International Standard

# ISO 9613-2

Second edition
2024-01

# Acoustics — Attenuation of sound during propagation outdoors —

## Part 2:
## Engineering method for the prediction of sound pressure levels outdoors

*Acoustique — Atténuation du son lors de sa propagation à l'air libre —*

*Partie 2: Méthode d'ingénierie pour la prédiction des niveaux de pression acoustique en extérieur*



Reference number
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# Contents

Page

# Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

This second edition cancels and replaces the first edition (ISO 9613-2:1996), which has been technically revised.

The main changes are as follows:

— subdivision of extended sources improved (more detailed to decrease uncertainty with software implementations);

— improved classification of the source-directivity;

— improved and more detail specified in the determination of the ground factor $G$ (projection to horizontal plane);

— integration of a correction for $A_{gr}$ to account for the decreasing ground effect for small values of distance/height – harmonizing the General method 7.3.1 and the Simplified method 7.3.2;

— modified definition of the mean height $h_m$ for the application of the Simplified method 7.3.2;

— integration of the strategy to calculate screening as it was developed with ISO/TR 17534-3;

— modified specification of the barrier attenuation $D_z$ and the correction for meteorological effects $K_{met}$ to eliminate well known shortcomings with low barriers and large source-to-receiver distances;

— inclusion of clear specifications on how to combine vertical and lateral diffraction (from ISO/TR 17534-3);

— improved specification of the minimal extension (width or height) of a reflecting surface;

— multi-reflections up to higher orders (in accordance with ISO/TR 17534-3);

— reflections at vertical cylindrical surfaces;

— additional to the simple method for the attenuation of foliage without any parameter dependencies of the old version ISO 9613-2:1996, A.2.2, a new and more detailed method including the influence of forestal parameters (see A.2.3);

— the directivity correction $D_c$ for chimney stacks (see Annex B);

— proposal for a meteorological correction derived from the local wind-climatology (see Annex C);

— calculation of sound pressure levels caused by wind turbines (see Annex D).

A list of all parts in the ISO 9613 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

# Introduction

The ISO 1996 series[1][2][3] of standards specifies methods for the description of noise outdoors in community environments. Other standards specify methods for determining the sound power levels emitted by various noise sources, such as machinery and specified equipment (ISO 3740 series[4]), or industrial plants (ISO 8297[5]). This document is intended to bridge the gap between these two types of standards, to enable noise levels in the community to be predicted from sources of known sound emission. The method described in this document is general in the sense that it may be applied to a wide variety of noise sources and covers most of the major mechanisms of attenuation. There are, however, constraints on its use, which arise principally from the description of environmental noise in the ISO 1996 series.

This version includes the modifications developed for reasons of quality assurance if the method is implemented in software as described in ISO 17534-1[6] and ISO/TR 17534-3[7] and some improvements to make the applied strategy fit for broad software-based application.

# Acoustics — Attenuation of sound during propagation outdoors —

## Part 2:
## Engineering method for the prediction of sound pressure levels outdoors



## 1 Scope

This document specifies an engineering method for calculating the attenuation of sound during propagation outdoors in order to predict the levels of environmental noise at a distance from a variety of sources. The method predicts the equivalent continuous A-weighted sound pressure level (as described in ISO 1996-series) under meteorological conditions favourable to propagation from sources of known sound emission.

These conditions are for downwind propagation or, equivalently, propagation under a well-developed moderate ground-based temperature inversion, such as commonly occurs in clear, calm nights. Inversion conditions over extended water surfaces are not covered and may result in higher sound pressure levels than predicted from this document (see e.g. References [11] and [12]).

The method also predicts a long-term average A-weighted sound pressure level as specified in ISO 1996-1 and ISO 1996-2. The long-term average A-weighted sound pressure level encompasses levels for a wide variety of meteorological conditions.

Guidance has been provided to derive a meteorological correction based on the angular wind distribution relevant for the reference or long-term time interval as specified in ISO 1996-1:2016, 3.2.1 and 3.2.2. Examples for reference time intervals are day, night, or the hour of the night with the largest value of the sound pressure level. Long-term time intervals over which the sound of a series of reference time intervals is averaged or assessed representing a significant fraction of a year (e.g. 3 months, 6 months or 1 year).

The method specified in this document consists specifically of octave band algorithms (with nominal mid-band frequencies from 63 Hz to 8 kHz) for calculating the attenuation of sound which originates from a point sound source, or an assembly of point sources. The source (or sources) may be moving or stationary. Specific terms are provided in the algorithms for the following physical effects:

— geometrical divergence;

— atmospheric absorption;

— ground effect;

— reflection from surfaces;

— screening by obstacles.

Additional information concerning propagation through foliage, industrial sites and housing is given in Annex A. The directivity of chimney-stacks to support the sound predictions for industrial sites has been included with Annex B. An example how the far-distance meteorological correction $C_0$ can be determined from the local wind-climatology is given in Annex C. Experiences of the last decades how to predict the sound pressure levels caused by wind turbines is summarized in Annex D.

The method is applicable in practice to a great variety of noise sources and environments. It is applicable, directly, or indirectly, to most situations concerning road or rail traffic, industrial noise sources, construction activities, and many other ground-based noise sources. It does not apply to sound from aircraft in flight, or to blast waves from mining, military, or similar operations.

To apply the method of this document, several parameters need to be known with respect to the geometry of the source and of the environment, the ground surface characteristics, and the source strength in terms of octave band sound power levels for directions relevant to the propagation.

If only A-weighted sound power levels of the sources are known, the attenuation terms for 500 Hz may be used to estimate the resulting attenuation.

The accuracy of the method and the limitations to its use in practice are described in Clause 9.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 9613-1:1993, *Acoustics — Attenuation of sound during propagation outdoors — Part 1: Calculation of the absorption of sound by the atmosphere*

## 3 Terms, definitions, symbols and units

### 3.1 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

**3.1.1**
**A-weighted equivalent continuous sound pressure level**
$L_{AT}$
sound pressure level defined by Formula (1):

$$L_{AT} = 10 \lg \left\{ \left[ \left( \frac{1}{T} \right) \int_0^T p_A^2(t) \mathrm{d}t \right] / p_0^2 \right\} \mathrm{dB} \quad (1)$$

where

$p_A(t)$ is the instantaneous A-weighted sound pressure, expressed in pascals;

$p_0$ is the reference sound pressure (= $20 \times 10^{-6}$ Pa);

$T$ is a specified time interval, expressed in seconds

Note 1 to entry: The A-frequency weighting is that specified for sound level meters in IEC 61672-1[10].

Note 2 to entry: The time interval $T$ should be long enough to average the effects of varying meteorological parameters. Two different situations are considered in this document, namely short-term downwind and long-term overall averages.

**3.1.2**
**equivalent continuous downwind octave band sound pressure level**
$L_{fT}\,(\mathrm{DW})$
sound pressure level is given as follows:

$$L_{fT}\,(\mathrm{DW}) = 10\,\lg\left\{\left[\left(\frac{1}{T}\right)\int_0^T p_f^2\,(t)\,\mathrm{d}t\right] / \,p_0^2\right\}\mathrm{dB} \tag{2}$$

where $p_f(t)$ is the instantaneous octave band sound pressure downwind, in pascals, and the subscript $f$ represents a nominal mid-band frequency of an octave band filter

Note 1 to entry: The electrical characteristics of the octave band filters should comply at least with the class 2 requirements of IEC 61260-1[8].

**3.1.3**
**insertion loss (of a barrier)**
difference between the sound pressure levels in decibels at a receiver in a specified position under two conditions:

a) with the barrier removed; and

b) with the barrier present (inserted);

and no other significant changes that affect the propagation of sound

Note 1 to entry: The insertion loss is expressed in decibels.

## 3.2 Symbols and units

Table 1 provides a summary of symbols and units.

**Table 1 — Symbols and units**

| Symbol | Definition | Unit |
|---|---|---|
| $a$ | component distance parallel to the barrier edge between source and receiver | m |
| $A$ | octave band attenuation | dB |
| $A_{atm}$ | attenuation due to atmospheric absorption | dB |
| $A_{bar}$ | attenuation due to a barrier, including possible correction | dB |
| $A_{div}$ | attenuation due to geometrical divergence | dB |
| $A_{curv}$ | attenuation due to reflection at a cylindrical surface | dB |
| $A_{gr}$ | attenuation due to the ground effect | dB |
| $A_m$ | middle region | — |
| $A_{misc}$ | attenuation due to miscellaneous other effects | dB |
| $C_{met}$ | meteorological correction | dB |
| $C_0$ | factor, which depends on local meteorological statistics for wind speed and direction, and temperature gradients | dB |
| $d_p$ | distance from point source to receiver projected onto the ground plane (see Figure 3) | m |
| $d_{S,O}$ | distance between source and point of reflection on the reflecting obstacle (see Figure 13) | m |
| $d_{O,R}$ | distance between point of reflection on the reflecting obstacle and receiver (see Figure 13) | m |
| $D_c$ | directivity correction | dB |
| $D_z$ | barrier attenuation | dB |
| $D_{wd}$ | apparent large-distance directivity | dB |
| $e$ | distance between the first and last diffraction edge | m |
| $G$ | ground factor | — |

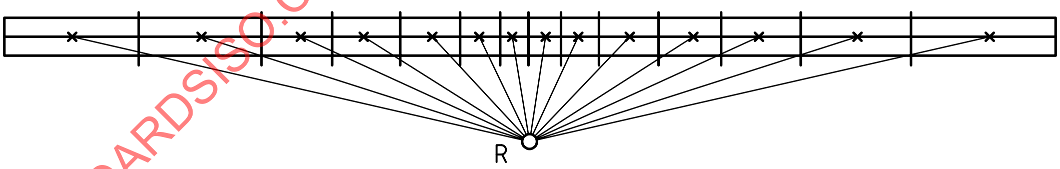
**Table 1** *(continued)*

| Symbol | Definition | Unit |
|---|---|---|
| $h_S$ | height of point source above ground | m |
| $h_R$ | height of receiver above ground | m |
| $h_m$ | mean height of the propagation path above the ground | m |
| $k$ | raster factor | — |
| $K_{geo}$ | correction factor for geometry | — |
| $L_p$ | sound pressure level | dB |
| $L_{AT}(DW)$ | equivalent continuous A-weighted downwind sound pressure level | dB |
| $L_{AT}(LT)$ | long-term average A-weighted sound pressure level | dB |
| $L_{fT}(DW)$ | equivalent continuous downwind octave band sound pressure level at a receiver location | dB |
| $L_W$ | sound power level | dB |
| $\alpha_{atm}$ | atmospheric attenuation coefficient | dB/km |
| $\alpha$ | absorption coefficient | — |
| $\beta$ | angle of incidence | rad |
| $\beta_b$ | angle of incidence projected to the horizontal plane | rad |
| $\beta_h$ | angle of incidence projected to a vertical plane rectangular to the reflecting surface | rad |
| $\lambda$ | wavelength of sound | m |

## 4 Source description

Formulae to be used are for the attenuation of sound from point sources.

Extended noise sources, therefore, such as road and rail traffic or an industrial site (which may include several installations or plants, together with traffic moving on the site) shall be broken down into small sections that can be replaced by a central point source as starting point for the calculation of sound propagation, see Figure 1. This subdivision shall be chosen in such a way that the propagation conditions from each point of a section to the receiver can be considered representative. If no acoustically opaque objects block the direct path between any point of a section and the receiver, the propagation conditions shall be considered representative if no extent of the section is larger than the distance of its centre from the receiver multiplied by the raster factor *k*. A well proven value for the factor *k* is 0,5.

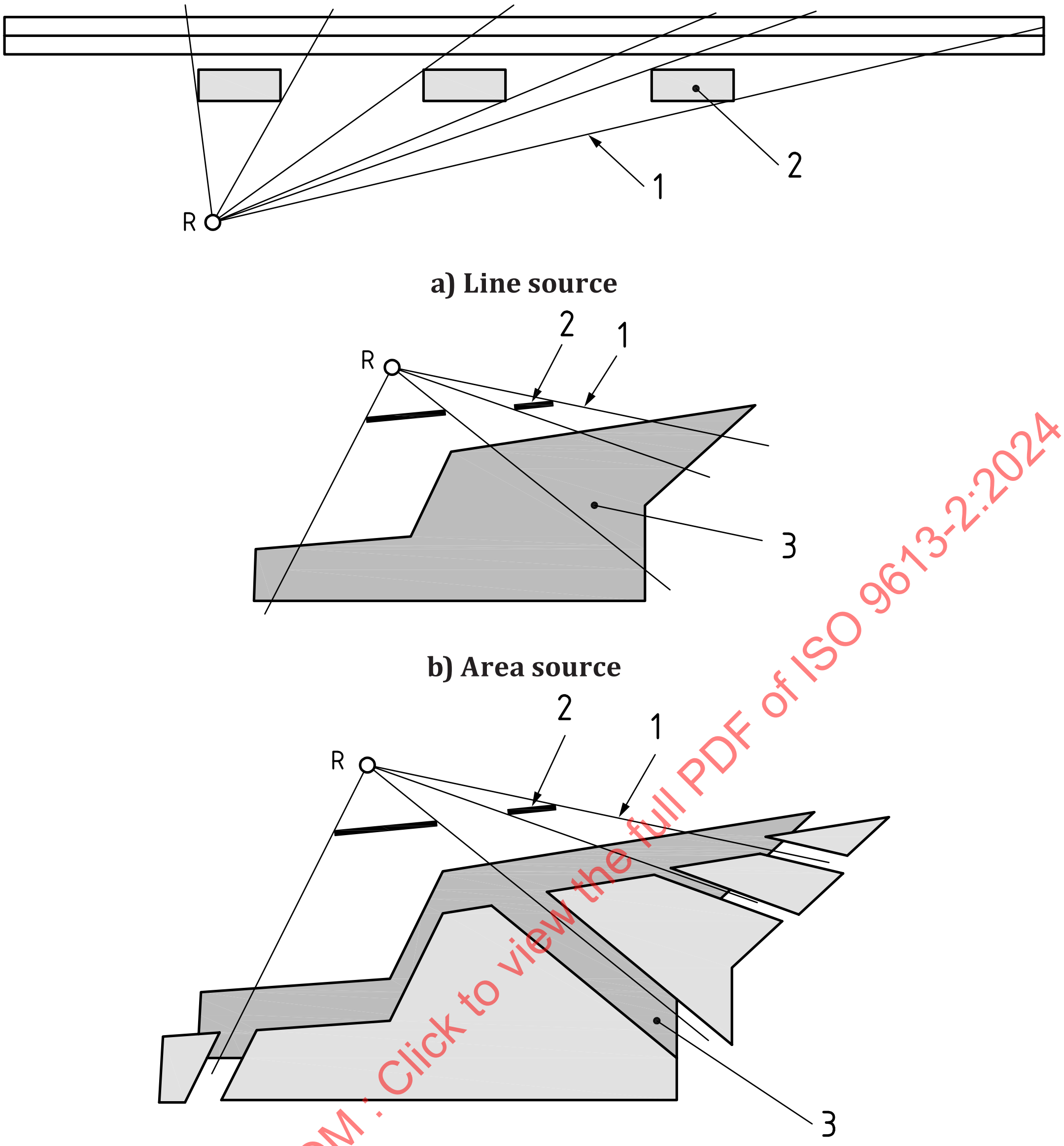



**Key**

R receiver

**Figure 1 — Principle of subdivision for a line source**

If buildings, barriers or other screening objects are located between the extended source and the receiver, the subdivision of the source is made in such a way that all points of a section are either screened or not screened. The subsections can be separated by lines connecting the receiver with the edges of all facades or with the two edges of each object forming the largest possible angle between them in 2D top view.




c) Area source (dark grey), partitioned in 5 sub-parts (light grey)

**Key**

1 projection lines

2 barriers

3 area source



**Figure 2 — Projection method for line source and area source**

The principle is shown with Figure 2 a) for a line source and Figures 2 b) and 2 c) for an area source. A further subdivision is made if a sloping edge of a screening object is only partially blocking the direct view. This subdivision caused by screening objects is called "projection method".

For line sources that are geometrically defined by successive polygon points the subdivision is performed in three steps:

a) each polygon point is the edge point of one or two polygon elements;

b) if the direct propagation path is blocked by a screening object, a further subdivision is carried out by applying the projection method;

c) finally, these resulting parts are further subdivided according to the distance criterion applying the raster factor *k*.

Area sources are subdivided applying a similar strategy.

The area source is separated in convex shaped parts. These parts are subdivided further depending on the receiver position and all screening objects (walls, buildings, and other objects). This is carried out by cutting the subsections obtained in the first step by straight lines between receiver and edge-points of all screening objects (producing smaller subsections of second order). Then it is checked if the individual sources of each subsection meet the distance criterion. If not, they are subdivided further till the distance criterion is fulfilled.

Similar as with extended sources, a group of point sources may be described by an equivalent point sound source situated in the middle of the group, in particular if

a) the sources have approximately the same strength and height above the local ground, and

b) the same propagation conditions exist from the sources to the receiver, and

c) no extent of the group of point sources is larger than the distance of its centre from the receiver multiplied by the raster factor *k*. A well proven value for the factor *k* is 0,5.

If the distance *d* is smaller (as expressed in c)) or if the propagation conditions for the component point sources are different (e.g. due to screening), the total sound source shall be divided into its component point sources.

NOTE In addition to the real sources described above, image sources will be introduced to describe the reflection of sound from walls and ceilings (but not by the ground) as described in 7.5. Images of extended sources are constructed taking into account the extension of all relevant reflectors between original source and receiver.



## 5 Meteorological conditions

Downwind propagation conditions for the method specified in this document are namely:

— wind direction within an angle of ±45° of the direction connecting the centre of the dominant sound source and the centre of the specified receiver region, with the wind blowing from source to receiver, and

— wind speed between approximately 1 m/s and 5 m/s, measured at a height of 3 m to 11 m above the ground.

When applying this standard to wind turbines, higher wind speeds may be considered (see Annex D).

The formulae for calculating the equivalent continuous A-weighted downwind sound pressure level $L_{AT}$(DW) in this document, including the formulae for attenuation given in Clause 7, are the average for meteorological conditions within these limits. The term average here means the average over a short time interval.

These formulae also hold, equivalently, for average propagation under a well-developed moderate ground-based temperature inversion, such as commonly occurs on clear, calm nights.

The long-term averaged A-weighted sound pressure level $L_{AT}$(LT) can be determined by applying the meteorological correction described in Clause 8. It depends generally on the long-term variation of the angular distribution of the horizontal wind speed and the effective vertical sound speed gradient. Owing to this influence of the sound speed gradient the vertical gradients of the wind speed and the air temperature may be important and should generally be considered.

## 6 Basic formulae

The equivalent continuous downwind octave band sound pressure level at a receiver location, $L_{fT}$(DW), shall be calculated for each point source, and its image sources, and for the eight octave bands with nominal mid-band frequencies from 63 Hz to 8 kHz from Formula (3):

$$L_{fT}(\mathrm{DW}) = L_\mathrm{W} + D_\mathrm{c} - A \tag{3}$$

where

$L_\mathrm{W}$ is the octave band sound power level produced by the point sound source relative to a reference sound power of one picowatt (1 pW), expressed in decibels;

$D_\mathrm{c}$ is the directivity correction, in decibels, that describes the extent by which the equivalent continuous sound pressure level from the point sound source deviates in a specified direction from the level of an omnidirectional point sound source producing the sound power level $L_W$, expressed in decibels;

$A$ is the octave band attenuation that occurs during propagation from the point sound source to the receiver, expressed in decibels.

Sound power levels in Formula (3) can be determined from measurements, for example as described in the ISO 3740 series (for machinery) or in ISO 8297 (for industrial plants).

NOTE 1 The letter symbol *A* (in italic type) signifies attenuation in this document except in subscripts, where it designates the A-frequency weighting (in roman type).

The directivity correction $D_\mathrm{c}$ in connection with the sound power level $L_\mathrm{W}$ describes

— the direction-dependent emission of the real source (case 1), or

— an apparent direction-dependent emission, resulting from reflecting structures near the source that reduce the solid angle available for radiation (case 2).

In case 1 $D_\mathrm{c}$ is a necessary part of the source emission data for all directions relevant for the calculation at receiver positions.

In case 2 the directivity $D_\mathrm{c}$ with an omnidirectional point source due to nearby reflecting surfaces is given by Formula (4):

$$D_\mathrm{c} = 10\lg\left(\frac{4\pi}{\Omega}\right)\mathrm{dB} \tag{4}$$

where $\Omega$ is the solid angle remaining for radiation.

Table 2 gives values for the resulting directivity of an omnidirectional point source near reflecting surfaces.

**Table 2 — Resulting directivity $D_\mathrm{c}$ of an omnidirectional point source near reflecting surfaces**

| Reflecting surface | | Solid angle $\Omega$ | $D_\mathrm{c}$ |
|---|---|---|---|
| **Configuration** | **Number** | **rad** | **dB** |
| Surface | 1 | 4π/2 | 3 |
| Edge | 2 | 4π/4 | 6 |
| Corner | 3 | 4π/8 | 9 |

NOTE 2 Formula (4) and the values of $D_\mathrm{c}$ in Table 2 are based on the premise of the superposition of sound energies. In case of distances of source-to-reflector smaller $\lambda/4$ coherent superposition will occur, the factor 10 in Formula (4) and the values of $D_\mathrm{c}$ in Table 2 will increase up to twice the values given. However, an increase over the values shown is only possible if the source can produce and radiate the additional sound power.

NOTE 3 In software-based calculations of the increase of sound pressure levels from an omnidirectional point source caused by reflecting surfaces nearby a directivity $D_c$ with Formula (4) or with values from Table 2 replaces the calculation of reflections at these surfaces with image sources (see 7.5).

The attenuation term $A$ in Formula (3) is given by Formula (5):

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc} \quad (5)$$

where

$A_{div}$ is the attenuation due to geometrical divergence, expressed in decibels (see 7.1);

$A_{atm}$ is the attenuation due to atmospheric absorption, expressed in decibels (see 7.2);

$A_{gr}$ is the attenuation due to the ground effect, expressed in decibels (see 7.3);

$A_{bar}$ is the attenuation due to a barrier, expressed in decibels (see 7.4);

$A_{misc}$ is the attenuation due to miscellaneous other effects, expressed in decibels (see 7.5.4 and Annex A).

General methods for calculating the first four terms in Formula (5) are specified in this document. Information on four contributions to the last term $A_{misc}$ is given in Annex A (the attenuation due to the curvature of reflecting surfaces in 7.5.4, the attenuation due to propagation through foliage, industrial sites and through regions built up of houses).

The equivalent continuous A-weighted downwind sound pressure level shall be obtained by summing the contributing time-mean-square sound pressures calculated according to Formulae (3) and (5) for each point sound source, for each of their image sources, and for each octave band, as specified by Formula (6):

$$L_{AT}(\mathrm{DW}) = 10\lg\left\{\sum_{i=1}^{n}\left[\sum_{j=1}^{8} 10^{0,1\left[L_{fT}(i,j)+A_f(j)\right]}\right]\right\}\mathrm{dB} \quad (6)$$

where

$n$ is the number of contributions $i$ (sources and paths);

$j$ is an index indicating the eight standard octave mid-band frequencies from 63 Hz to 8 kHz;

$A_f$ denotes the standard A-weighting (see IEC 61672-1).

The long-term average A-weighted sound pressure level $L_{AT}(\mathrm{LT})$ shall be calculated according to Formula (7).

$$L_{AT}(\mathrm{LT}) = L_{AT}(\mathrm{DW}) - C_{met} \quad (7)$$

where $C_{met}$ is the meteorological correction described in Clause 8.

The calculation and significance of the various terms in Formulae (1) to (7) are explained in Clauses 7 and 8.

# 7 Calculation of the attenuation terms

## 7.1 Geometric divergence, $A_{div}$

The geometrical divergence accounts for spherical spreading in the free field from a point sound source, making the attenuation, in decibels, equal to Formula (8):

$$A_{div} = [20\lg(d/d_0) + 11]\,\mathrm{dB} \quad (8)$$

where

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

$d_0$ is the reference distance (= 1 m).

NOTE 1 The constant in Formula (8) relates the sound power level to the sound pressure level at a reference distance $d_0$ which is 1 m from an omnidirectional point sound source.

## 7.2 Atmospheric absorption, $A_{atm}$

The attenuation due to atmospheric absorption $A_{atm}$, expressed in decibels, during propagation through a distance *d,* in metres, is given by Formula (9):

$$A_{atm} = \alpha_{atm} d / 1\,000 \quad (9)$$

where $\alpha_{atm}$ is the atmospheric attenuation coefficient for each octave band at the mid-band frequency, expressed in decibels per kilometre.

It shall be calculated with ISO 9613-1:1993, Formulae (2) to (6) in connection with ISO 9613-1:1993, B.1 to B.3. With ISO 9613-1:1993, Formula (6) the exact octave band related centre-frequencies are applied (different to all other frequency dependent calculations based on the nominal and rounded octave band centre-frequencies).

If no specific requirements are defined, default values should be defined related to representative conditions for the investigated area.

NOTE For example, a temperature of 10 °C and a relative humidity of 70 % are typical default parameters applied in some countries in Mid-Europe. The atmospheric attenuation coefficient depends strongly on the frequency of the sound, the ambient temperature and relative humidity of the air, but only weakly on the ambient pressure.

For calculation of environmental noise levels, the atmospheric attenuation coefficient should be based on average values determined by the range of ambient weather, which is relevant to the locality.

## 7.3 Ground attenuation, $A_{gr}$

### 7.3.1 General method of calculation

Ground attenuation, $A_{gr}$, is mainly the result of sound reflected by the ground surface interfering with the sound propagating directly from source to receiver.

The downward-curving propagation path (downwind) ensures that this attenuation is determined primarily by the ground surfaces near the source and near the receiver. This method of calculating the ground effect is based on a scenario with ground, which is approximately flat, either horizontally or with a constant slope. Three distinct regions for ground attenuation are specified (see Figure 3):

a) the source region, stretching over a distance from the source towards the receiver of 30 $h_S$, with a maximum distance of $d_p$ ($h_S$ is the source height, and $d_p$ the distance from source to receiver, as projected on the ground plane);

b) the receiver region, stretching over a distance from the receiver back towards the source of 30 $h_R$, with a maximum distance of $d_p$ ($h_R$ is the receiver height);

c) a middle region, stretching over the distance between the source and receiver regions. If $d_p < (30\ h_S + 30\ h_R)$, the source and receiver regions will overlap, and there is no middle region.

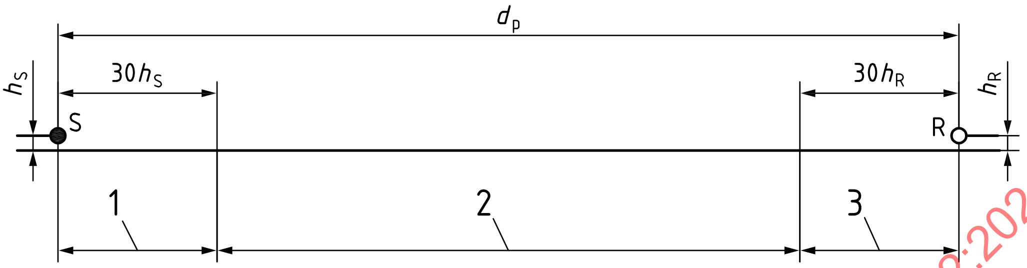
According to this scheme, the ground attenuation does not increase with the size of the middle region but is mostly dependent on the properties of source and receiver regions.

The acoustical properties of each ground region are taken into account through a ground factor *G*.

If a region is characterized by $N$ sections with length $d_n$ and ground factor $G_n$ for section $n$ the ground factor of the region is given by Formula (10):

$$G(\text{region}) = \sum_{n=1}^{N} G_n d_n \Big/ \sum_{n=1}^{N} d_n \tag{10}$$

The source, middle and receiver regions are projections to the horizontal reference plane.




**Key**

1 source region
2 middle region
3 receiver region
$h_S$ height of point source above ground
$h_R$ height of receiver above ground

**Figure 3 — Three distinct regions for determination of ground attenuation**

Three categories of reflecting surface are specified as follows:

a) **Hard ground,** which includes paving, water, ice, concrete, and all other ground surfaces having a low porosity. Tamped ground, for example, as often occurs around industrial sites, can be considered hard. For hard ground $G = 0$.

b) **Porous ground,** which includes ground covered by grass, trees or other vegetation, and all other ground surfaces suitable for the growth of vegetation, such as farming land. For porous ground $G = 1$. For more information, see e.g Reference [19].

c) **Mixed ground,** if the surface consists of both hard and porous ground, then $G$ takes on values ranging from 0 to 1, the value being the fraction of the region that is porous.

NOTE 1 Instead of the term "porous ground," the term "absorbing ground" is used in some countries.

To calculate the ground attenuation for a specific octave band, first calculate the component attenuations $A_S$ for the source region specified by the ground factor $G_S$ (for that region). Then calculate $A_R$ for the receiver region specified by the ground factor $G_R$, and $A_m$ for the middle region specified by the ground factor $G_m$, using the expressions in Table 3. (The functions $a'$, $b'$, $c'$ and $d'$ in Table 3 are shown as curves in Figure 4.) The total ground attenuation for that octave band shall be obtained from Formulae (11), (12) and (13):

$$A_{gr} = -10\lg\left[1+\left(10^{-A'_{gr}/10}-1\right)\cdot K_{geo}\right]\text{dB} \tag{11}$$

where

$$A'_{gr} = A_S + A_R + A_m \tag{12}$$

$$K_{geo} = \frac{{d_p}^2 + (h_S - h_R)^2}{{d_p}^2 + (h_S + h_R)^2} \tag{13}$$

$h_S$ the height of the source above ground, expressed in metres;

$h_R$ the height of the receiver above ground, expressed in metres;

$d_p$ the distance source-to-receiver projected on the horizontal plane, expressed in metres

NOTE 2 Formula (10) characterizes the 2D-projected surface between source and receiver independent of screening by elevated terrain or objects like buildings.

NOTE 3 Formula (11) with Formula (12) and (13) accounts for the vanishing ground influence if the distance $d_p < h_S$ and/or $d_p < h_R$.

**Table 3 — Expressions to be used for calculating ground attenuation contributions $A_S$, $A_R$ and $A_m$ in octave bands**

| Nominal midband frequency<br>Hz | $A_S$ or $A_R$ [a]<br>dB | $A_m$<br>dB |
|---|---|---|
| 63 | −1,5 | $-3q$ [b] |
| 125 | $-1{,}5 + G \times a'(h)$ | $-3q(1-G_m)$ |
| 250 | $-1{,}5 + G \times b'(h)$ | |
| 500 | $-1{,}5 + G \times c'(h)$ | |
| 1 000 | $-1{,}5 + G \times d'(h)$ | |
| 2 000 | $-1{,}5(1 - G)$ | |
| 4 000 | | |
| 8 000 | | |

NOTE

$$a'(h) = 1{,}5 + 3{,}0 \times e^{-0{,}12(h-5)^2}\left(1 - e^{\frac{-d_p}{50}}\right) + 5{,}7 \times e^{-0{,}09h^2}\left(1 - e^{-2{,}8 \times 10^{-6} \times d_p^2}\right)$$

$$b'(h) = 1{,}5 + 8{,}6 \times e^{-0{,}09h^2}\left(1 - e^{\frac{-d_p}{50}}\right)$$

$$c'(h) = 1{,}5 + 14{,}0 \times e^{-0{,}46h^2}\left(1 - e^{\frac{-d_p}{50}}\right)$$

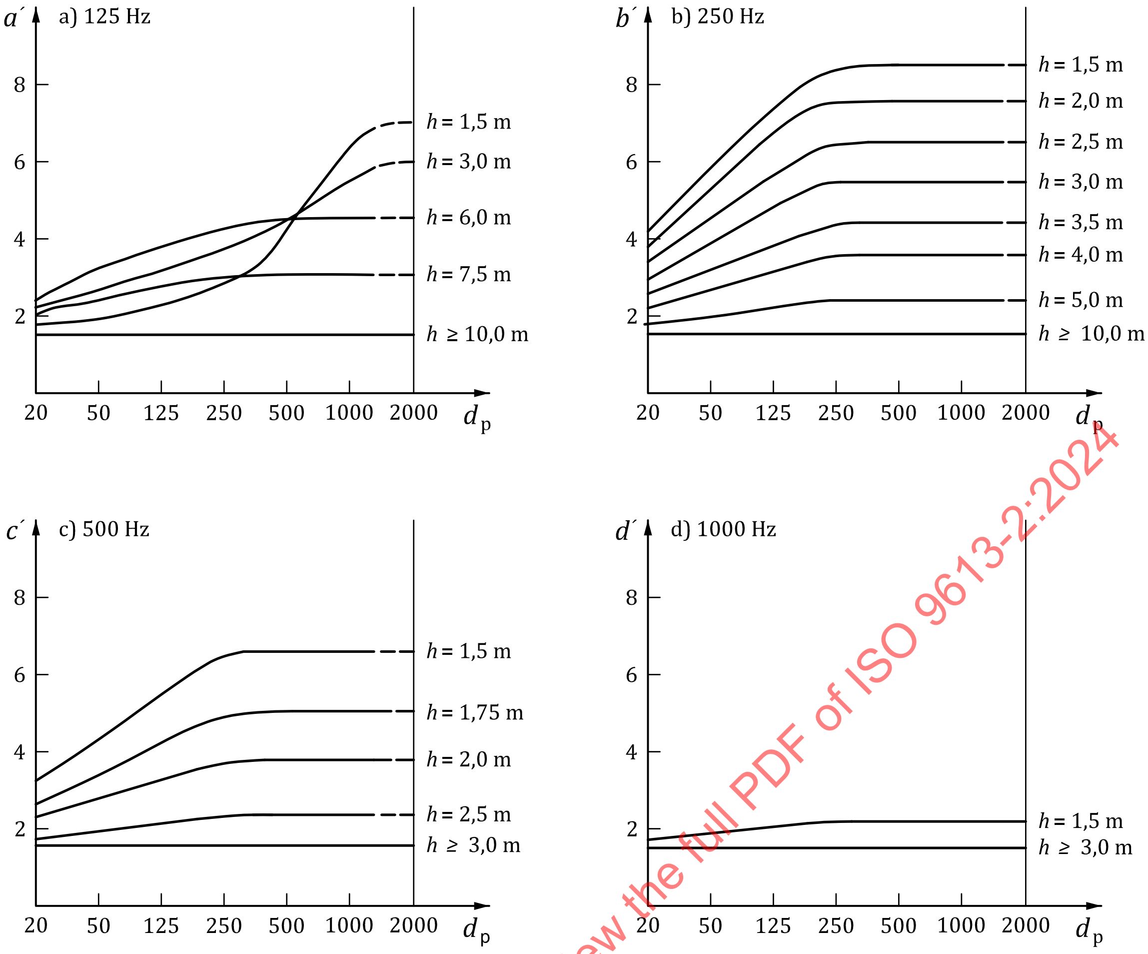
$$d'(h) = 1{,}5 + 5{,}0 \times e^{-0{,}9h^2}\left(1 - e^{\frac{-d_p}{50}}\right)$$

[a] For calculating $A_S$, take $G = G_S$ and $h = h_S$. For calculating $A_R$, take $G = G_R$ and $h = h_R$. See 7.3.1 for values of $G$ for various ground surfaces.

[b] $q = 0$ when $d_p \le 30(h_S + h_R)$

$$q = 1 - \frac{30(h_S + h_R)}{d_p} \quad \text{when } d_p > 30(h_S + h_R)$$

where $d_p$ is the source-to-receiver distance, in metres, projected onto the ground plane.




**Key**

$d_p$ distance source-to-receiver projected on the horizontal plane, expressed in metres

**Figure 4 — Functions *a′*, *b′*, *c′* and *d′* representing the influence of the source-to-receiver distance $d_p$ and the source or receiver height *h*, respectively, on the ground attenuation $A_{gr}$ (computed from Formulae in Table 3)**

### 7.3.2 Simplified method of calculation for A-weighted sound pressure levels

The ground influence calculated with the simplified method is independent from the observable ground cover and its acoustic properties.

Under the following specific conditions and for ground surfaces of any shape, the ground attenuation can be calculated from Formula (14):

— only the A-weighted sound pressure level at the receiver position is of interest;

— the sound propagation occurs over porous ground or mixed ground most of which is porous (see 7.3.1);

— the sound is not a pure tone.

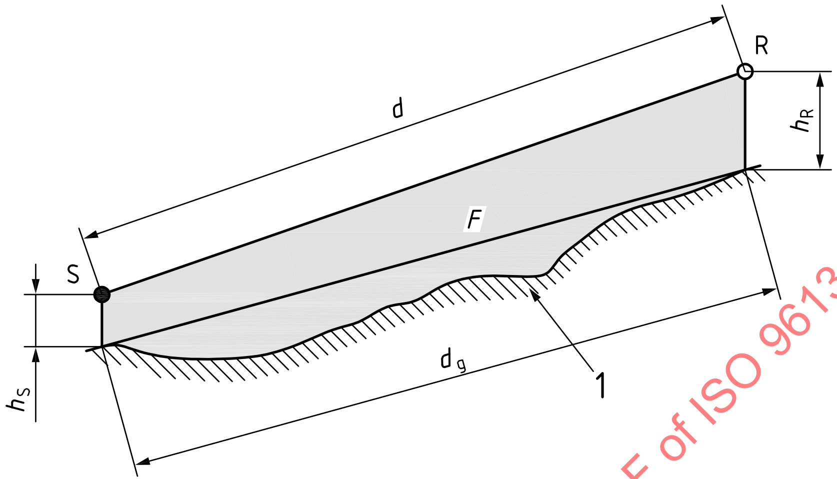
$$A_{gr} = 4{,}8 - \left(\frac{2h_m}{d}\right)\left[17 + \left(\frac{300}{d}\right)\right] \geq 0\ \text{dB} \tag{14}$$

where

$h_m$ is the mean height of the propagation path above the ground, expressed in metres;

$d$ is the distance from the source to receiver, expressed in metres.

The mean height $h_m$ is evaluated by $h_m = F/d_g$, applying the method shown in Figure 5. Negative values for $A_{gr}$ from Formula (14) shall be replaced by zeros.




**Key**

1 ground profile

S source

R receiver

$F$ is the area limited by the ground profile and the straight line from the source to the receiver;

$d$ distance between source and receiver;

$d_g$ is the distance between the base points of source and receiver;

$h_S$ the height of the source above ground, expressed in metres;

$h_R$ the height of the receiver above ground, expressed in metres;

**Figure 5 — Method for evaluating the mean height $h_m$**

When the ground attenuation is calculated using Formula (14), the directivity correction $D_c$ in Formula (3) shall include a term $D_\Omega$ in decibels, to account for the apparent increase in sound power level of the source due to reflection from the ground without any reflection-loss.

$$D_\Omega = 10 \lg \left( 1 + K_{geo} \right) \text{dB} \tag{15}$$

$K_{geo}$ defined in Formula (13) is the correction for geometry due to distance-height relations.

NOTE The influence of the ground relative to free-field propagation calculated with this simplified method is comparable to that calculated with the "General method" described in 7.3.1 with reflecting ground ($G$ = 0) near the source and porous or vegetated ground ($G$ = 1) in larger distances.

## 7.4 Screening, $A_{bar}$

### 7.4.1 General method of calculation

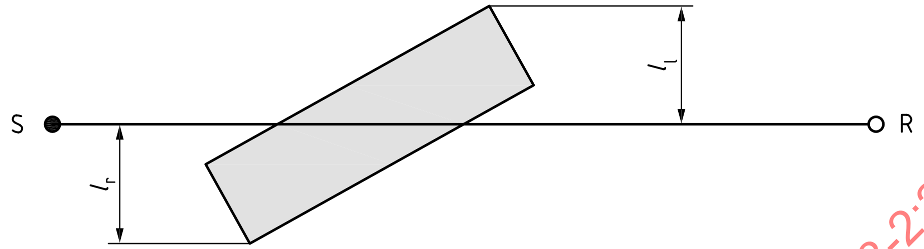
An object shall be taken into account as a screening obstacle (often called a barrier), if it meets the following requirements:

— the surface density is at least 10 kg/m$^2$;

— the object has a closed surface without large cracks or gaps (consequently process installations in chemical plants, for example, are ignored);

— the horizontal dimension of the object normal to the source-to-receiver line is larger than the acoustic wavelength, $\lambda$, at the nominal midband frequency for the octave band of interest (based on a reference sound speed of 340 m/s); in other words, $l_l + l_r > \lambda$ (see Figure 6).

Each object that fulfils these requirements shall be represented by a barrier with vertical edges. The top edge of the barrier is a straight line that may be sloping.




**Key**

S source

R receiver

$l_l$, $l_r$ extention of the object to the left/right in the direction of propagation

**Figure 6 — Plan view of an obstacle between the source (S) and the receiver (R)**



For the purposes of this document, the attenuation by a barrier, $A_{bar}$, shall be given by the insertion loss. Diffraction over the top edge and around vertical edges of a barrier may both be important (see Figure 7). For downwind sound propagation, the effect of diffraction (expressed in decibels) over top edges when $A_{gr} > 0$ shall be calculated by Formula (16):

$$A_{bar} = D_z - A_{gr} > 0 \qquad (16)$$

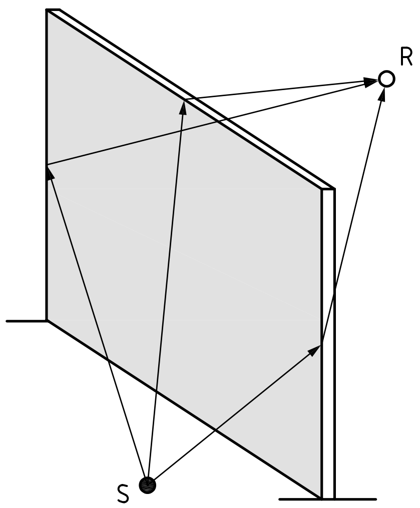
and for diffraction around vertical edges or over top with $A_{gr} < 0$ by Formula (17):

$$A_{bar} = D_z > 0 \qquad (17)$$

where

$D_z$ is the barrier attenuation for each octave band;

$A_{gr}$ is the ground attenuation in the absence of the barrier (i.e. with the screening obstacle removed) (see 7.3).




**Key**

S source

R receiver

**Figure 7 — Different sound propagation paths at a barrier**

NOTE 1 For large distances and high barriers, the insertion loss calculated by Formula (16) is not sufficiently confirmed by measurements.

In calculation of the insertion loss for multi-source industrial plants by high buildings (more than 10 m above the ground) and for high-noise sources within the plant, Formula (17) should be used in both cases for determining the long-term average sound pressure level $L_{AT}$(LT), using Formula (7).

NOTE 2 For sound from a depressed highway, there can be attenuation due to a ground surface outside the depression in addition to the attenuation given in Formula (16).

To calculate the barrier attenuation $D_z$ assume that only one significant sound-propagation path exists from the sound source to the receiver. The final insertion loss caused by objects blocking the direct straight propagation from source to receiver may be influenced by further contributions of sound energy diffracted around the vertical edges, see Formula (25).

Independent from the number of screening obstacles and from their relative orientation, the ray path over the top is constructed like a rubber-band in a vertical plane perpendicular to the reference plane x-y and containing source and receiver and thus forming a polygon with straight segments (example see Figure 8).

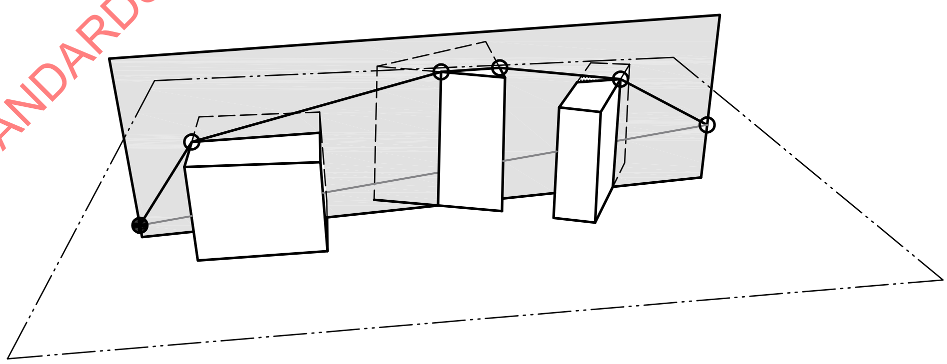


**Figure 8 — Three objects blocking the line of sight, the vertical plane with source and receiver and the ray paths to determine the path length difference *z***

The barrier attenuation $D_z$ in decibels, shall be calculated for this path by Formula (18) with Formula (19):

$$D_z = 10\lg\left[1+\left(2+\left(\frac{C_2}{\lambda}\right)C_3 z\right)K_{met}\right]\text{dB} \quad \text{for } z > z_{min} \tag{18}$$

and

$$D_z = 0\text{ dB} \qquad \text{for } z \leq z_{min}$$

with

$$z_{min} = -2\lambda/(C_2 C_3) \tag{19}$$

where

$C_2$ is equal to 20, and includes the effect of ground reflections; if in special cases ground reflections are taken into account separately by image sources, $C_2 = 40$;

$C_3$ is equal to 1 for single diffraction ($e = 0$);

$C_3$ is calculated by Formula 20 for multiple diffraction;

$e$ is the length of the ray path between the first diffracting edge behind the source and the last diffracting edge in front of the receiver in case of more than one diffracting edge, expressed in metres. In case of one single diffracting edge $e$ equals zero;

$\lambda$ is the wavelength of sound at the nominal mid-band frequency of the octave band, expressed in metres;

$z$ is the difference between the path lengths of diffracted and direct sound, as calculated by Formulae (22) or (24), expressed in metres;

$K_{met}$ is the correction factor for meteorological effects, given by Formula (21).

$$C_3 = \left[1+(5\lambda/e)^2\right] / \left[\left(\frac{1}{3}\right)+(5\lambda/e)^2\right] \tag{20}$$

$$K_{met} = \exp\left\{-(1/2000)\sqrt{[\max(d_{SS}, d_{SR})+e]\cdot\min(d_{SS}, d_{SR})\cdot d/[2(z-z_{min})]}\right\} \tag{21}$$

where

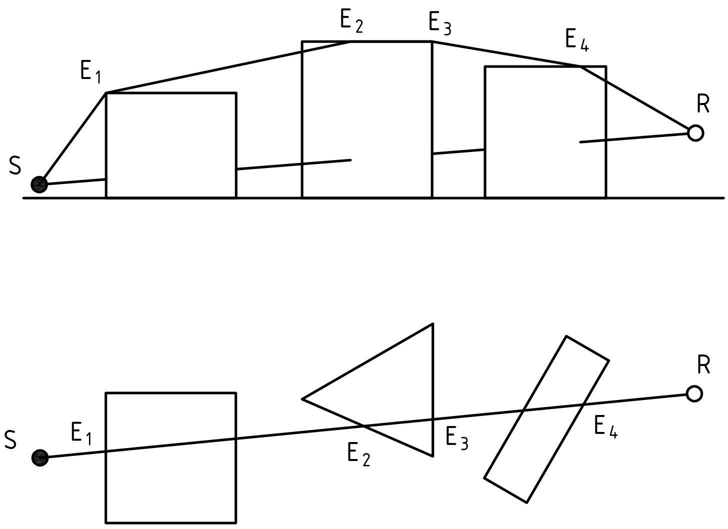
$d_{SS}$ is the length of the ray path from the source to the (first) diffraction edge, expressed in metres (S-$E_1$ in Figure 9);

$d_{SR}$ is the length of the ray path from the (last) diffraction edge to the receiver, expressed in metres ($E_4$-R in Figure 9);

$d$ is the distance from the source to the receiver; expressed in metres (S-R in Figure 9).

For lateral diffraction around obstacles, it shall be assumed that $K_{met} = 1$.

With example Figures 8 and 9 the first and last diffracting edges are $E_1$ and $E_4$ – $e$ is consequently the sum of the lengths $E_1$-$E_2$, $E_2$-$E_3$ and $E_3$-$E_4$.




**Key**

S source

R receiver

$E_n$ diffracting edges

**Figure 9 — Plan- and side-view of the three buildings with the relevant edges $E_1$ – $E_4$ for diffraction over top**

The path length difference shall be calculated by means of Formula (22):

$$z = (d_{SS} + d_{SR} + e) - d \tag{22}$$

If the line of sight between the source S and receiver R passes above the top edge of a single barrier, $z$ is given a negative sign.

If the direct line of sight is not blocked and the ray surpasses more edges $E_n$ along the profile S-R, the largest value determines the relevant path length difference according to Formula (23):

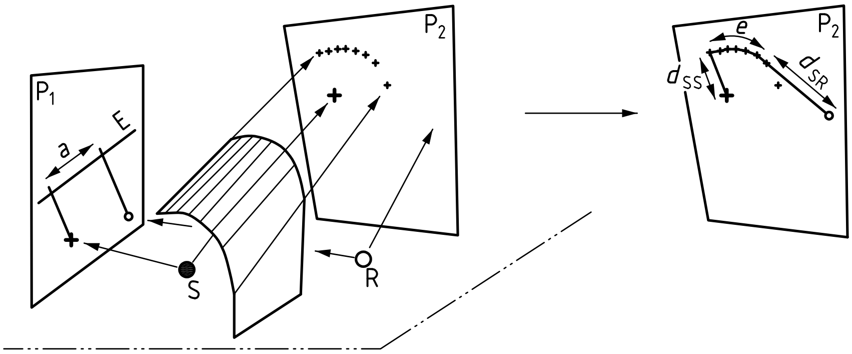
$$z = \max(z_n) \tag{23}$$

where $z_n$ is the negative path length difference to the edge $n$ and where all edges under the propagation path are included to find the maximum value with Formula (22) with $e$ equal 0.

### 7.4.2 Alternative method to calculate the path length difference $z$ with one edge or with more parallel edges

The construction of the ray path in a vertical plane according to 7.4.1 constitutes the general method of this document. Based on this model the sound wave propagating from the source to the receiver with diffraction is approximated by a ray path that is a straight line in plan view.

In special cases it is possible, and can be appropriate, to calculate the path length difference $z$ on the basis of the shortest possible polygon line crossing the diffracting edge(s). The resultant barrier attenuation will then be lower and more accurate.




**a) Original scenario with two projection-planes to determine the parameters $a$, $d_{SS}$, $d_{SR}$ and $e$**

**b) Projection-plane $P_2$ to find the relevant diffracting edges with the ribbon-band method in a first step and the to determine the parameters $d_{SS}$, $d_{SR}$ and $e$**

**Key**

S source
R receiver
$P_1$ vertical projection-plane parallel to the (parallel) diffracting edges
$P_2$ projection-plane vertical to the (parallel) diffracting edges
E barrier edge (any one of the barrier edges projected to plane $P_1$)
a component distance between S and R in direction of barrier edge E (see projection-plane $P_1$)
e summarized partial distances between all adjacent relevant diffraction edges (see projection-plane $P_2$)
$d_{SS}$ distance between source and nearest relevant diffraction edge (see projection-plane $P_2$)
$d_{SR}$ distance between receiver and nearest relevant diffraction edge (see projection-plane $P_2$)

**Figure 10 — The relevant parameters to calculate the path length difference $z$ shown in case of a bended barrier (here not parallel to the ground)**



This is the case if the line between the source and receiver is not perpendicular to the diffracting edge in plan view and the heights of source and receiver are different or/and the diffracting edge is sloping. In such cases the shortest ray path is generally not a straight line in plan view. The path length difference $z$ for this shortest ray path can be calculated for one or more parallel potentially diffracting edges with the following steps:

— source, receiver and edge(s) are projected to a plane perpendicular to the edges (plane $P_2$ in Figure 10);

— with a polygon line like a rubber-band from source to receiver enveloping the edge/s (points in this projection) the relevant edges are found (see Figure 10 b));

— the parameters $d_{SS}$, $e$, $d_{SR}$ and $a$ are determined.

The path length difference $z$ shall be calculated by means of Formula (24):

$$z = [(d_{SS} + d_{SR} + e)^2 + a^2]^{1/2} - d \tag{24}$$

where $d$ is the 3D distance between the source and the receiver; expressed in metres;

NOTE For this alternative method, $d_{SS}$ and $d_{SR}$ are distances point-edge and therefore perpendicular to the relevant edge. This is different from the general method where $d_{SS}$ and $d_{SR}$ are the lengths of the first and the last segment of the ray path in the vertical propagation plane.

### 7.4.3 Lateral diffraction around vertical edges

Lateral diffraction around vertical edges of obstacles, as shown in Figure 7 for a single barrier, and in Figure 11 for more objects, may reduce the attenuation effect $A_{bar}$ calculated.

In addition to the propagation path over the top, up to two laterally bent propagation paths are taken into account. To calculate the path length difference $z$ for one or both of these lateral diffracted rays, these are constructed analogous to the ray path over top as a rubber band type polygon line in a lateral plane containing the source and receiver perpendicular to the vertical plane. The lateral ray paths are the shortest possible convex polygon lines not blocked by objects or by elevated ground at both sides of the line from source to receiver with supporting points on the intersection of vertical edges with the lateral plane. A lateral diffraction path is neglected if the maximal distance of one or more of its supporting points from the direct line from source to receiver exceeds the maximal distance of the supporting points in the vertical plane from the direct line from source to receiver by a factor more than 8.

Lateral diffraction is not considered if elevated ground contributes to the ray path over the top. Figure 11 shows the lateral plane and the two laterally diffracted rays for the example with 3 buildings.

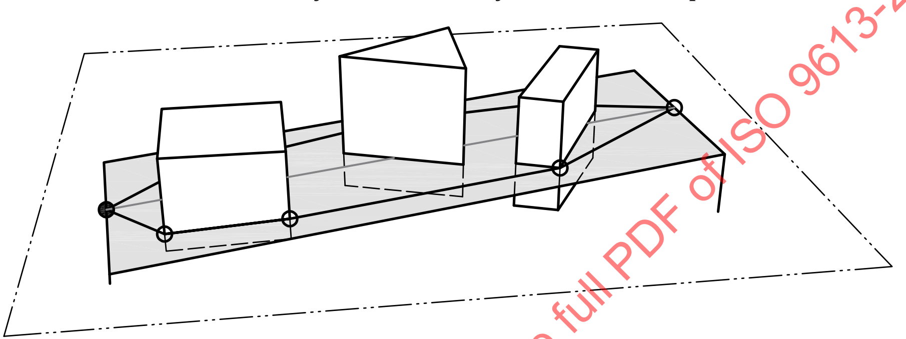
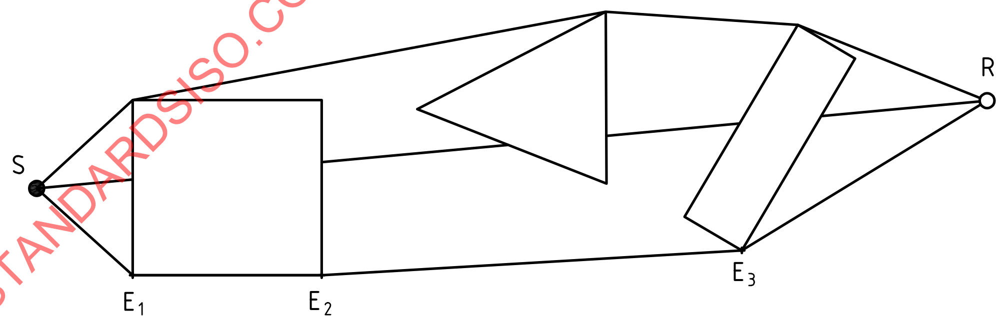


**Figure 11 — Three objects blocking the line of sight, the lateral plane with source and receiver and the ray paths to determine the path length difference $z$**

With this example the first and last diffracting edges right side are $E_1$ and $E_3$, as it is shown in Figure 12, $e$ is consequently the sum of the lengths $E_1$-$E_2$ and $E_2$-$E_3$ (left side analogous). The attenuation effect $A_{bar}$ for the relevant lateral diffracted ray path is calculated with Formula (17).

NOTE Path-length differences $z$ are positive with laterally diffracted rays following from their construction.




**Key**

S source

R receiver

$E_n$ diffracting edges

**Figure 12 — Plan view of the three buildings with the relevant edges $E_1$ – $E_3$ for lateral diffraction right side**

#### 7.4.4 Combining vertical and lateral diffractions and limitations

The final barrier attenuation $A_{bar}$ resulting from $A_{bar,top}$ calculated with the ray path in the vertical plane and $A_{bar,side1}$ and $A_{bar,side2}$ calculated with the ray paths in the lateral plane is calculated with Formula (25).

$$A_{bar} = -10\lg\left(10^{-0,1 A_{bar,top}} + 10^{-0,1 A_{bar,side1}} + 10^{-0,1 A_{bar,side2}}\right)\text{dB} \quad (25)$$

If a ray path is not relevant, the corresponding summand in the bracket is 0.

If the result of Formula (25) is negative, the effective $A_{bar}$ is 0.

This strategy is based on the idea that laterally diffracted sound causes a reduction of the barrier effect if the extension of the arrangement of relevant objects perpendicular to the line of sight is small.

For diffraction over the top in the vertical plane the barrier attenuation $D_z$, in any octave band, should not be taken to be greater than 20 dB in the case of single diffraction (i.e. thin barriers) and 25 dB in the case of multiple diffraction (with $e > 0$).



### 7.5 Reflections

#### 7.5.1 General

Reflections are considered here in terms of image sources. These reflections originate from more or less vertical surfaces, such as building facades, which can increase the sound pressure levels at the receiver. The effect of reflections from the ground is not considered because it is included in the calculation of $A_{gr}$ in case of the “General method” in 7.3.1 and in the calculation of $A_{gr}$ and $D_{\Omega}$ in case of the “Simplified method” in 7.3.2.

#### 7.5.2 Single reflection at a flat surface – conditions and calculation

The reflections from an obstacle shall be calculated for all octave bands for which all of the following requirements are met:

— a specular reflection can be constructed, as shown in Figure 13;

— the surface is large enough for the nominal midband wavelength $\lambda$ (in metres) for the octave band under consideration to obey the relationship according to Formulae (26) and (27).

$$\frac{1}{\lambda} > \left[2 / l_{eff}^2\right]\left[d_{S,O} d_{O,R} / \left(d_{S,O} + d_{O,R}\right)\right] \quad (26)$$

$$l_{eff} = \min\left(a \cdot \cos\beta_a , h \cdot \cos\beta_h\right) \quad (27)$$

where

$a$ is the horizontal extension of the reflecting surface, expressed in metres;

$h$ is the vertical extension of the reflecting surface at the point of reflection, expressed in metres;

$\lambda$ is the wavelength of sound at the nominal midband frequency $f$ (in hertz) of the octave band ($\lambda$= 340 m/s/$f$), expressed in metres;

$d_{S,O}$ is the distance between the source and the point of reflection on the obstacle, expressed in metres;

$d_{O,R}$ is the distance between the point of reflection on the obstacle and the receiver; expressed in metres;

$\beta_a$ is the angle of incidence projected to the horizontal plane; expressed in radians;

$\beta_h$ is the angle of incidence projected to a vertical plane rectangular to the reflecting surface; expressed in radians.

If this condition is not met for a given octave band, then its reflection shall be neglected.

The real source and source image are handled separately. The sound power level of the source image $L_{W,im}$ shall be calculated in each relevant octave band from Formula (28).

$$L_{W,im}\,(\text{dB}) = L_W + 10\lg(1-\alpha) + D_{Ir} \tag{28}$$

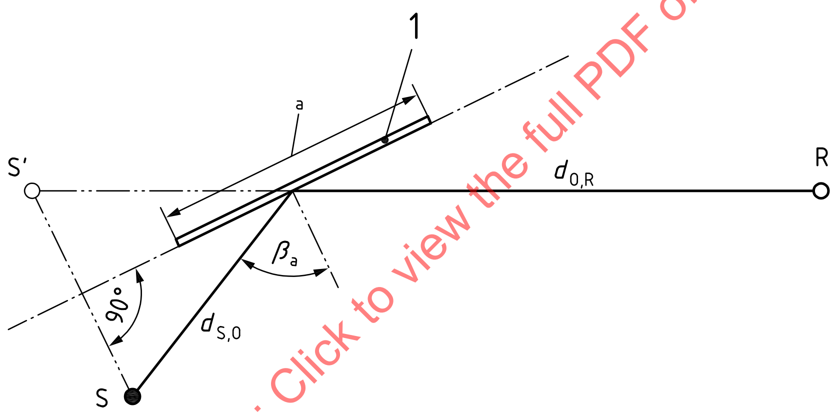
where

$\alpha$ is the sound absorption coefficient of the reflecting surface;

$D_{Ir}$ is the directivity index of the source in the ray-path direction from the source to the reflector.

For building facades and surfaces of industrial facilities an absorption coefficient of 0,1 shall be applied as default value in all octave bands if individual data are not available.

For the sound source image, the attenuation terms of Formulae (3) and (5), as well as $\alpha$ and $D_{Ir}$ in Formula (28), shall be determined according to the propagation path of the reflected sound for each relevant octave band.




**Key**

1 obstacle

a relevant extension of the reflecting obstacle

S source

S' first order image source

R receiver

$d_{S,0}$ distance from source to obstacle

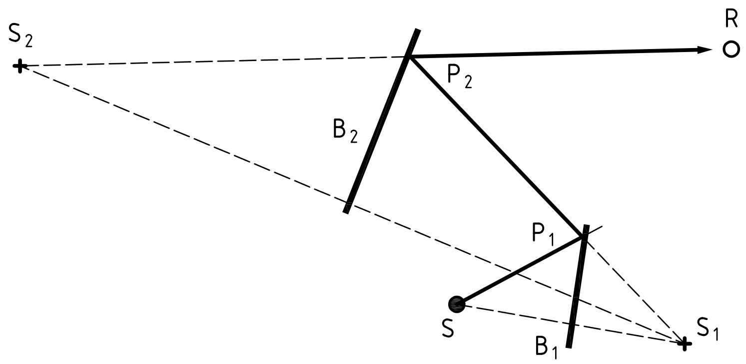
$d_{0,R}$ distance from obstacle to receiver

$\beta_a$ angle of incidence projected to the horizontal plane

**Figure 13 — Specular reflection from an obstacle (here shown as top view)**

### 7.5.3 Multi-reflection up to higher orders

The $n^{th}$ order image source $S_n$ is the image of the image source $S_{n-1}$. The construction of the real ray path of a second order reflection is shown in Figure 14.




**Key**

$B_1$, $B_2$ barriers

$P_1$, $P_2$ points of reflection

S source

$S_n$ $n^{th}$ order image source

R receiver

**Figure 14 — Example to explain the construction of a 2nd order reflection with image sources $S_1$ and $S_2$**



Calculation of reflected sound shall include higher order reflections if source and receiver are located between parallel or nearly parallel reflecting surfaces or are surrounded by reflecting surfaces.

The condition according to Formulae (26) and (27) shall be validated for each reflector separately. The lengths $d_{S,O}$ and $d_{O,R}$ are the lengths of the ray-paths from source to reflector and from reflector to receiver, even if these are bent at other reflectors.

With the absorption coefficient $\alpha_n$ at the $n^{th}$ point where the ray is reflected, the sound power level of the image source of order $N$, $L_{w,im,N}$, is given by Formula (29):

$$L_{W,im,N}\ (\text{dB}) = L_W + 10\lg\left[\prod_n (1-\alpha_n)\right] + D_{Ir} \tag{29}$$

where

$L_W$ is the sound power level, expressed in decibels

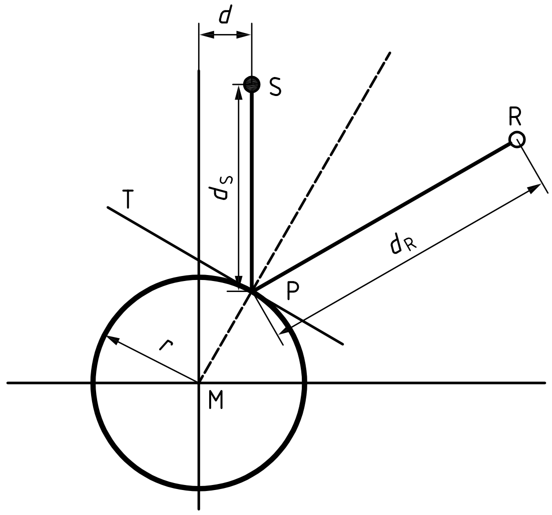
$\alpha_n$ is absorption coefficient at the $n^{th}$ point where the ray is reflected.

$D_{Ir}$ is the directivity index of the source in the ray-path direction from the source to the first reflector (relevant for the octave band), expressed in decibels.

### 7.5.4 Reflections at cylindrical surfaces

The general method to calculate reflections is to approximate all vertical or nearly vertical surfaces of objects by planes. This allows them to be included correctly in a path-finding algorithm and to calculate even higher order reflections.

In some cases, cylindrical surfaces such as vessels, tanks and even curved building facades shall be considered as reflectors. Based on geometrical considerations, – true for $\lambda << R$ with $\lambda$ the wavelength and $R$ the radius of the cylinder – the level at the receiver weakened by the curvature of the cylindrical shape can be calculated. For details see Reference [13].




**Key**

M centre-point
S point source
R receiver
*r* radius in metres
P point of reflection
T tangent in P
$d_S$ distance S – P, expressed in metres
$d_R$ distance P – R, expressed in metres
*d* distance of the straight line defined by the incident ray from the centre-point M, in metres

**Figure 15 — Sound ray reflected at a cylinder – all dimensions in projection parallel to the axis**



The relevant parameters as shown in Figure 15 are determined in projection on a plane perpendicular to the cylinder-axis. The tangent T and the reflection point P are defined by the mirror-condition of equal angles of incident and reflected ray with the normal defined by M and P. From these parameters the additional attenuation $A_{curv}$ caused by the curvature of the reflecting surface is calculated with Formula (30):

$$A_{curv} = 10\lg\left[1 + \frac{2 d_S d_R}{r(d_S + d_R)}\left(1 - k^2\right)^{-1/2}\right] \text{dB} \tag{30}$$

where $k = \frac{d}{r}$

The partial sound pressure level caused by the reflection at the cylinder surface is then obtained by:

— calculating $A_{curv}$ from the parameters determined in projection view (see Formula (30));

— calculating the sound pressure level caused by the sound reflected by the tangential plane T with the absorption coefficient of the cylinder surface at the reflection point (7.5.2);

— applying $A_{curv}$ as part of $A_{misc}$ in Formula (5).

Reflections of order >1 are not considered with curved surfaces.

## 8 Meteorological correction, $C_{met}$

Use of Formula (3) leads directly to an equivalent continuous A-weighted sound pressure level $L_{AT}$ at the receiver for meteorological conditions which are favourable for propagation from the sound source to that receiver, as described in Clause 5. This can be the appropriate condition for meeting a specific community noise limit, i.e. a level which is seldom exceeded. Often, however, a long-term average A-weighted sound pressure level $L_{AT}$(LT) is required in line with legal requirements, where the time interval $T$ is several months or even a year. Such a period will normally include a variety of meteorological conditions, both favourable and unfavourable to propagation. A value for $L_{AT}$(LT) may be obtained in this situation from that calculated for $L_{AT}$(DW) via Formula (3), by using the meteorological correction $C_{met}$ in Formula (7).

A value (expressed in decibels) for $C_{met}$ in Formula (7) may be calculated using Formulae (31) and (32) for the case of a point sound source with an output which is effectively constant with time:

$$C_{met} = 0 \quad \text{if } d_p \leq 10(h_S + h_R) \tag{31}$$

$$C_{met} = C_0 \left[1 - 10(h_S + h_R)/d_p\right] \text{ if } d_p > 10(h_S + h_R) \tag{32}$$

where

$h_S$ is the source height, expressed in metres;

$h_R$ is the receiver height, expressed in metres;

$d_p$ is the distance between the source and receiver projected to the horizontal ground plane, expressed in metres;

$C_0$ is a factor, expressed in decibels, which depends on local meteorological statistics for wind speed and direction, and temperature gradients which may depend on the angular orientation of the direction between the source and receiver.

The effects of meteorological conditions on sound propagation are small for short distances $d_p$, and also for larger distances with increased source height and/or receiver height. Formulae (31) and (32) account approximately for these factors, as shown in Figure 16.

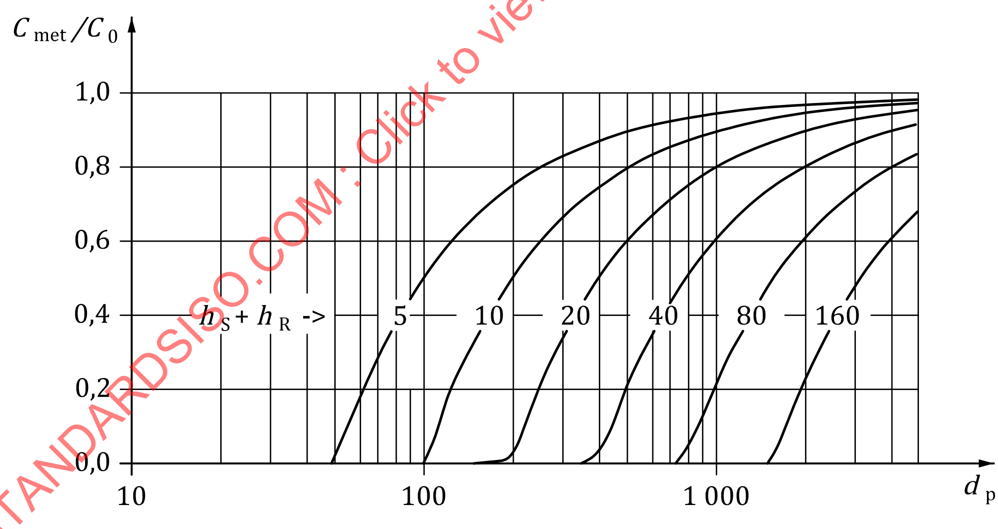



**Figure 16 — Meteorological correction, $C_{met}$**

A value for $C_0$ in Formulae (31) and (32) can be estimated from an elementary analysis of the local meteorological statistics. For example, if the meteorological conditions favourable to propagation described in Clause 5 are found to occur for 50 % of the time-period of interest, and the attenuation during the other 50 % is higher by 10 dB or more, then the sound energy which arrives for meteorological conditions unfavourable to propagation may be neglected, and $C_0$ will be approximately +3 dB.

Experience indicates that values of $C_0$ in practice are limited to the range from zero to approximately +5 dB, and values in excess of 2 dB are exceptional. Thus only very elementary statistics of the local meteorology are needed for a ±1 dB accuracy in $C_0$.

For a source that is composed of several component point sources, $h_S$ in Formulae (31) and (32) represents the predominant source height, and $d_p$ the distance from the centre of that source to the receiver.

A proposal for a method to determine $C_0$ for a given source and receiver exclusively on the basis of the local wind–climatology is given in Annex C.

## 9 Accuracy and limitations of the method

The attenuation of sound propagating outdoors between a fixed source and receiver fluctuates due to variations in the meteorological conditions along the propagation path. Restricting attention to moderate downwind conditions of propagation, as specified in Clause 5, limits the effect of variable meteorological conditions on attenuation to reasonable values.

There is information to support the method of calculation given in Clauses 4 to 8 for broadband noise sources. The agreement between calculated and measured values of the average A-weighted sound pressure level for downwind propagation, $L_{AT}$(DW), supports the estimated accuracy of calculation shown in Table 4. These estimates of accuracy are restricted to the range of conditions specified for the validity of the Formulae in Clauses 3 to 8 and are independent of uncertainties in sound power determination. (See the empirically extended range of heights expressed in the footnote c in Table 4).

The estimates of accuracy in Table 4 are for downwind conditions averaged over independent situations (as specified in Clause 5). They should not necessarily be expected to agree with the variation in measurements made at a given site on a given day. The latter can be expected to be considerably larger than the values in Table 4.

The estimated errors in calculating the average downwind octave band sound pressure levels, as well as pure-tone sound pressure levels, under the same conditions, may be somewhat larger than the estimated errors given for A-weighted sound pressure levels of broadband sources in Table 4.

In Table 4, an estimate of accuracy is not provided in this document for distances $d$ greater than the 1 000 m upper limit.

Throughout this document, the meteorological conditions under consideration are limited to only two cases:

a) moderate downwind conditions of propagation, or their equivalent, as defined in Clause 5;

b) a variety of meteorological conditions as they exist over months or years.

The use of Formulae (1) to (6) and (8) to (30) (and therefore also Table 4) is limited to case

a) meteorological conditions only;

b) is relevant only to the use of Formulae (7), (31) and (32).

There are also a substantial number of limitations (non-meteorological) in the use of individual Formulae. Formulae (7) and (10) to (13) are, for example, limited to approximately flat terrain. These specific limitations are described in the text accompanying the Formulas.

**Table 4 — Estimated accuracy for broadband noise of $L_{AT}$(DW) calculated using Formulae (1) to (15)**

| Height, $h$[a] | Distance, $d$[b] | |
|---|---|---|
| | 0 < $d$ <100 m | 100 m < $d$ < 1 000 m |
| 0 < $h$ < 5 m | ±3 dB | ±3 dB |
| 5 m < $h$ (< 30 m)[c] | ±1 dB | ±3 dB |

[a] $h$ is the mean height of the source and receiver.

[b] $d$ is the distance between the source and receiver.

[c] 30 m average height from source to receiver was included in the first edition due to existing experience with sources that time. Further experience gathered during more than two decades by applying the calculation of the attenuation of sound during propagation with sources in larger heights up to about 200 m (e. g. industrial sources like chimney openings of power plants, wind turbines) has shown that even these larger heights are characterised by the uncertainties given (see Annex D for wind turbines).

NOTE These estimates have been made from situations where there are no effects due to reflection or attenuation due to screening.

# Annex A
(informative)

# Additional types of attenuation, $A_{misc}$

## A.1 General

The term $A_{misc}$ in Formula (5) covers contributions to the attenuation from miscellaneous effects not accessible by the general methods of calculating the attenuation specified in Clause 7. These contributions include

— $A_{fol}$ the attenuation of sound during propagation through foliage,

— $A_{site}$ the attenuation during propagation through an industrial site, and

— $A_{hous}$ the attenuation during propagation through a built-up region of houses,

which are all considered in this annex.

For calculating these additional contributions to the attenuation, the curved downwind propagation path may be approximated by an arc of a circle of radius 5 km, as shown in Figure A.1.



## A.2 Foliage, $A_{fol}$

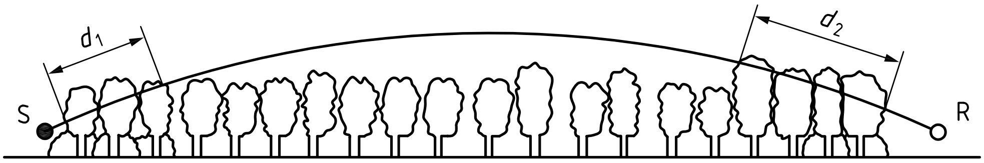
### A.2.1 General

Additional to the simplified method for the calculation of the attenuation by foliage $A_{fol}$ (see A.2.2) a more detailed method using forestal parameters for the description of the foliage has been added to take into account the local situation (see A.2.3). The method used should be clearly stated if the attenuation by foliage is a relevant part of expert-work.

### A.2.2 Simplified method

The foliage of trees and shrubs provides a small amount of attenuation, but only if it is sufficiently dense to completely block the view along the propagation path, i.e. when it is impossible to see a short distance through the foliage. The attenuation may be by vegetation close to the source, or close to the receiver, or by both situations, as illustrated in Figure A.1. Alternatively, the path for the distances $d_1$ and $d_2$ may be taken as falling along lines at propagation angles of 15° to the ground.

The first line in Table A.1 gives the attenuation to be expected from dense foliage if the total path length through the foliage is between 10 m and 20 m, and the second line if it is between 20 m and 200 m. For path lengths greater than 200 m through dense foliage, the attenuation for 200 m should be used.




**Key**

S source

R receiver

NOTE $d_f = d_1 + d_2$

For calculating $d_1$ and $d_2$, the curved path radius may be assumed to be 5 km.

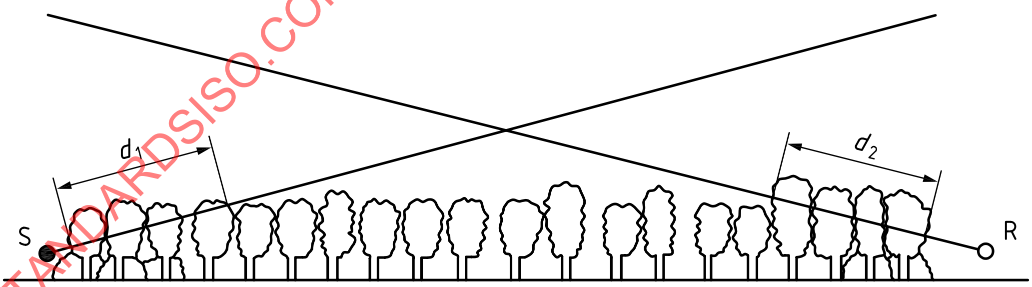
**Figure A.1 — Attenuation due to propagation through foliage increases linearly with propagation distance $d_f$ through the foliage**

**Table A.1 — Attenuation of an octave band of noise due to propagation a distance $d_f$ through dense foliage**

| **Propagation distance $d_f$** | **Nominal mid-band frequency**<br>Hz | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| m | 63 | 125 | 250 | 500 | 1 000 | 2 000 | 4 000 | 8 000 |
| | Attenuation dB: | | | | | | | |
| $10 \leq d_f \leq 20$ | 0 | 0 | 1 | 1 | 1 | 1 | 2 | 3 |
| | Attenuation, dB/m: | | | | | | | |
| $20 \leq d_f \leq 200$ | 0,02 | 0,03 | 0,04 | 0,05 | 0,06 | 0,08 | 0,09 | 0,12 |

### A.2.3 Detailed method using forestal parameters

This detailed method is described in References [14] and [15]. The foliage and the trunks of trees and shrubs can provide a relevant amount of attenuation. This effect depends on the frequency and the geometric parameters. The attenuation can be by vegetation close to the source, or close to the receiver, or by both situations, as illustrated in Figure A.2. The paths for the distances $d_1$ and $d_2$ are taken as falling along lines at propagation angles of 15° to the ground.




**Key**

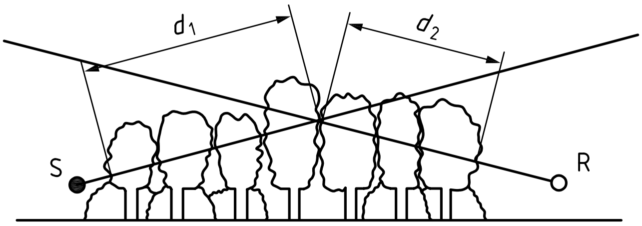
S source

R receiver

NOTE $d_f = d_1 + d_2$

**Figure A.2 — Attenuation due to propagation through foliage increases linearly with propagation distance $d_f$ through the foliage**

NOTE 1 Even if the two falling lines intercept in the vegetation, the length $d_f$ is calculated as the sum of $d_1$ and $d_2$, not by the direct line to prevent a saltus in the result.




**Key**
S source
R receiver
$d_n$ length of the ray path elements inside the foliage

**Figure A.3 — Calculation of the propagation length $d_f$ at shorter distances**



The attenuation of the vegetation is calculated by five forestal parameters given in Table A.2.

**Table A.2 — Forestal parameters**

| Parameter | Unit | Name |
|---|---|---|
| Stem diameter | cm | *D* |
| Basal area | $m^2/10^4 m^2$ | *G* |
| Standing stock | $m^3/10^4 m^2$ | *V* |
| Horizontal structuring (classing) | 1 | *S* |
| Low height foliage (classing) | 1 | *Z* |

If no values are given for the basal area and the standing stock, these values can be calculated approximately from the stem diameter *D*, the stem density *SD* (stems per $10^4 m^2$) and the height *H* of the vegetation according to Formulae (A.1) and (A.2):

$$G = D^2 \pi / 4 \times SD \qquad (A.1)$$

$$V = G \times H / 2{,}5 \qquad (A.2)$$

The values for "horizontal structuring" and "low height foliage" can be 0 or 1 or 2 according to the meaning given in Table A.3.

**Table A.3 — Classification**

| Value | Horizontal structuring | Low height foliage |
|---|---|---|
| 0 | homogeny | not present |
| 1 | minor structured | minor present |
| 2 | intense structured | much present |

If no information is given for the parameters "horizontal structuring" and "low height foliage" these two parameters are set to 0.

The frequency dependent attenuation factor $K_{lin}$ is calculated by the Formula (A.3):

$$K_{lin} = G_0 + G_D \times D + G_G \times G + G_V \times V + G_S \times S + G_Z \times Z \geq 0 \text{ dB} \qquad (A.3)$$

NOTE 2 Values less than 0 resulting from the regression calculation with measured values are set to 0.

The values for the weighting factors are given dependent on the nominal octave frequency in Table A.4:

**Table A.4 — Weighting factors for forest stands**

| Weighting-factor | Octave band frequency Hz | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 63 | 125 | 250 | 500 | 1 000 | 2 000 | 4 000 | 8 000 |
| $G_0$ dB/km | −9,32 | −17,70 | −17,16 | −8,34 | −3,31 | 3,27 | 8,05 | 12,84 |
| $G_V$ (dB/km)/(m$^3$/10$^4$m$^2$) | 0,03 | 0,05 | 0,08 | 0,07 | 0,07 | 0,07 | 0,07 | 0,08 |
| $G_G$ (dB/km)/(m$^2$/10$^4$m$^2$) | 0,23 | 0,61 | 0,85 | 0,80 | 0,74 | 0,70 | 0,64 | 0,58 |
| $G_D$ (dB/km)/(cm) | 0,08 | 0,15 | −0,02 | −0,12 | −0,19 | −0,32 | −0,38 | −0,44 |
| $G_S$ dB/km | −0,87 | −1,63 | −0,63 | 1,35 | 2,99 | 4,62 | 4,65 | 4,68 |
| $G_Z$ dB/km | −2,97 | −5,42 | −5,38 | −2,53 | −0,52 | 2,74 | 7,47 | 12,21 |

The stem diameter *D*, the stem density *SD* (stems per 10$^4$m$^2$) and the height *H* of the vegetation have to be specified to calculate an appropriate value for the damping of the vegetation. If no values are given for the forestal parameters, no attenuation shall be used due to the vegetation. For shrubs the parameters $D$=7 cm, $G$=10 m$^2$, $V$=50 m$^3$, $S$=0 und $Z$=2 can be used.

Table A.5 lists ranges of forestal parameters for different types of foliage/fouling.

**Table A.5 — Ranges of forestal parameters for different types of foliage/fouling**

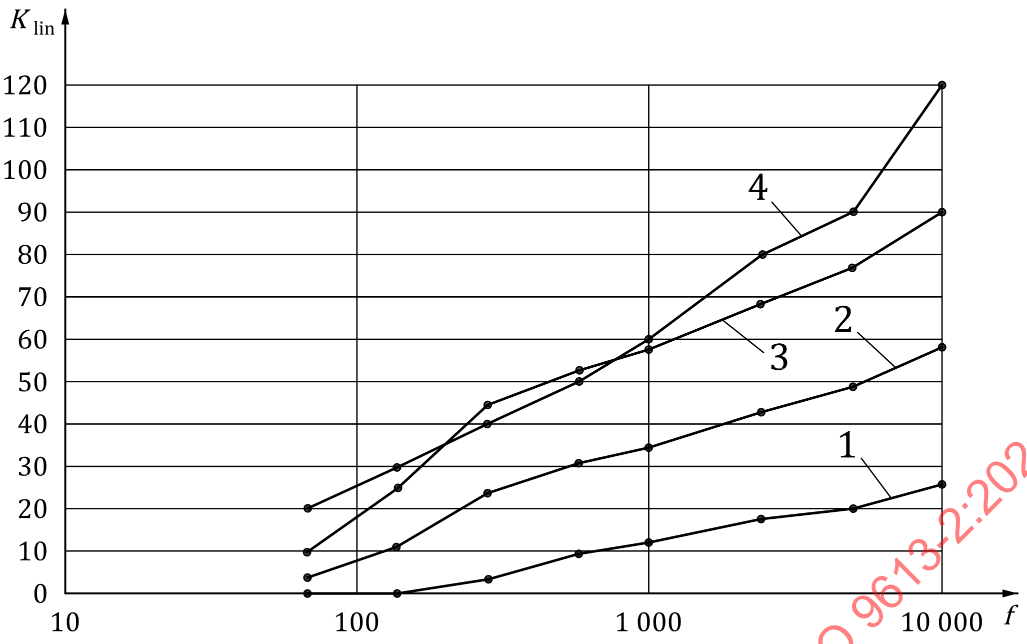
| Parameter | Unit | Name | Typical range |
|---|---|---|---|
| Stem diameter | cm | D | 10 cm to 40 cm |
| Basal area | m$^2$/10$^4$ m$^2$ | G | 15 m$^2$/10$^4$ m$^2$ to 50 m$^2$/10$^4$ m$^2$ |
| Standing stock | m$^3$/10$^4$ m$^2$ | V | 100 m$^3$/10$^4$ m$^2$ to 400 m$^3$/10$^4$ m$^2$ |
| Horizontal structuring (classing) | 1 | S | 0 to 2 |
| Low hight fouling (classing) | 1 | Z | 0 to 2 |

With the typical range of the forestal parameters, three classes of forest densities can be defined. Such classes are given in Table A.6.

**Table A.6 — Classes of forest densities**

| Name | Unit | Light forest | Normal forest | Dense forest |
|---|---|---|---|---|
| D | cm | 10 | 25 | 40 |
| G | m$^2$/10$^4$ m$^2$ | 15 | 32 | 50 |
| V | m$^3$/10$^4$ m$^2$ | 100 | 250 | 400 |
| S | - | 0 | 1 | 2 |
| Z | - | 0 | 1 | 2 |

Corresponding attenuation values are given in Figure A.4.




**Key**

$K_{lin}$ attenuation factor, expressed in decibels per kilometre

$f$ frequency, expressed in hertz

1 light forest

2 normal forest

3 dense forest

4 attenuation with simplified method A.2.2 for 20 m ≤ $d_f$ ≤ 200 m

**Figure A.4 — Attenuation values of forest densities**



## A.3 Industrial sites, $A_{site}$

At industrial sites, attenuation can occur due to scattering from installations (and other objects), which may be described as $A_{site}$ unless accounted for under $A_{bar}$ or the sound source radiation specification. The term ‘installations’ includes miscellaneous pipes, valves, boxes, structural elements, etc.

As the value of $A_{site}$ depends strongly on the type of site, it is recommended that it is determined by measurements. However, for an estimate of this attenuation, the values in Table A.7 may be used. The attenuation increases linearly with the length of the curved path $d_s$ through the installations (see Figure A.5), with a maximum of 10 dB.

**Table A.7 — Attenuation coefficient of an octave band of noise during propagation through installations at industrial plants**

| **Nominal mid-band frequency,** Hz | 63 | 125 | 250 | 500 | 1 000 | 2 000 | 4 000 | 8 000 |
|---|---|---|---|---|---|---|---|---|
| $A_{site}$ dB/m | 0 | 0,015 | 0,025 | 0,025 | 0,02 | 0,02 | 0,015 | 0,015 |

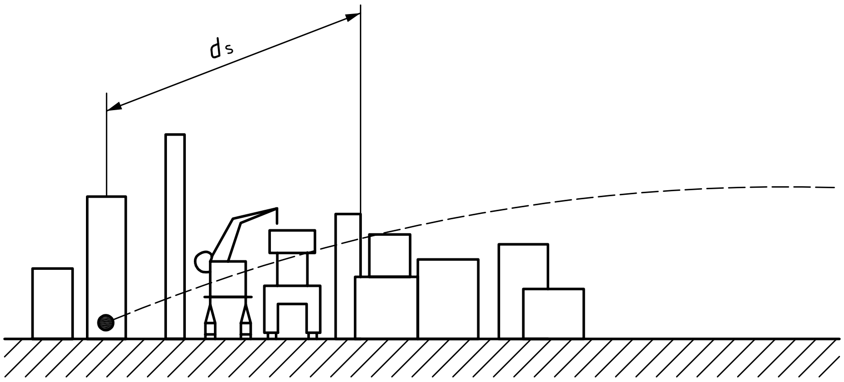



**Figure A.5 — Attenuation $A_{site}$ increases linearly with the propagation distance $d_s$ through the installations at industrial plants (5 km radius of the curved path)**



## A.4 Housing, $A_{hous}$

When either the source or receiver, or both are situated in a built-up region of houses, attenuation will occur due to screening by the houses. However, this effect may largely be compensated for by the propagation between houses and by reflections from other houses in the vicinity. This combined effect of screening and reflections that constitutes $A_{hous}$ can be calculated for a specific situation, at least in principle, by applying the procedures for both $A_{bar}$ and reflections described in 7.4 and 7.5. Because the value of $A_{hous}$ is very situation-dependent, such calculation may need to be justified in practice. A more useful alternative, particularly for the case of multiple reflections where the accuracy of calculation suffers, may be to measure the effect, either in the field or by modelling.

An approximate value for the A-weighted attenuation $A_{hous}$ which should not exceed 10 dB, can also be estimated as follows.

There are two separate contributions:

$$A_{hous} = A_{hous,1} + A_{hous,2} \quad \text{(A.4)}$$

An average value for $A_{hous,1}$ (in dB) can be calculated using:

$$A_{hous,1} = 0{,}1 B d_b \text{ dB} \quad \text{(A.5)}$$

where

- $B$ is the density of the buildings along that path, given by the total plan area of the houses divided by the total ground area (including that covered by the houses);
- $d_b$ is the length of the sound path, in metres, through the built-up region of houses, determined by a procedure analogous to that shown in Figure A.1.

The path length $d_b$ can include a portion $d_1$ near the source and a portion $d_2$ near the receiver, as indicated in Figure A.1.

The value of $A_{hous}$ shall be set equal to zero in the case of a small source with a direct, unobstructed line of sight to the receiver through a corridor between housing structures.

NOTE The A-weighted sound pressure level at specific individual positions in a region of houses can differ by up to 10 dB from the average value predicted using Formulae (A.4) and (A.5).

If there are well-defined rows of buildings near a road, a railway, or a similar corridor, an additional term $A_{house,2}$ may be included (provided this term is less than the insertion loss of a barrier at the same position with the mean height of the buildings):

$$A_{hous,2} = -10\lg[1-(p/100)]\mathrm{dB} \tag{A.6}$$

where

$p$ the percentage of the length of the facades relative to the total length of the road or railway in the vicinity; and

$p$ ≤ 90 %.

In a built-up region of houses, the value of $A_{hous,1}$ (as calculated by Formula (A.5)) interacts with the value for $A_{gr}$, the attenuation due to the ground (as calculated by Formulae (10) or (11)) as follows:

Let $A_{gr,b}$ be the ground attenuation in the built-up region, and $A_{gr,0}$ be the ground attenuation if the houses were removed (i.e. as calculated by Formulae (11) or (14)). For propagation through the built-up region in general, $A_{gr,b}$ is assumed to be zero in Formula (5). If, however, the value of $A_{gr,0}$ is greater than that of $A_{hous}$, then the influence of $A_{hous}$ is ignored and only the value of $A_{gr,0}$ is included in Formula (5).

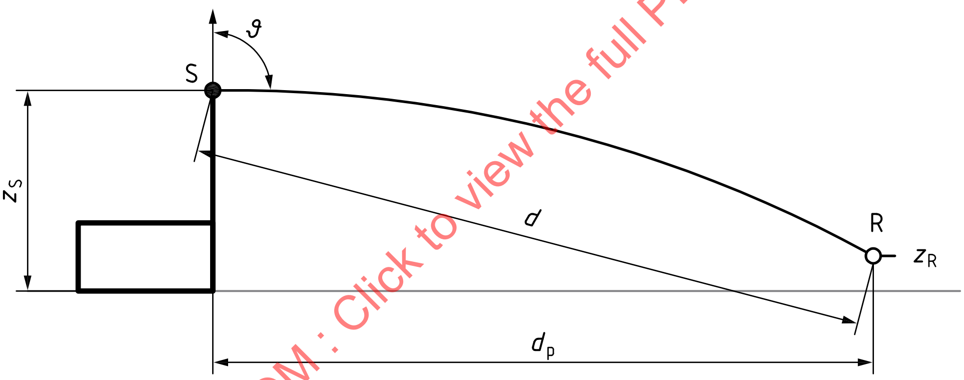
The interaction above is essential to allow for a range of housing density $B$. For low-density housing, the value of $A_{gr}$ is dominant, while for high-density housing $A_{hous}$ dominates.

# Annex B
(informative)

# Directivity correction, $D_c$, for chimney stacks

## B.1 Dependency of the directivity correction from parameters

The sound emitted by chimneys and other vertical and upward-facing open pipes is modelled as a point sound source in the middle of the opening cross-section. Research projects on the radiation of chimney openings[16] have shown that the radiation of the entire sound power is not omnidirectional. With these investigations, the frequency-dependent directivity corrections required for modelling were determined and communicated in diagram form. In order to enable precise and quality-assured application, these results are communicated here in tabular form with predefined support points, whereby the directivity correction $D_c$ applicable to any geometry of the chimney opening relative to the receiver position can be clearly determined by interpolation of the determining parameters. Since the value of $D_c$ is intended to refer to a downwind condition, the angle $\vartheta$ of a sound ray curved with a radius of 5 km from the opening to the receiver according to Figure B.1 is used in the application of this table. The directivity correction $D_c$ for an octave band determined taking into account the geometry according to Figure B.1 is included in the calculation of the receiver level with the octave band sound power level $L_W$ according to Formula (3).




**Key**

S source
R receiver
$z_S$ source height
$z_R$ receiver height
$\vartheta$ direction of radiation
$d$ distance source – receiver
$d_p$ distance source – receiver projected to the horizontal plane

**Figure B.1 — Geometry chimney opening – receiver**

The reference direction of the source with $\vartheta = 0$ is in the vertical direction upwards. The geometry of the true ground profile is insignificant. The relevant direction $\vartheta$ due to the curvature of the ray results from the quantities mentioned in the diagram to

$$\vartheta = 180° - \text{arctg}\left(\frac{d_p}{z_S - z_R}\right) - \arcsin\left(\frac{d}{2r}\right) \quad \text{(B.1)}$$

with

$z_S$ absolute height of the source (chimney opening)

$z_R$ absolute height of the receiver

$r$ radius of curvature of the ray S – R (5 000 m)

The correction $\Delta\vartheta$, already part of Formula (B.1) with

$$\Delta\vartheta = \arcsin\left(\frac{d}{2r}\right) \quad \text{(B.2)}$$

takes into account the steeper radiation angle of the curved ray to the receiver compared to straight propagation. This correction shall be taken into account for all sources that have a directivity dependent angle in the vertical propagation plane if the calculated receiver-level is to refer to downwind conditions.

The directivity correction is listed in Table B.1 for discrete values depending on the direction ϑ and *ka* (product of wave number *k* and radius *a* of the chimney opening). Since the speed of sound and thus the wavelength for a given octave band centre frequency *f* depends on the current temperature *T*, *ka* is determined from Formula (B.3).

$$ka = \frac{2\pi af}{331{,}4 \cdot \sqrt{1 + \frac{T}{273°C}}} \quad \text{(B.3)}$$

with

*a* radius of the chimney-opening, in metres;

*f* octave band mid-frequency, in hertz;

*T* temperature at the chimney mouth, in degrees celsius.

**Table B.1 — Directivity correction $D_c$ in dB in dependence of the product *ka* for different discrete direction angles $\vartheta$ related to downwind-conditions ($v \sim 3$ m/s).**

| ϑ in deg | *ka* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 4,0 | 5,0 | 6,3 | 8,0 | 101 | 12,7 | 16,0 | 20,2 | 25,4 | 32,0 |
| 30 | 2,4 | 2,1 | 1,9 | 2,0 | 2,1 | 2,6 | 3,1 | 3,4 | 3,4 | 3,3 |
| 45 | 4,0 | 3,4 | 3,1 | 3,1 | 3,4 | 4,0 | 4,4 | 4,6 | 4,6 | 4,5 |
| 60 | 4,0 | 3,4 | 3,1 | 3,1 | 3,4 | 4,0 | 4,4 | 4,6 | 4,6 | 4,5 |
| 75 | 2,4 | 2,1 | 1,9 | 2,0 | 2,1 | 2,6 | 3,1 | 3,4 | 3,4 | 3,3 |
| 90 | -2,4 | -2,2 | -2,0 | -1,9 | -1,9 | -1,9 | -1,9 | -2,1 | -2,3 | -2,7 |
| 105 | -4,3 | -4,6 | -5,0 | -5,4 | -5,9 | -6,4 | -6,9 | -7,3 | -7,6 | -7,9 |
| 120 | -6,3 | -7,0 | -77 | -8,2 | -8,7 | -9,1 | -9,6 | -10,2 | -11,0 | -12,1 |

For quality-assured and thus precise application, the value range of the two parameters covered by measurements are extended in the following way:

— for $ka < 4$ $D_c = 0$ for $ka \le 1$ and interpolation for $1 \le ka \le 4$

— for $ka > 32$ $D_c$ constant as for $ka = 32$

— for $\vartheta < 30°$ $D_c$ constant as for $\vartheta = 30°$

— for $\vartheta > 120°$ $D_c$ constant as for $\vartheta = 120°$

NOTE The directivity corrections $D_c$ on which Table B.1 is based were determined by measurement on large industrial chimneys[16], with measurement results available for the ranges $4 \le ka \le 32$ and $30° \le \vartheta \le 120°$. They were usually gas pipes built of bricks that were not lined with absorption. For chimneys of very different design, the determined values are not fully representative and can only be applied as an approximation.

## B.2 Determination of $D_c$ with specifically given parameters

The first step is to determine the two parameters required to apply Table B.1, $\vartheta$ by Formula (B.1) and $ka$ by Formula (B.3). From these two parameters, the appropriate directivity correction $D_c$ is then determined in the second step.

For interpolation, the lower and upper interval limits are searched for adjacent to the current parameter on the scale of the given support values. With $\vartheta_1$ as the lower support value and $\vartheta_2$ as the upper support value for the current value of the angle $\vartheta$ and $ka_1$ as the lower support value and $ka_2$ as the upper support value for the current value $ka$, the value of $D_c(ka, \vartheta)$ results directly from Table B.1, with linear or bilinear interpolation.

For interpolation, the following generally applies:

$$x = \frac{\ln(ka) - \ln(ka_1)}{\ln(ka_2) - \ln(ka_1)} \qquad \text{(B.4)}$$

$$y = \frac{\vartheta - \vartheta_1}{\vartheta_2 - \vartheta_1} \qquad \text{(B.5)}$$

Case 1 — no interpolation

Case 1a — $ka \le 1$ and $\vartheta \le 30°$ → $ka_r = 1$, $\vartheta_r = 30°$

Case 1b — $ka \le 1$ and $\vartheta \ge 120°$ → $ka_r = 1$, $\vartheta_r = 120°$

Case 1c — $ka \ge 32$ and $\vartheta \le 30°$ → $ka_r = 32$, $\vartheta_r = 30°$

Case 1d — $ka \ge 32$ and $\vartheta \ge 120°$ → $ka_r = 32$, $\vartheta_r = 120°$

$$D_c(ka, \vartheta) = D_c(ka_r, \vartheta_r) \qquad \text{(B.6)}$$

Case 2 — linear interpolation

Case 2a — $ka \le 1$ and $30° < \vartheta < 120°$ → $ka_r = 1$

Case 2b — $ka \ge 32$ and $30° < \vartheta < 120°$ → $ka_r = 32$

$$D_c(ka, \vartheta) = D_c(ka_r, \vartheta_1) \cdot (1 - y) + D_c(ka_r, \theta_2) \cdot y \qquad \text{(B.7)}$$

Case 2c — $1 < ka < 32$ and $\vartheta < 30°$ → $\vartheta_r = 30°$

Case 2d — $1 < ka < 32$ and $\vartheta > 120°$ → $\vartheta_r = 120°$

$$D_c(ka, \vartheta) = D_c(ka_1, \vartheta_r) \cdot (1 - x) + D_c(ka_2, \vartheta_r) \cdot x \qquad \text{(B.8)}$$

Case 3 — bilinear interpolation

$$D_c(ka, \vartheta) = D_c(ka_1, \vartheta_1)(1 - x)(1 - y) + D_c(ka_2, \vartheta_1)x(1 - y) + D_c(ka_1, \vartheta_2)(1 - x)y + D_c(ka_2, \vartheta_2)xy \qquad \text{(B.9)}$$

## B.3 Examples

For three examples, the directivity corrections $D_c$ for the octave bands 63 Hz to 8 000 Hz were calculated using the specified method. In Table B.2 the parameters according to Figure B.1 for the examples 1 to 3 are shown.

**Table B.2 — Input parameters for examples 1 to 3**

| Parameter | Symbol | Unit | Example | | |
|---|---|---|---|---|---|
| | | | 1 | 2 | 3 |
| Source height | $Z_S$ | m | 100 | 100 | 100 |
| Radius of opening | $A$ | m | 2 | 2,5 | 3 |
| Receiver height | $Z_R$ | m | 5 | 5 | 5 |
| Horizontal distance | $d_p$ | m | 300 | 500 | 1 000 |
| Temperature | $T$ | °C | 110 | 110 | 110 |
| Radius of circular ray | $R$ | m | 5 000 | 5 000 | 5 000 |
| Interim results | | | | | |
| Angle of straight ray | $\vartheta_0$ | grad | 107,6 | 100,8 | 97,1 |
| Deviation with curvature | $\Delta\vartheta$ | grad | 1,8 | 2,9 | 5,8 |
| Relevant angle | $\vartheta$ | grad | 105,8 | 97,8 | 91,3 |

Table B.3 shows for each of the three examples and for each octave band the value of *ka* calculated with Formula (B.3), the case number applied according to the above classification and the calculated value of the directivity correction $D_c$.

**Table B.3 — Calculation results for examples 1 to 3**

| Example | | Octave band centre-frequencies *f* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 63 | 125 | 250 | 500 | 1 000 | 2 000 | 4 000 | 8 000 |
| 1 | ka | 2,02 | 4,00 | 8,00 | 16,01 | 32,01 | 64,03 | 128,06 | 256,11 |
| | Case | 3 | 3 | 3 | 3 | 2b | 2b | 2b | 2b |
| | $D_c$ in dB | −2,2 | −4,4 | −5,5 | −7,0 | −8,1 | −8,1 | −8,1 | −8,1 |
| 2 | ka | 2,52 | 4,00 | 10,00 | 20,01 | 40,02 | 80,03 | 160,07 | 320,14 |
| | Case | 3 | 3 | 3 | 3 | 2b | 2b | 2b | 2b |
| | $D_c$ in dB | −2,3 | −3,5 | −4,0 | −4,8 | −5,4 | −5,4 | −5,4 | −5,4 |
| 3 | ka | 3,03 | 6,00 | 12,01 | 24,01 | 48,02 | 96,04 | 192,08 | 384,17 |
| | Case | 3 | 3 | 3 | 3 | 2b | 2b | 2b | 2b |
| | $D_c$ in dB | −2,1 | −2,3 | −2,3 | −2,7 | −3,2 | −3,2 | −3,2 | −3,2 |