects under the term “excess attenuation”, as can be seen in 6.6.

6.2 Geometric divergence

The attenuation, A_{div}, in decibels, due to geometrical divergence shall be calculated assuming spherical spreading of the wave front surface area with distance from a point sound source in non-moving and non-refracting air. This calculation is as follows:

$$A_{\text{div}} = 20\,\lg\left(d / d_0\right)\ \text{dB} \tag{26}$$

where

A_{div} is the attenuation of geometric divergence, in decibels;

d is the distance from the source to the receiver, in metres;

d_0 is the reference distance for source sound exposure, equal to one metre ($d_0 = 1$ m).

6.3 Atmospheric absorption

Tabulations of atmospheric-absorption attenuation coefficients can be found in ISO 9613-1 for frequencies of 50 Hz and above and for one static atmospheric pressure only. For the purposes of this International Standard, the equations given in ISO 9613-1 are adequate for calculating attenuation by atmospheric absorption at other frequencies and at other static atmospheric pressures. The values of atmospheric temperature and humidity can also be partitioned into discrete ranges (atmospheric-absorption classes) before calculating the atmospheric absorption. In this way, band attenuation coefficients (see ISO 9613-1) and their probabilities of occurrence can be calculated and stored for subsequent rapid retrieval. The relevant heights and quantities for evaluation of atmospheric absorption appear in ISO 9613-1.

The band attenuation, in decibels, during propagation over a given distance due to atmospheric absorption shall be calculated as follows:

$$A_{\text{atm},k}(j) = \alpha_k(j) d \tag{27}$$

where

$A_{\text{atm},k}(j)$ is the band attenuation, in decibels, along the direct path (see ISO 9613-1) for the kth atmospheric-absorption class;

$\alpha_k(j)$ is the band attenuation coefficient, in decibels per metre (see ISO 9613-1), for the kth atmospheric-absorption class;

d is the distance from source to receiver, in metres;

j is the frequency band index;

k is the atmospheric-absorption class index.

NOTE For reasons of accuracy, it is usually not adequate to arithmetically average attenuations or attenuation coefficients, nor is it adequate to use a single “typical” value of temperature or humidity for calculating attenuation.

6.4 Insertion loss by screening objects

The band attenuation, $A_{\text{rec}}(j)$, in decibels, due to the presence of barriers (e.g. walls, berms or sound-attenuating screens) which are not included in the source description and affect propagation shall be calculated in accordance with ISO 9613-2.

NOTE 1 The quantity $A_{\text{rec}}(j)$ as used in this International Standard amounts to a special case of insertion loss compared with the situation in which the receiver is above flat ground. For the case of an unscreened receiver above flat ground, the receiver site attenuation is given by $A_{\text{rec}}(j) = 0$ dB.

NOTE 2 The insertion loss due to barriers is a function of the meteorological class because of the observed effect of refraction of the sound waves by the atmosphere in addition to their diffraction by the barriers. However, with situations where the barrier is near to the receiver, the approximate insertion loss can be calculated by the method given in ISO 9613-2 without the requirement for a downwind situation.

6.5 Terrain shielding

In principle, terrain interposed between the source and the receiver can attenuate immission. However, a few phenomena act to reduce the potential attenuation, namely 1) boundary reflection, 2) refraction and 3) turbulent scattering. Moreover, phenomena such as turbulent scattering of sound and irregularly shaped terrain add to the uncertainty in evaluating the attenuation due to terrain shielding. Large-scale terrain features, such as mountains, or groups of tall buildings, such as occur in urban areas, can pose additional problems and lie beyond the scope of this subclause. Complex terrain features require special evaluation which may include flow modelling or boundary element methods, using, for example, the methods mentioned in Reference [30].

In this subclause, the thin-screen model of ISO 9613-2 is adapted to evaluate the attenuation of sound by terrain shielding. In the calculation, two distances are compared: the direct line-of-sight path between the source and the receiver and the shortest path tangential to the terrain. In constructing the model, it is anticipated that the thin-screen model of ISO 9613-2 will overestimate the attenuation at low frequencies. Thus, two coefficients are adjusted to eliminate attenuation caused by the terrain below the direct line of sight. Additionally, the influences in ISO 9613-2 of meteorology (K_{met}) and multiple diffraction (C_3) have been omitted.

The vertical plane containing the source and the receiver intersects the terrain and defines the terrain profile. Only if the terrain intercepts the line-of-sight path will terrain shielding be considered here. If the line of sight is indeed intercepted by the terrain, the shortest path over the terrain is the convex hull of a set of points (source, receiver and terrain profile vertices) in the dimensions of distance and elevation. Only the upper portion of the hull connecting the source and receiver is then of interest. For situations involving many sources and receivers or complex terrain, a digital elevation map can be helpful to identify the terrain profile. In situations where a shorter airborne path exists outside the vertical plane, the shorter distance is preferred.

The attenuation by terrain shielding is given by

$$A_{\text{diff}}(j) = \begin{cases} 0 \text{ dB}, & N_1 < 0{,}0 \\ 10 \lg(1 + 10 N_1) \text{ dB}, & 0 \leqslant N_1 \leqslant 12{,}5 \\ 21 \text{ dB} & N_1 > 12{,}5 \end{cases} \tag{28}$$

where

$$N_1 = 2\delta / \lambda(j) \tag{29}$$

$$\delta = D - d \tag{30}$$

$A_{\text{diff}}(j)$	is the attenuation, in decibels, due to terrain shielding between source and receiver;
δ	is the difference, in metres, between the paths from source to receiver, with a positive sign if the shortest tangential path, D, lies above the direct path, d;
D	is the distance, in metres, along the shortest path from source to receiver above the terrain with at least one point where it is tangential to the terrain;
d	is the direct-path distance, in metres, from source to receiver irrespective of the terrain;
$\lambda(j)$	is the wavelength, in metres, given by $\lambda(j) = c/f(j)$;
$f(j)$	is the centre frequency of the jth band, in hertz;
c	is a representative sound speed, in metres per second (see e.g. 6.6.2).

6.6 Contributions to excess attenuation

6.6.1 General

It is common for the sound field outdoors to be significantly attenuated (or enhanced) by refraction and ground reflection. It is important to emphasize that the attenuations resulting from these two phenomena are not simply additive. Refraction is dealt with in 6.6.2. Ground reflection is discussed in 6.6.3.

6.6.2 Refraction

Refraction is evaluated based on the wind and temperature fields and the locations of source and receiver. In general, wind and temperature vary with position. The effects of time dependence for wind and temperature are considered in the following paragraphs.

The adiabatic sound speed in air, considered in a reference frame moving along with the local ambient flow, is given by

$$c = \left(\kappa R \theta\right)^{1/2} \tag{31}$$

where

κ is the specific heat ratio of air (dimensionless) (for dry air, $\kappa = 1{,}4$);

R is the gas constant, in joules per kilogram per kelvin (for dry air, $R = 287\ \text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$);

θ is the air temperature, in kelvins.

NOTE In general, the temperature, and therefore the adiabatic sound speed, vary with position and time.

Sound travelling with the wind travels faster than in any other direction because of advection effects.

Sound propagation near the direct path is affected by refraction, primarily by vertical gradients of the directed sound speed. In situations where the range of temperatures is small compared to a central value, an approximate expression for the sound speed directed towards a given azimuth can be calculated using a Taylor expansion as shown below:

$$c_{\phi} = c + V \cos\alpha \approx c_0 + \frac{1}{2}\frac{\kappa R}{c_0}(\theta - \theta_0) + V \cos\alpha \tag{32}$$

where

c_ϕ is the directed sound speed, in metres per second, in the direction of the direct path;

V is the horizontal wind velocity, in metres per second;

θ_0 is the reference temperature, in kelvins (= 273,15 K);

α is the angle between the wind direction and the direct path to the receiver, given by $\alpha = -\phi_R + \phi_V - 180°$;

ϕ_R is the azimuth angle of the direct path toward the receiver, relative to a reference direction;

ϕ_V is the azimuth angle of the wind direction, relative to a reference direction;

c_0 is the adiabatic sound speed, in metres per second, at temperature θ_0 (in air, it is 331,5 m/s).

NOTE 1 The temperature and the wind velocity are general functions of height and horizontal position. In a few situations of interest, neither is a strong function of horizontal position, allowing for simplifications.

NOTE 2 The height dependence of sound speed on the air humidity is negligible when compared to the height dependence of sound speed on the temperature or wind, for example.

For the purposes of accuracy, θ shall be chosen to be near to the spatial- and time-average temperature for the situation under study.

The vertical component of the gradient of the directed sound speed in Equation (32) is given by

$$\frac{\partial c_\phi}{\partial z} = \frac{1}{2}\frac{\kappa R}{c_0}\frac{\partial T}{\partial z} + \frac{\partial V}{\partial z}\cos\alpha - V\frac{\partial \alpha}{\partial z}\sin\alpha \qquad (33)$$

where all symbols are as defined previously.

Since the meteorological conditions will change, the sound speed profile will vary with time. When estimating the statistical distribution of sound exposure levels, the variability of this profile has to be taken into account. This can readily be done by classification of the profiles (see 7.3).

Various methods exist for the calculation of the excess-attenuation spectra for different sound speed profiles. In the European project Harmonoise, a set of methods using a parabolic equation was selected as the basis for the so-called Harmonoise reference model [22]. A detailed description of the parabolic-equation methods can be found in Reference [31], including relevant references to the acoustics literature.

Parabolic-equation methods take into account the effects of atmospheric refraction caused by the non-constant vertical profiles of the wind and temperature in the atmosphere. Furthermore, it is possible to take into account the effects of atmospheric turbulence on sound propagation, in particular the effect of the scattering of sound waves into refractive shadow regions.

6.6.3 Ground reflection and absorption

6.6.3.1 General

Several methods exist for the calculation of the ground reflection and absorption of sound. These methods employ the normalized ground impedance, Z (normalized with respect to the impedance of the air), and some additionally use the bulk wave number, k_b. Various empirical and theoretical models exist to calculate Z and k_b, as a function of frequency, from parameters that characterize the absorbing material, such as flow resistivity and porosity. This International Standard gives examples of ground reflection and absorption models and discusses two of them in 6.6.3.2 and 6.6.3.3.

Some ground surfaces are modelled as a layer of porous material with a rigid backing. In these cases, the impedance is calculated from the relationship

$$Z_{\mathrm{layer}} = Z \coth(-\mathrm{i} k_{\mathrm{b}} d_Z) \tag{34}$$

where

Z_{layer} is the complex ratio of the impedance of the surface layer of the ground to sound at vertical incidence to the impedance of air to sound (dimensionless);

Z is the complex ratio of the impedance of the underlying ground to that of air (dimensionless);

k_{b} is the complex wave number for sound waves in the ground, in units per metre;

d_Z is the surface layer thickness, in metres.

Table 1 lists impedance models and parameters for various ground surfaces. The values of the parameters in the table are “default” values which can be replaced by values obtained from measurements.

An unusually high degree of surface roughness can increase the imaginary part of the surface impedance to a level above that obtained by using Table 1. This additional contribution can be evaluated by using one of many rough-surface impedance models.

Table 1 — Impedance models and parameters for various ground surfaces

Surface type	Impedance model	“Default” parameters	
Concrete, (dense) asphalt, ice, water	Rigid surface	$Z = \infty$	
Compacted soil	Delany and Bazley	σ = 2 000 kPa·s/m^2	$d_Z = \infty$
Grassland, cultivated land	Delany and Bazley	σ = 200 kPa·s/m^2	$d_Z = \infty$
Forest humus	Exponential porosity	σ = 8 kPa·s/m^2	α_Ω = 25 m^{-1}
Snow	Delany and Bazley	Fresh snow: σ = 5 kPa·s/m^2 Old snow: σ = 30 kPa·s/m^2	Thin layer: d_Z = 0,1 m
			Medium layer: d_Z = 0,3 m
			Thick layer: d_Z = 1,0 m
Mixed ground (asphalt/grassland)	Delany and Bazley	100 % grass: σ = 200 kPa·s/m^2	$d_Z = \infty$
		67 % grass: σ = 400 kPa·s/m^2	
		50 % grass: σ = 600 kPa·s/m^2	
		33 % grass: σ = 1 000 kPa·s/m^2	
		0 % grass: $\sigma = \infty$	

σ is the flow resistivity;

α_Ω is the logarithmic decrement of the porosity with depth.

6.6.3.2 Impedance model of Delany and Bazley

Delany and Bazley [17] have developed an empirical model for fibrous absorbent materials which is also used for natural ground such as grassland. The basic equations are

$$Z = 1 + 0{,}051\,1\left(\frac{\sigma}{f}\right)^{0{,}75} + \mathrm{i}0{,}076\,8\left(\frac{\sigma}{f}\right)^{0{,}73} \tag{35}$$

and

$$\frac{k_{\mathrm{b}}}{\omega / c}=1+0{,}085\,8\left(\frac{\sigma}{f}\right)^{0{,}70}+\mathrm{i}\,0{,}175\left(\frac{\sigma}{f}\right)^{0{,}59} \tag{36}$$

where

σ is the flow resistivity, in pascal seconds per square metre (Pa·s/m^2);

f is the frequency, in hertz;

the other symbols are as defined previously.

Flow resistivity is a parameter equal to the ratio of the pressure gradient to the velocity of the fluid for small values of imposed steady pressure. The positive sign of the imaginary parts in the above equations corresponds to the choice of the harmonic time factor exp($-\mathrm{i}\omega t$) in sound propagation models.

6.6.3.3 Impedance model for exponentially graded porosity

The impedance model for exponentially graded porosity [15] yields an expression for Z only:

$$Z=0{,}484\left(\frac{\sigma}{f}\right)^{0{,}5}+\mathrm{i}\left[0{,}484\left(\frac{\sigma}{f}\right)^{0{,}5}+30\frac{\alpha_{\Omega}}{f}\right] \tag{37}$$

where

α_{Ω} is the logarithmic decrement of the porosity with depth, in reciprocal metres (m^{-1});

the other symbols are as defined previously.

7 Classification

7.1 General

As outlined in 4.3, the atmospheric absorption and the excess attenuation are subject to classification. For practical computations in routine applications, only a limited number of classes can be managed.

7.2 Classification of atmospheric absorption

The classification for the atmospheric absorption is described in 6.3. The calculation of the atmospheric absorption can be performed using ISO 9613-1.

7.3 Classification of excess attenuation

7.3.1 General

The calculation of the excess attenuation for the various classes can be very laborious. A lookup table shall be used to constrain the number of these calculations by accessing the results of previous calculations for the set of excess-attenuation classes. The lookup table of excess attenuations shall be partitioned into excess-attenuation classes with the following properties:

N_{exc} is the number of classes into which excess-attenuation conditions are divided;

$A_{\mathrm{exc},l}$ is the excess attenuation, in decibels, of the lth excess-attenuation class;

$\wp_{\mathrm{exc},l}$ is the probability of occurrence of the lth excess-attenuation class, such that $\sum_{l=1}^{N_{\mathrm{exc}}} \wp_{\mathrm{exc},l}=1$.

An excess-attenuation class is defined by the combination of the directed sound speed profile and the ground characteristics (type and condition). See 7.3.2 for a more detailed description of lookup table requirements. Directed sound speed profiles are discussed in 7.3.4.

If the ground conditions (moisture content, snow cover, etc.) within the period of interest change, the ground impedance will vary accordingly, resulting in varying excess attenuations. The actual variation in the ground impedance within the period of interest shall be taken into account.

The probability of occurrence of a profile is estimated from the combined probability of the observable quantities describing meteorological situations. In Clause 8, several approaches are described to determine this probability for the situation under study.

7.3.2 Lookup table requirements

The lookup table of excess attenuations shall consist of functional dependencies on the following:

- parameters describing the directed sound speed profile;
- the ground type (grass, sand, concrete, etc.);
- the ground conditions (moisture content, snow cover, etc.);
- the height of the source above the ground;
- the height of the receiver above the ground;
- the source-receiver distance;
- the frequency band.

The number of excess-attenuation classes is equal to the product of the number of sound speed profiles and the number of different types of ground conditions. The probabilities of occurrence of an excess-attenuation class shall be estimated from the probabilities of the sound speed profile and — if relevant — the ground conditions. It is assumed that the probabilities of the ground conditions and the sound speed profile are approximately independent, though clearly the sound speed profiles are themselves influenced by the ground.

NOTE The sound speed profile and the ground conditions are statistical quantities. The probability of occurrence of an excess-attenuation class is determined by these quantities only. Therefore, it makes sense to define an excess-attenuation class solely on the basis of the sound speed profile and the ground conditions.

From a practical point of view, any lookup table is restricted to a finite size. Restricting the size of the lookup table can be accomplished by constraining the parameters to discrete ranges, or classes. The number of classes depends on the utilization of the lookup table. If it is used to estimate a long-term averaged level as a weighted average over the different classes, the accuracy will be expected to increase with the number of classes. The choice of an appropriate number of classes is a trade-off between accuracy and computational effort.

To extract a distribution of excess attenuations from the lookup table for a specific situation under study, the situation shall be matched with the “nearest” combination that can be found in the lookup table. The matching shall take place with respect to the ground type and the geometrical quantities (e.g. source height, receiver height and source-receiver distance). The matching with respect to the geometrical quantities can be achieved by using an eight-point linear-interpolation scheme within a rectangular parallelopiped comprising the nearest source heights, receiver heights and source-receiver distances in the lookup table. Where possible, the reciprocity principle can be used to extend the number of results the lookup table contains. Based on this principle, the following relationship can be used:

$$A_{\text{exc},l}\left(h_{\text{r}},h_{\text{s}}\right)=A_{\text{exc},l}\left(h_{\text{s}},h_{\text{r}}\right) \tag{38}$$

where

h_s is the height of the source above the ground, in metres;

h_r is the height of the receiver above the ground, in metres.

Extrapolation, i.e. evaluations beyond the tabulated range of values, with respect to source and receiver heights and source-receiver distance shall be avoided.

For this matching, the lookup table shall give, for each excess-attenuation class (as a function of the sound speed profile and the ground conditions), the excess attenuation for each frequency band, with one-third-octave bands preferred.

The probability of occurrence of an excess-attenuation class shall be derived from the lookup table on the basis of the profile, the ground conditions and the angle of the sound propagation path with respect to the reference direction. The last-mentioned is relevant because the probability of any given wind direction is, in general, angle-dependent. In Clause 8, several approaches are described to determine the probability of occurrence of an excess-attenuation class.

7.3.3 Range-dependent sound speed profiles

In the preceding, it has implicitly been assumed that the sound speed profile is constant along the sound propagation path. This will be true for flat, homogeneous terrain. Over complex terrain, such as hills, the refraction will be range-dependent. Other types of range-dependent surface include those whose roughness height or soil temperature changes along the direct sound path (e.g. coastlines, lake shores and city or forest limits). Where refraction depends on position, the temperature and wind fields may require sophisticated treatment, such as with fluid-dynamical meteorological models (see Reference [29]).

7.3.4 Directed sound speed profiles

The sound speed profiles in the atmospheric surface layer may be approximated by logarithmic-linear functions, as follows:

$$c_l(z) = a_0 + G_l \ln(1 + z/z_0) + H_l z \tag{39}$$

where

$c_l(z)$ is the sound speed as a function of height, in metres per second, for the lth excess-attenuation class;

a_0 is the sound speed, in metres per second, at ground level;

z_0 is the roughness height, in metres;

G_l is a fit parameter, expressed in metres per second, for the lth excess-attenuation class;

H_l is a fit parameter, expressed in reciprocal seconds (s^{-1}), for the lth excess-attenuation class.

As the excess attenuation is dependent mainly on the sound speed gradient, the parameter α_0 does not have to be included as a parameter to describe the set of sound speed profiles. Small changes in z_0 (< 35 cm) can be neglected. Only 25 logarithmic-linear profile classes suffice to determine the long-term averaged sound exposure level at 1 000 m range with an uncertainty of better than 2 dB [11]. Understandably, longer distances will incur lower accuracy or require increasingly more classes to achieve the same accuracy.

The values of the parameters G_l and H_l shall be distributed within their respective intervals as follows:

$$-1\,\mathrm{m/s} < G_l < 1\,\mathrm{m/s} \tag{40}$$

$$-0{,}2\,\mathrm{s}^{-1} < H_l < 0{,}2\,\mathrm{s}^{-1} \tag{41}$$

By increasing the numbers of tabulated values of G_l and H_l over their respective intervals, the spacings are made smaller, the variations between excess attenuations are made smaller and the accuracy can be improved. If, on the basis of the actual weather data, it can be concluded that the tabulated values do not correspond to the observed situation, the range of values shall be adjusted to fit the range in the actual weather data. The atmospheric surface layer encompasses a range of heights above the ground, up to approximately $2l_{\mathrm{MO}}$ in the stable case and up to $|l_{\mathrm{MO}}|$ in the unstable case, where l_{MO} is the Monin-Obukhov length (see 8.3).

Above the atmospheric surface layer, the wind direction turns towards the direction of the mean free atmosphere, known as the geostrophic wind. This elevated portion of the wind profile becomes more important when horizontal distances exceed ten times the height of the atmospheric surface layer. For such situations, the log-lin profile may be insufficient; the profile may need additional characterizations and/or measurements and thus require direct calculation for sound propagation analyses.

Functions other than the log-lin sum may be used. In Reference [30], examples are given of profiles consisting of a combination of power functions and log functions. One such example is shown in Equations (A.1) to (A.3) in Annex A. Computationally fast constant-curvature ray models require that the gradient of the sound speed is independent of height, i.e. $G_l = 0$ in Equation (39). Enforcing linear speed variation throughout the layer from ground level to heights greater than 1,5 km above the ground is generally not realistic and shall be avoided unless the situation can be measured.

8 Probability of occurrence of sound speed profiles

8.1 General

Three different approaches will be described to determine, from a representative set of sound speed profiles, the probability of occurrence of sound speed profiles for the situation under study:

- using direct measurements of the vertical profile of the horizontal wind and the temperature (see 8.2 and 8.6);
- using measurements of turbulent fluxes of momentum and heat (see 8.4);
- using routinely gathered weather station data (see 8.5).

The last two approaches are based on similarity relationships for the atmospheric surface layer (see 8.3).

8.2 Using direct measurements of wind and temperature profiles

Wind and temperature profiles can be measured with sensors disposed at different heights on a meteorological tower. The usual choices for sensor heights include 2 m, 5 m and 10 m to establish the height of the atmospheric surface layer.

Additional coverage, such as by radiosonde flights, may be required to evaluate the region above the surface layer for long-distance propagation.

The measurements shall be performed over a long period, say one year, over regular time intervals (e.g. averaged values each hour) to obtain a representative statistical picture. Measurements relevant to the assessment period under study shall take into account the time at which the sound-generating activities occur. If, for instance, during the summer no sound-producing activities occur, the summer period shall not be considered part of the measurement period. The measured sound speed profiles shall be transformed into directed sound speed profiles for the relevant sound propagation directions. The directed sound speed profiles shall be matched to the chosen set of profiles by applying a curve-fitting algorithm which is based on gradient expansion to compute a non-linear least-squares fit (see Reference [13]). The probability of occurrence of a profile is equal to the ratio of the number of matches found to the total number of measured profiles.

8.3 Similarity relationships for the atmospheric surface layer

Similarity relationships for turbulence in the atmospheric surface layer are based on the original developments in Reference [26]. Several empirical relationships between dimensionless quantities related to wind and temperature have also been developed. The following method incorporates the relationships as first employed in References [14] and [18]. However, other methods may also be appropriate in some situations. Situations in which the model is inapplicable are described at the end of this subclause.

Key quantities are the (dimensionless) vertical gradient of the (mean) wind velocity, given by

$$\phi_{\mathrm{M}} = \frac{\kappa z}{u_*}\frac{\partial V}{\partial z} \quad \Rightarrow \quad \frac{\partial V}{\partial z} = \frac{u_*}{\kappa z}\phi_{\mathrm{M}} \tag{42}$$

and the vertical component of the (mean) temperature gradient, given by

$$\phi_{\mathrm{H}} = \frac{\kappa z}{\theta_*}\left(\frac{\partial \theta}{\partial z} - \gamma\right) \quad \Rightarrow \quad \frac{\partial \theta}{\partial z} = \phi_{\mathrm{H}}\frac{\theta_*}{\kappa z} + \gamma \tag{43}$$

where

V	is the wind velocity, in metres per second;
γ	is the vertical gradient of the temperature, in kelvins per metre, under adiabatic conditions (for dry air, $\gamma = -0{,}009\,8$ K/m);
κ	is the specific heat ratio (dimensionless) (for dry air, $\kappa = 1{,}4$);
u_*	is the turbulent velocity scaling parameter, in metres per second;
θ_*	is the turbulent temperature scaling parameter, in kelvins.

The turbulent fluxes of momentum, F_{M}, and heat, F_{H}, are given by

$$F_{\mathrm{M}} \equiv \rho\left\langle V'W'\right\rangle = -\rho u_*^2 \tag{44}$$

$$F_{\mathrm{H}} \equiv c_{\mathrm{p}}\rho\left\langle \theta'W'\right\rangle = -c_{\mathrm{p}}\rho u_*\theta_* \tag{45}$$

where

ρ	is the ambient-air density, in kilograms per cubic metre;
c_{p}	is the specific heat capacity at constant pressure, in joules per kilogram per kelvin (J·kg^{-1}·K^{-1});
$\langle\ \rangle$	is a time average over a short duration (a few seconds or minutes);
V'	is the short-term fluctuation in horizontal wind velocity, in metres per second, given by $V' = V - \langle V\rangle$;
W'	is the short-term fluctuation in vertical wind velocity, in metres per second, given by $W' = W - \langle W\rangle$;
θ'	is the short-term fluctuation in temperature, in kelvins, given by $\theta' = \theta - \langle\theta\rangle$.

The following empirical relationships (Businger-Dyer relationships) are used:

$$\left.\begin{aligned}\phi_\mathrm{M} &= 1+4{,}7\zeta \\ \phi_\mathrm{H} &= 0{,}74+4{,}7\zeta\end{aligned}\right\} \text{ for } 0 \leqslant \zeta < 1 \tag{46}$$

$$\left.\begin{aligned}\phi_\mathrm{M} &= (1-15\zeta)^{-0{,}25} \\ \phi_\mathrm{H} &= 0{,}74(1-9\zeta)^{-0{,}5}\end{aligned}\right\} \text{ for } \zeta < 0 \tag{47}$$

$$\zeta = z / l_\mathrm{MO} \tag{48}$$

$$l_\mathrm{MO} = \frac{1}{k_\mathrm{Kármán}} \frac{\theta}{g} \frac{u_*^2}{\theta_*} \tag{49}$$

where

ζ is the scaled height (dimensionless);

l_MO is the Monin-Obukhov length, in metres;

$k_\mathrm{Kármán}$ is the von Kármán constant (dimensionless);

g is the acceleration due to gravity (at sea level, $g = 9{,}8$ m/s^2).

Slightly differing values can be found reported for the von Kármán constant, $k_\mathrm{Kármán}$, for which this International Standard uses the value $k_\mathrm{Kármán} = 0{,}39$ (see Reference [20]).

The Monin-Obukhov length is an important parameter in the Businger-Dyer relationships. This length is a measure of atmospheric stability (by the use of empirical relationships). The Monin-Obukhov length can be derived from the Pasquill class (see e.g. Reference [21]) and the roughness height. There are six Pasquill classes, denoted by the letters A to F. Class A represents a very unstable atmosphere (i.e. an atmosphere with strong vertical transport which occurs for instance on a hot day with no cloud cover), class F represents a very stable atmosphere. The Pasquill class is determined from empirical tables as a function of cloud cover and wind velocity at a height of 10 m.

The applicability of the similarity relationships is restricted to topographical situations with a uniform roughness height. In the wake of a jump in roughness height (e.g. crossing a coastline, lake shoreline or city or forest limit), a new boundary layer forms. The so-called internal boundary layer (see e.g. Reference [28]) increases in thickness with increasing distance downstream from the discontinuity. Therefore, the similarity relationships cannot be applied in the transition zone of a jump in roughness height. The similarity relationships also fail over sloping or structured terrain where shallow, thermally driven slope winds or drainage flows may develop. Finally, the Monin-Obukhov similarity cannot be applied in the case of very stable stratification when the constant-flux layer assumption is no longer valid.

The atmospheric surface layer has a finite upward extent and is usually bounded in height by the Monin-Obukhov length (or twice this length for stable situations). Above the atmospheric surface layer, the similarity statistics and parameters such as temperature and wind velocity tend towards the values for the geostrophic winds.

8.4 Using measurements of turbulent fluxes

This approach is based on the measurement of turbulent fluxes by means of a rapidly sampling thermometer and a rapidly sampling anemometer, such as an ultrasonic anemometer. The scaling parameters u_* and θ_* are calculated from measured fluxes using Equations (44) and (45), and the Monin-Obukhov length, l_MO, is given by Equation (49). Next, the wind and temperature gradients are given by Equations (42), (43), (46) and (47). The vertical sound speed gradient is then given by Equation (33). Integration of the sound speed gradient over height yields the sound speed profile. As already stated, the usual heights for sensors include

2 m, 5 m and 10 m, although additional coverage may be needed to evaluate the region above the atmospheric surface layer.

By analogy with 8.2, the probabilities of the various profiles can be found by taking the propagation path direction into account.

8.5 Using routinely gathered weather station data

This approach employs routinely acquired weather station data, for example data collected over a period (in the past) of 10 years or 30 years. Taking into account these data, five wind-velocity classes, W1 to W5, and five atmospheric-stability classes, S1 to S5, are defined in Table 2 and Table 3 in terms of the following three observable quantities:

— the wind velocity at height 10 m;

— the time of day (day or night);

— the cloud cover (in octas).

NOTE Daytime includes the period between one hour after sunrise and one hour before sunset; night-time is defined as the period between one hour before sunset and one hour after sunrise.

An automated weather station equipped with a tower supporting a cup-and-vane anemometer at 10 m height, combined with a light-sensing pyranometer (or radiometer), and reporting (or recording) 5-minute sample averages would be sufficient to establish the necessary statistics.

Table 2 and Table 4 give representative values of u_* and θ_* for the 5 × 5 (= 25) combinations of classes. Note that, given the chosen class widths, only nine unique values of θ_* result from the 25 combinations.

Statistical weights of the sound speed profiles follow from the frequency distributions of the wind velocity at 10 m and the cloud cover. In addition, the frequency distribution of the wind direction shall be taken into account. For example, one can distinguish between 12 wind direction intervals (classes), which results in 9 × 12 (= 108) different profiles, each having an associated probability of occurrence. These profiles may be used as alternatives to the set of profiles defined in Equation (39). Otherwise, these profiles shall be matched against the given set of profiles.

In Reference [30], a similar approach is presented. In this study, a set of 1 620 Businger-Dyer profiles were condensed into a smaller set of 27 logarithmic and power profiles. Statistical weights were derived from long-term wind statistics and the Pasquill classification for atmospheric stability.

Table 2 — Classification of wind velocity using the representative turbulent velocity scaling parameter, u_*

Wind-velocity class	Mean wind velocity, u, at height 10 m m/s	u_* m/s
W1	$0 \leqslant u < 1$	0,00
W2	$1 \leqslant u < 3$	0,13
W3	$3 \leqslant u < 6$	0,30
W4	$6 \leqslant u < 10$	0,53
W5	$10 \leqslant u$	0,87

Table 3 — Classification of atmospheric stability according to time of day and cloud cover

Atmospheric-stability class	Time of day	Cloud cover
S1	Day	0/8 to 2/8
S2	Day	3/8 to 5/8
S3	Day	6/8 to 8/8
S4	Night	5/8 to 8/8
S5	Night	0/8 to 4/8

Table 4 — Temperature scaling parameter, θ_*, for the various wind-velocity and atmospheric-stability classes

Wind-velocity class	Temperature scaling parameter, θ_* K				
	Atmospheric-stability class				
	S1	S2	S3	S4	S5
W1	−0,4	−0,2	0,0	+0,2	+0,4
W2	−0,2	−0,1	0,0	+0,1	+0,2
W3	−0,1	−0,05	0,0	+0,05	+0,1
W4	−0,05	0,0	0,0	0,0	+0,05
W5	0,0	0,0	0,0	0,0	0,0

8.6 Using directly measured or calculated sound speed profiles as input

It is not necessary to approximate the profiles obtained from the approaches described in 8.2, 8.4 and 8.5 as log-lin functions. One may prefer to use the original profiles. Directly measured or calculated profiles (the approach in 8.2) must be used if similarity relationships do not hold, such as in situations mentioned in 8.3. This is described in more detail in Reference [30].

9 The source

9.1 General

Impulsive sound sources can be divided roughly into those in 9.2 involving rapidly expanding gases from demolition and muzzle blasts and those in 9.3 involving objects in supersonic motion.

9.2 Demolition and muzzle blasts

9.2.1 General

This International Standard requires free-field parameters of the source. However, military weapons are often mounted on supports or carriers that directly influence the radiation of sound. As a consequence, the same weapon will almost certainly exhibit different source data if mounted on different supports; in particular, the directivity may change. Hence, in many cases, the source sound emission properties intrinsically tie the source to its support. For confined demolition blasts and demolition blasts within, or near to, a structure, the same considerations apply.

9.2.2 Source descriptors

The source descriptors of ISO 17201-1 shall be used to specify the acoustic features of demolition and muzzle blasts. According to ISO 17201-1, the source strength is described in terms of the total acoustic energy and the angular sound energy distribution. The directivity is given in terms of the coefficients of the cosine series of direction.

Structures within a distance of one Weber radius (see ISO 17201-2) from the source centre shall be treated as part of the source.

9.2.3 Determination by measurement

A method of measuring and analysing source data is specified in ISO 17201-1. For the purposes of this International Standard, the method of ISO 17201-1 shall be modified by the following, due to the wider range of non-linear sound propagation and due to the particular geometry of the source:

a) The measurement plan and the equipment specified in VDI MSR 8/559 shall be used to measure the angle-dependent sound exposure. The radius of the measurement circle can be modified with respect to the source strength. However, the Z-weighted peak level shall not exceed 154 dB at any measurement position. See also Note 1.

b) The quantity measured shall be the Z-weighted, one-third-octave sound exposure spectrum.

c) The frequency range shall cover at least 99 % of the acoustic energy of the source.

d) The signal measurement duration shall always exceed 1 s.

e) The methods in ISO 17201-1 of correcting for the ground reflection shall be reconsidered with respect to the particular geometry for large measuring distances and low source and receiver heights. The ground correction specified in ISO 9613-2 is not applicable. Time gating is not a favourable method because the time gap between direct and reflected signal is less than 1 s in typical measuring layouts.

   The test plan in VDI MSR 8/559 specifies the use of so-called “squiring” sources, i.e. measurements to accompany the source of interest with well-known standard demolition sources paired close in time and location with the source of interest. The analysis of squiring measurements with respect to those made under known ground reflection conditions can be used to determine the influence of the ground reflection.

   The height-of-burst effect, which is seen to increase peak sound pressure for open-air explosions, is normally not observed in outdoor firing over typical terrain. However, if a gun is fired over a flat, smooth metal plate (or similar object), the height-of-burst gain shall be taken into consideration.

   See also Note 2.

f) Measurements at increased distances are influenced by the weather conditions during the tests. In particular, refraction due to wind and temperature gradients will change the test results and need to be taken into account for the ground correction. The angle of incidence and the type of ground are the most important parameters.

Measurements of sound pressure above a (circular) plate do not ensure frequency-independent pressure doubling and shall not be used.

NOTE 1 The apparent source centre of muzzle blasts may appear shifted to a location up to a few metres away from the muzzle along the direction of fire. The position of the fireball can be used to indicate the location of the blast centre. The shifting of the source centre may also change the apparent source height.

NOTE 2 At frequencies of 80 Hz and below, sound pressure doubling at the ground surface is observed in most cases. The frequency range from 100 Hz to 400 Hz may be dominated by the superposition of direct and reflected blast waves. From experience, any free demolition blast produces a Weber-like blast spectrum. Muzzle blasts show a spectrum that approximates to the shape of a Weber spectrum in the absence of any strong frequency-dependent directivity arising from the presence of the supporting structure.

NOTE 3 Measuring sound pressure near to the ground surface typically leads to sound pressure doubling at low frequencies and to pressure release (a very small sound pressure) at all other frequencies. Therefore, such near-ground measurements can be used at larger distances only if the source spectrum is well known and refraction is towards the ground along the direct path to the receiver.

9.2.4 Determination by estimation

ISO 17201-2 describes methods of estimating the source data for small, free (unbounded) demolition blasts and small civilian weapons. These methods can also be applied to sources covered by this International Standard.

NOTE In general, guns have a directivity which is stronger towards the firing direction. If a muzzle brake is used, however, the directivity is reduced.

9.3 Projectile sound

9.3.1 General

Projectile sound sources, including high-velocity supersonic projectiles following nearly flat trajectories, are considered in 9.3.2. Lower-velocity supersonic ballistic projectiles fired from howitzers or mortars, following elevated, curved (approximately parabolic) trajectories are discussed in 9.3.3. Rockets can be included in either class, depending on the trajectory and acceleration profile.

9.3.2 Flat trajectories

ISO 17201-4 shall be used to predict the projectile sound from projectiles following flat trajectories if applicable in view of the constraints given in ISO 17201-4.

NOTE The method in ISO 17201-4 is an engineering method for favourable sound propagation conditions.

9.3.3 High-elevation trajectories and rocket trajectories

If ISO 17201-4 is not applicable because of the curvature of the trajectory, the trajectory shall be calculated by kinematic methods, and the procedures laid down in ISO 17201-2 shall be used to estimate the source parameters of the projectile sound. Calculation of sound propagation shall include the attenuation due to geometric spreading as specified in ISO 17201-2 and attenuation due to air absorption.

NOTE Sound propagation through the atmosphere from large source heights is less affected by sound speed gradients close to the ground. Instead, the dependence of sound absorption by the air on temperature and humidity becomes more important.

10 Uncertainties

In order to calculate a statistical distribution of the sound exposure levels for impulsive sound events, the key quantity is the single-event sound exposure level outlined in 4.3. Its uncertainty is the topic of this clause and it shall be evaluated in compliance with ISO/IEC Guide 98-3.

The uncertainty in the calculation of the single-event sound exposure level arises from the following constituents:

- the uncertainty in the angular source energy distribution level (see ISO 17201-1 for situations in which this level is determined by measurements or ISO 17201-2 when the level is estimated from the chemical energy of the propellant);
- the uncertainty concerning the position of the sound source with respect to propagation-influencing objects and the actual shooting direction;

- the uncertainty resulting from approximations made in calculating the propagation through a fully specified, precise and complete model of the actual situation, including sound barriers, the atmosphere and the ground;
- the uncertainty resulting from approximations made in reducing a fully specified, precise and complete model of an actual situation to a simple model that needs only a small number of input parameters (e.g. atmospheric temperature and humidity, wind velocity and direction, surface porosity, flow resistivity and roughness height).

Additional uncertainties arise in the estimation of quantities other than the single-event sound exposure level.

The expanded uncertainty, together with the corresponding coverage factor, shall be stated for a coverage probability of 95 % as defined in ISO/IEC Guide 98-3.

Guidance on how to express the uncertainty is given in Annex B.

Annex A
(informative)

Example of the estimation of the statistical distribution of single-event sound exposure levels

A.1 General

Sound propagation is strongly influenced by the meteorological situation. In particular, the wind-velocity gradient and wind direction are important, but the temperature gradient is also of importance. Together, they determine the sound speed profile. To determine a statistical distribution of the sound exposure levels, variations in the meteorological situation (described by the sound speed profile) have to be taken into account.

This annex gives an example showing how to estimate the statistical distribution of the A-weighted single-event sound exposure level at a location distant from high-energy impulsive sound sources. In this example, a number of excess-attenuation classes are used as described in Reference [30]. The procedure for determining the probability of occurrence of these classes is also described in that reference.

A.2 Example

A noise assessment was performed at location A of shooting activities at location B for the period from 07:00 to 19:00. An estimate was needed of the statistical distribution of the A-weighted single-event sound exposure level at location A. At location B, shots were fired from a TOW anti-tank missile launcher. The distance from the shooting location to location A was 3 020 m. Because only one location was investigated, only the sound emission in the direction of location A was relevant. The sound level in that direction was obtained by measurement and is shown in Table A.1. The sound level is given in octave bands instead of the preferred one-third-octave band levels.

Table A.1 — Octave-band sound exposure levels towards location A for TOW

Band centre frequency, in Hz	31	63	125	250	500	1 000	2 000	4 000
Octave-band sound exposure level, in dB	115	119	134	135	134	136	133	126

Making use of meteorological data — wind velocity, wind direction and cloud cover — collected in the local area for over 30 years, sound speed profiles were constructed using the Businger-Dyer relationships.

The wind velocity from the meteorological data was divided into 15 classes, the wind direction into 12 classes and the cloud cover into 9 classes. On the basis of these data, and taking into account one (average) roughness height along the sound propagation path, $15 \times 12 \times 9$ (= 1 620) sound speed profiles were constructed for both daytime and night-time.

NOTE In this study, daytime was defined as the period between one hour after sunrise and one hour before sunset; night-time was defined as the period between one hour before sunset and one hour after sunrise.

To lessen the amount of calculation, the daytime and night-time sets of profiles were reduced to a smaller number. Three different groups of functions were used to describe the two sets of 1 620 profiles (see Reference [30]). Using these groups of functions, described by the equations below, the 1 620 profiles were reduced to 27 excess-attenuation classes. The groups were as follows:

group 1: $c_n(h) = c_{10} + b_n[(h/h_0 + 1)^{-0,3} - 1]$ for $n = 1,...,7$, (A.1)

group 2: $c_n(h) = c_{10} + b_n \ln(h/h_0 + 1)$ for $n = 8,...,18$, (A.2)

group 3: $c_n(h) = c_{10} + b_n[(h/h_0 + 1)^{+0,3} - 1]$ for $n = 19,...,27$, (A.3)

where

$c_n(h)$ is the sound speed profile for the nth excess-attenuation class;

h is the height, in metres, above local ground level;

h_0 is the reference height, in metres (= 0,1 m);

c_{10} is the speed of sound, in metres per second, at 10 °C and 1 atmosphere;

b_n is the strength parameter, in metres per second, for the sound speed profile (see Table A.2).

Table A.2 — Values for Equations (A.1) to (A.3) (upwind and neutral conditions are marked in grey)

Group 1	n	1	2	3	4	5	6	7				
	b_n, in m/s	10	3	1	–1	–3	–6	–10				
Group 2	n	8	9	10	11	12	13	14	15	16	17	18
	b_n, in m/s	–1	–0,4	–0,2	0	0,2	0,4	0,7	1,1	1,5	2	2,5
Group 3	n	19	20	21	22	23	24	25	26	27		
	b_n, in m/s	–1	–0,5	–0,2	0,2	0,4	0,65	1	1,4	2		

The probability of occurrence of each of the 1 620 profiles for both daytime and night-time is a function of the probability of the wind velocity, wind direction and cloud cover from which they are derived. The probability of occurrence of each of the 27 excess-attenuation classes can therefore be obtained by summation of the probability of occurrence of each of the profiles within this excess-attenuation class.

Using the parabolic-equation model [31], the excess attenuation was calculated, for the eight octave bands and 27 excess-attenuation classes described by the profile, using Equations (A.1) to (A.3) ($n = 1,…,27$).

For each octave band, the sound exposure level at location A was calculated using Equations (7) and (8). From this, the A-weighted sound exposure level for each excess-attenuation class was determined. Table A.3 gives the results together with the probability of occurrence of the excess-attenuation class for daytime and night-time. The last column of the table gives the average probability for each excess-attenuation class. The average probability was calculated using, for this location and period of interest (07:00 to 19:00), daytime and night-time proportions equal to 80 % and 20 %, respectively.

Table A.3 —A-weighted single-event sound exposure level at location A due to shooting activities at location B and its probability of occurrence for different excess-attenuation classes

n	$L_{E,\text{A}}$ dB	$\wp_{\text{exc},l}$		
		Daytime	**Night-time**	**07:00 to 19:00**
1	30,5	0,036 0	0,000 0	0,028 8
2	31,2	0,005 3	0,000 0	0,004 2
3	31,3	0,000 3	0,000 0	0,000 2
4	36,1	0,073 1	0,066 4	0,071 8
5	38,3	0,095 1	0,096 6	0,095 4
6	38,8	0,063 4	0,096 2	0,070 0
7	39,2	0,000 0	0,000 0	0,000 0
8	30,8	0,203 7	0,115 1	0,186 0
9	31,8	0,108 7	0,029 5	0,092 9
10	31,8	0,018 4	0,000 0	0,014 7
11	33,7	0,027 9	0,026 8	0,027 7
12	40,2	0,000 1	0,008 4	0,001 8
13	41,0	0,000 0	0,000 0	0,000 0
14	41,6	0,054 9	0,066 5	0,057 2
15	42,2	0,048 2	0,044 5	0,047 5
16	42,4	0,020 9	0,017 2	0,020 2
17	42,7	0,003 9	0,003 3	0,003 8
18	43,1	0,000 3	0,000 3	0,000 3
19	28,4	0,000 0	0,006 9	0,001 4
20	30,8	0,035 6	0,079 8	0,044 4
21	32,2	0,2042	0,231 0	0,209 6
22	42,3	0,000 1	0,021 5	0,004 4
23	43,6	0,000 0	0,026 0	0,005 2
24	44,5	0,000 0	0,026 3	0,005 3
25	45,2	0,000 0	0,019 4	0,003 9
26	45,5	0,000 0	0,015 3	0,003 1
27	46,1	0,000 0	0,003 0	0,000 6

NOTE 1 The probability is given for each excess-attenuation class for both daytime and night-time, together with the value for the period between 07:00 and 19:00.

NOTE 2 The table is divided into the same three groups of excess-attenuation classes as Table A.2.

To estimate the statistical distribution of the frequency-weighted sound exposure levels, all the A-weighted single-event sound exposure levels given in Table A.3 were placed in order of increasing level. This can be viewed as a new classification of the sound exposure levels with 27 classes. The lower and upper boundaries, $g_{\text{L},m}$ and $g_{\text{U},m}$, between adjoining classes were chosen so that they lay half-way between consecutive values [see Equations (11) and (13)]. The results are given in Table A.4. The overall probability function is defined by Equation (16) and given in Figure A.1.

Table A.4 — Probability density function for the single-event sound exposure level

m	$L_{E,\mathrm{A},m}$ dB	$\wp_m$ **07:00 to 19:00**	$g_{\mathrm{L},m}$ dB	$g_{\mathrm{U},m}$ dB	ρ_m **07:00 to 19:00**
1	28,4	0,001 4	27,35	29,45	0,000 7
2	30,5	0,028 8	29,45	30,65	0,024 0
3	30,8	0,186 0	30,65	30,80	1,239 9
4	30,8	0,044 4	30,80	31,00	0,222 2
5	31,2	0,004 2	31,00	31,25	0,017 0
6	31,3	0,000 2	31,25	31,55	0,000 8
7	31,8	0,092 9	31,55	31,80	0,371 4
8	31,8	0,014 7	31,80	32,00	0,073 6
9	32,2	0,209 6	32,00	32,95	0,220 6
10	33,7	0,027 7	32,95	34,90	0,014 2
11	36,1	0,071 8	34,90	37,20	0,031 2
12	38,3	0,095 4	37,20	38,55	0,070 7
13	38,8	0,070 0	38,55	39,00	0,155 5
14	39,2	0,000 0	39,00	39,70	0,000 0
15	40,2	0,001 8	39,70	40,60	0,002 0
16	41,0	0,000 0	40,60	41,30	0,000 0
17	41,6	0,057 2	41,30	41,90	0,095 4
18	42,2	0,047 5	41,90	42,25	0,135 6
19	42,3	0,004 4	42,25	42,35	0,043 8
20	42,4	0,020 2	42,35	42,55	0,100 8
21	42,7	0,003 8	42,55	42,90	0,010 8
22	43,1	0,000 3	42,90	43,35	0,000 7
23	43,6	0,005 2	43,35	44,05	0,007 4
24	44,5	0,005 3	44,05	44,85	0,006 6
25	45,2	0,003 9	44,85	45,35	0,007 8
26	45,5	0,003 1	45,35	45,80	0,006 8
27	46,1	0,000 6	45,80	46,40	0,001 0

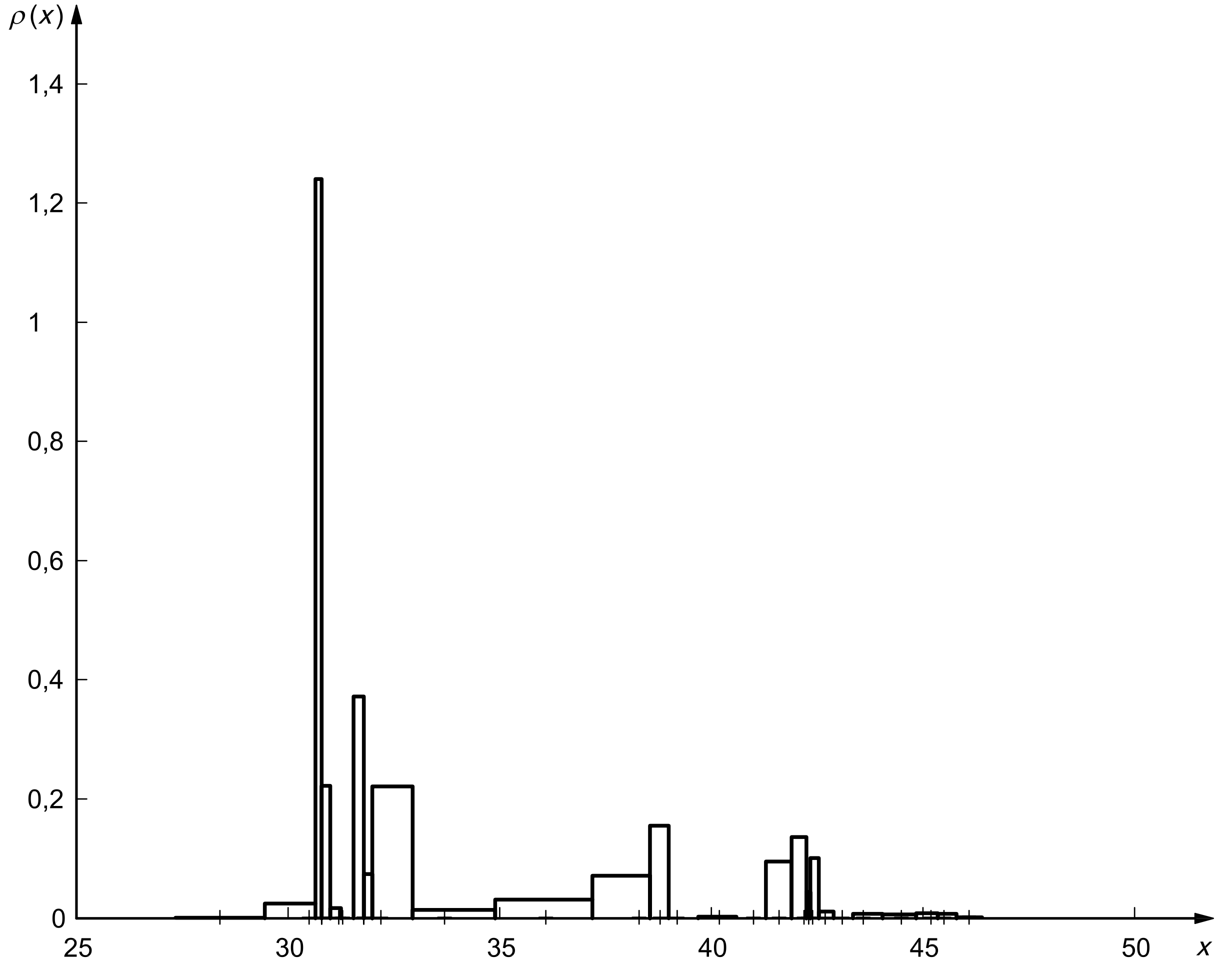


Figure A.1 — Probability density function, $\rho(x)$ (not taking into account turbulence), with constant values over the classes (see also Table A.3)

The spreading of levels due to turbulence was taken into account by a convolution of the function $\rho(x)$ with a normal distribution having a standard deviation equal to 5 dB. This operation was carried out in two steps. First, each class, m, in the example was divided into 10 equal, contiguous subclasses [see Equations (17) to (20)]. Next, the discrete probability density functions, $\rho_{m,j}(x)$, were replaced by continuous normalized Gaussian functions as defined by Equation (21). A shift in the mean value was introduced to ensure that the energetically averaged level remained at the value $\mu_{m,j}$ as defined by Equation (18). In this example, the mean value was shifted by an amount, $\Delta\mu$, equal to 1,04 dB [from Equation (22)]. Finally, the continuous overall probability density function was estimated using Equation (23). The result is shown in Figure A.2. The cumulative distribution is shown in Figure A.3. This figure shows the cumulative probability of situations where the frequency-weighted sound exposure level is higher than x dB, as described by Equation (24). From this distribution, the percentile exceedance levels can be read off directly [see also Equation (25)]. Various exceedance levels are given in Figure A.3.

Figure A.3 also gives the long-term average single-event sound exposure level, in decibels. This was calculated in two different ways, shown as LT1, i.e. $\langle L_{E,\mathrm{w}}\rangle_{\mathrm{LT1}}$, and LT2, i.e. $\langle L_{E,\mathrm{w}}\rangle_{\mathrm{LT2}}$. $\langle L_{E,\mathrm{w}}\rangle_{\mathrm{LT1}}$ was calculated using Equation (7) where $P_{\mathrm{r,atm},k} = 1$. $\langle L_{E,\mathrm{w}}\rangle_{\mathrm{LT2}}$ was calculated from Equation (A.4) using the derived statistical distribution $\rho^*(x)$:

$$\left\langle L_{E,\mathrm{w}}\right\rangle_{\mathrm{LT2}} = 10\ \mathrm{lg}\left[\int_{-\infty}^{\infty} \rho^*(x) \times 10^{0,1x}\,\mathrm{d}x\right] \quad \mathrm{dB} \tag{A.4}$$

The values calculated for $\langle L_{E,\mathrm{w}} \rangle_{\mathrm{LT1}}$ and $\langle L_{E,\mathrm{w}} \rangle_{\mathrm{LT2}}$ (rounded to 0,1 dB) are equal. This gives confidence that the statistical distribution derived is reliable.

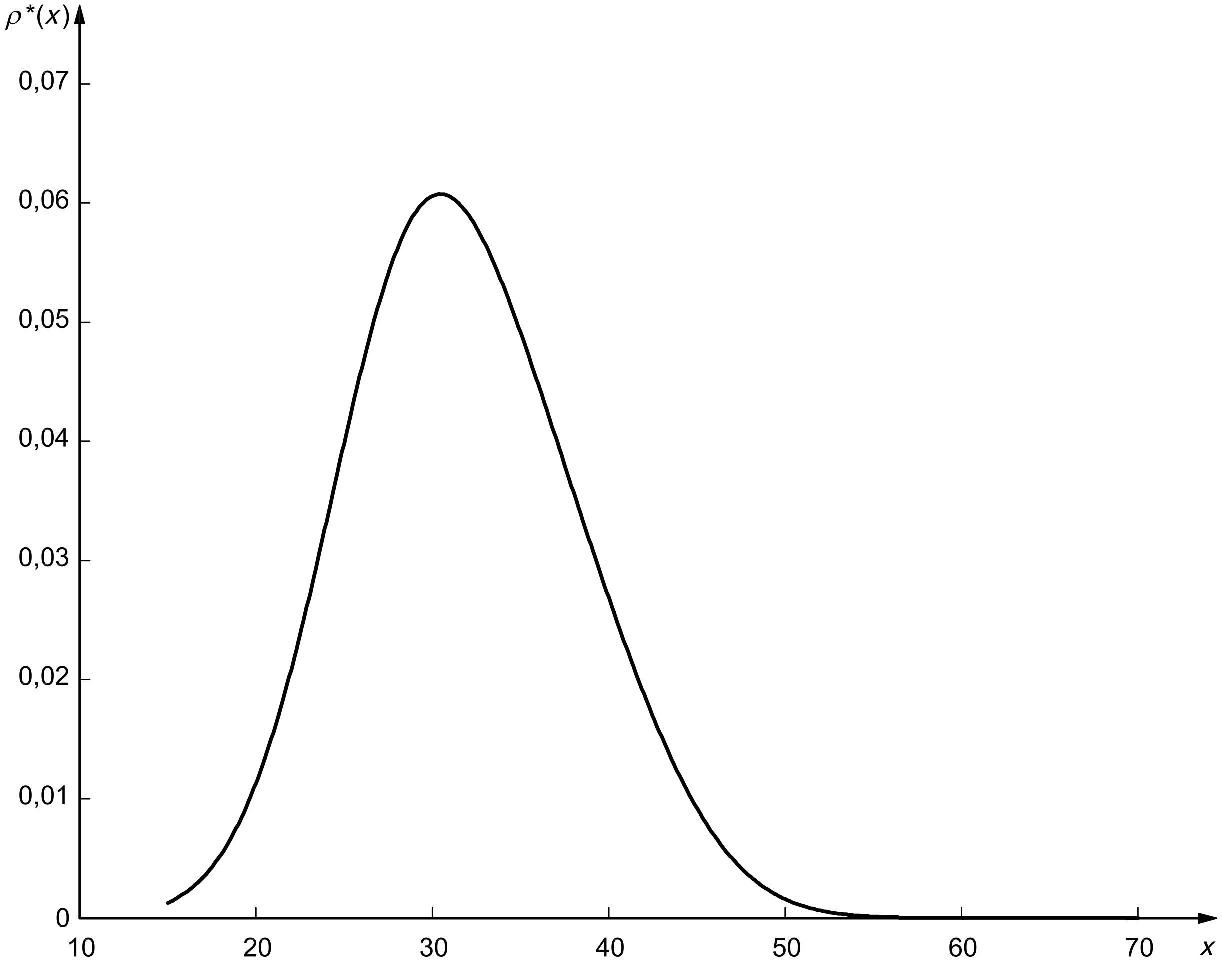


Figure A.2 — Continuous overall probability density function for the A-weighted single-event sound exposure levels

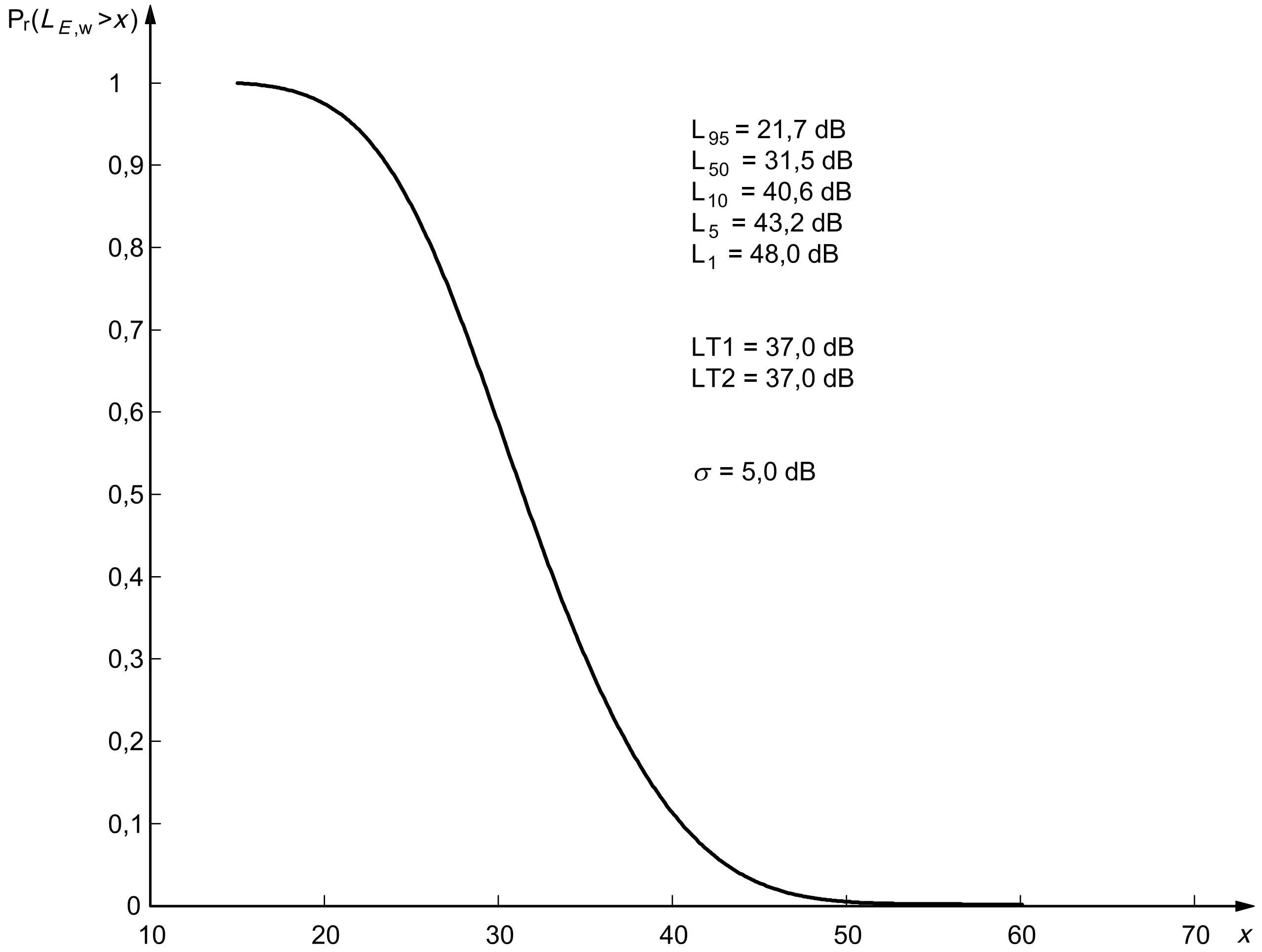


Figure A.3 — Cumulative distribution of the A-weighted single-event sound exposure levels
(The figure also gives some percentile levels)

Annex B
(informative)

Uncertainty

B.1 General

The accepted format for the expression of uncertainties is that given in ISO/IEC Guide 98-3. Its principles can be applied to the prediction method specified in this International Standard as well. The format for the expression of uncertainties incorporates an uncertainty budget in which the various sources of uncertainty are identified and quantified and from which the combined uncertainty can be obtained. The quantification of the uncertainties depends strongly, however, on the specific underlying situation. This annex therefore illustrates the general approach to the determination of the uncertainties appropriate to this International Standard.

B.2 Functional relationship

The functional relationship between the band sound exposure level and the related input quantities, i.e. source sound exposure level and attenuation quantities, is given by Equation (4).

A probability distribution (normal, rectangular, Student's, etc.) is associated with each of the input quantities. Its expectation value (mean value) is the best estimate of the value of the various input quantities. The standard deviation of the distribution is a measure of its variance, termed the standard uncertainty. The uncertainties of the input quantities contribute to the uncertainty in the estimated values of the sound exposure level.

For each input value, the expectation value, the standard uncertainty and the probability distribution are estimated, based on the information available or expert judgement.

B.3 Contributions to the prediction uncertainty

B.3.1 General

The contributions to the combined uncertainty in the value of the sound exposure level or the maximum level at a receiving point depend on the uncertainties, u_i, and the related sensitivity coefficients, c_i. The sensitivity coefficients are a measure of how the values of the sound exposure level are affected by changes in the values of the respective input quantities. Mathematically, they are equal to the partial derivative of the physical relationship, taken with respect to the relevant input quantity. Subsequently, the product of the standard uncertainty and the associated sensitivity coefficient gives the contribution of the respective input quantity to the combined uncertainty. Thus the information needed to derive the combined uncertainty is that given in Table B.1. Following this table is extra information offered as guidance in estimating the uncertainty.

Table B.1 — Uncertainty budget for determination of the sound exposure level at the receiver

Quantity dB	**Estimate**[a] dB	**Standard uncertainty**[a] u_i dB	**Probability distribution**[a]	**Sensitivity coefficient** c_i	**Uncertainty contribution** $c_i u_i$ dB
$S_{\phi,\theta}(j)$	$S_{\phi,\theta,\mathrm{est}}(j)$	u_1		1	u_1
A_{div}	$A_{\mathrm{div,est}}$	u_2		1	u_2
$A_{\mathrm{atm},k}(j)$	$A_{\mathrm{atm},k,\mathrm{est}}(j)$	u_3		1	u_3
$A_{\mathrm{rec}}(j)$	$A_{\mathrm{rec,est}}(j)$	u_4		1	u_4
$A_{\mathrm{diff}}(j)$	$A_{\mathrm{diff,est}}(j)$	u_5		1	u_5
$A_{\mathrm{exc},l}(j)$	$A_{\mathrm{exc},l,\mathrm{est}}(j)$	u_6		1	u_6

[a] The estimate, the standard uncertainty and the probability distribution have to be estimated for each quantity based on the information available or expert judgement.

B.3.2 Uncertainty concerning the direction-dependent source band sound exposure level

The uncertainty in the direction-dependent source band sound exposure level is equivalent to the uncertainty in the energy distribution level given in ISO 17201. If this source level is to be estimated by measurements, the uncertainty is described in ISO 17201-1; ISO 17201-2 gives the uncertainty if this level is estimated by calculation.

B.3.3 Uncertainty resulting from the position of the sound source

The uncertainty in the position and orientation of the source can give rise to uncertainties in the source level estimate, especially if reflections and/or barrier effects are of importance. The degree of uncertainty should be estimated based on information available or by expert judgement.

B.3.4 Uncertainty resulting from approximations made in calculating propagation parameters

Even a fully specified, precise and complete model of the actual situation, including the sound barriers, atmosphere and ground, involves some uncertainty in the calculated sound propagation parameters due to approximations made in the calculations. The degree of uncertainty should be estimated based on the information available or by expert judgement. High-resolution models can be used as benchmark references for estimating the uncertainty.

B.3.5 Uncertainty introduced by simply-specified models

All the quantities given in Table B.1 are influenced by the accuracy of their input parameters. It is inevitable that simplifications have to be made. It is impossible to include all aspects in detail. In Annex A, a model is discussed which includes only a limited number of input parameters to describe particular field conditions. Guidance in estimating the uncertainty when applying the model can be obtained only from long-term observations of the performance of the model.

B.3.6 Combined and expanded prediction uncertainty

The combined uncertainty in the band sound exposure level, $u(L_E(j))$, is given by the following equation:

$$u(L_E(j)) = \sqrt{\sum_{i=1}^{6} u_i^2} \tag{B.1}$$

ISO/IEC Guide 98-3 requires an expanded uncertainty, U, to be specified such that the interval $[L_E(j) - U, L_E(j) + U]$ covers, for example, 95 % of the values of $L_E(j)$ that might reasonably be attributed to $L_E(j)$. To that end, a coverage factor, k, is used, such that $U = ku$.

Table B.2 — Coverage factors associated with different coverage probabilities

Coverage probability	Coverage factor
68 %	1,0
80 %	1,3
90 %	1,6
95 %	2,0
99 %	2,6

B.4 Uncertainty in the overall level

Long-term measurements have determined that the overall sound exposure level, for a given distance and source level, produces a standard deviation of approximately 5 dB. Although this value has been observed under test conditions, it is by no means a constraint on the uncertainty in the overall levels, past or future.

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