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Report

Proposal for Nordtest Method: Nord2000 – Prediction of Outdoor Sound Propagation

Client: Nordic Innovation Centre, NICe

AV 1106/07

27 March 2007, revised 13 January 2014

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Proposal for Nordtest Method: Nord2000 – Prediction of Outdoor Sound Propagation

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Contents

1. Scope

Environmental noise from various sound sources such as roads, railways, air traffic, and industrial plants depends on the generation and propagation of sound. There exist methods for determining the sound power levels emitted by various noise sources. This Nordtest method specifies a calculation method for the prediction of the attenuation of noise during propagation outdoors.

The method described 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. The prediction method can be used for predicting the effect of propagation of noise in one-third octave bands from 25 Hz to 10 kHz when sound is propagating over ground from a point source to a receiver. More complex sources can be represented by collections of incoherent point sources.

The method can be used as one component in a method for the calculation of the EU noise indicators L_{den} and L_{night} and the production of noise mappings.

2. Field of Application

The method can be used for any normally occurring terrain shapes, and for a class of typical weather conditions. For noise sources close to the ground, such as roads and railways, the method can be used for propagation up to approximately 1 km. For high noise sources, e.g. wind turbines and airborne aircraft, the method can be used for propagation up to several kilometers.

The method predicts the effect of typical weather conditions on noise levels, and hence the method can be used for prediction of the yearly average noise levels. This includes the EU indicators L_{den} and L_{night}.

The method is valid for weather conditions where the vertical effective sound speed profile can be approximated by the so-called log-lin profile. Many typical weather conditions can be approximated by a log-lin profile with a good accuracy. This includes neutral as well as stably and unstably stratified atmospheres. The method cannot be expected to work well for special layered atmospheres. This imposes a limitation on the range of propagation since long-range propagation may include cases with more complicated layered atmospheres.

The calculation is valid for a point source. Most real noise source cannot be considered a point source. Therefore these sources normally have to be divided in a number of incoherent sub-sources as described in related methods for determining the sound power levels emitted by various noise sources.

The method is based on a simplified terrain description defined by a number of straight line segments, and therefore denoted a segmented terrain. The simplification of a real terrain into the segmented terrain is not included in the Nordtest method, but guidelines are included. The segmented terrain includes natural terrain, but also other obstacles such as buildings and noise barriers.

The geometry in the method is in general two-dimensional. The only exception from this rule is the case of reflection from vertical objects where the size of the reflector lateral to the propagation path has to be considered. This implies that the terrain shape and weather conditions are assumed to be constant perpendicular to the direction of propagation. The production of noise mappings must include three-dimensional effects, and in particular reflections from vertical obstacles. Reflections may contribute significantly to the sound pressure level at the receiver, particularly if the direct propagation path is blocked by obstacles. This is the reason why this 3D effect is included in the method while others has been left out. The Annex gives informative guidelines on how to include lateral diffraction around finite screens.

Due to the assumption in the basic method, screens are in principle assumed to have infinite horizontal length perpendicular to the direction of propagation. However, if a screen has a finite horizontal size a significant contribution of sound may propagate laterally from source to receiver around the vertical edges of the screen. Other three-dimensional effect from variation in terrain shape and surface conditions outside the propagation path may occur, and can be taken into account by similar ideas.

It is assumed that the terrain surface properties can be described by the Delany and Bazley impedance model. This model works well for many ground surfaces, but less well for some important special surfaces including porous asphalt. The use of other impedance model in the prediction method for such surfaces has shown acceptable results in some cases after a modification of the method. The use of other impedance models is not included in the method, and requires separate consideration for each particular case.

A complete definition of the input quantities and the effects included in the calculation is given in Section 4.

3. Normative References

The following standards contain provisions which, through reference in this text, constitute provisions of this method. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this method are encouraged to investigate the possibility of applying the most recent edition of the standards indicated below. Members of IEC and ISO maintain registers of currently valid international standards.

ISO 266:1997, *Acoustics - Preferred frequencies*

IEC 60050(801):1994, *International Electrotechnical Vocabulary - Chapter 801: Acoustics and electroacoustics*

IEC 61672-1:2002, *Electroacoustics - Sound level meters. Part 1: Specifications*

IEC 61260:1995, *Electroacoustics, Octave-band and fractional-octave band filters*

Nordtest NT ACOU 104:1999, *Ground surfaces: Determination of the acoustic impedance*

ISO GUM, PD 6461-3:1995, *General Metrology. Part 3: Guide to the expression of uncertainty in measurement*

4. Definitions

4.1 Conventions

$\hat{z}$ The symbol ^ placed over a variable indicates that the variable is a complex number.

z^* The symbol * indicates the complex conjugate

$\breve{z}$ The symbol ∪ placed over a variable indicates that the variable is refraction corrected (in case of refraction the geometry has been transformed into an equivalent geometry corresponding to non-refracting propagation)

⊕ The symbol ⊕ indicates energy summation of noise levels (incoherent summation): $L_1 \oplus L_2 = 10\log\left(10^{L_1/10} + 10^{L_2/10}\right)$

NA *NA* or *na* means Not Applied and is used where a value is not applied (may be a value in a two-dimensional table or a value returned by a function)

log The function *log* used in equations means the logarithm to the base 10

ln The function *ln* used in equations means the natural logarithm (base e)

4.2 Variables

a Mean stem radius, forest (m)

A Coefficient of the logarithmic part of the sound speed profile (m/s)

A_+ Upper limit of A (= A + 1.7 s_A) (m/s)

B Coefficient of the linear part of the sound speed profile (s^{-1})

B_+ Upper limit of B (= B + 1.7 s_B) (s^{-1})

C_v^2 Structure parameter of turbulent wind speed fluctuations ($m^{4/3}s^{-2}$)

C_T^2 Structure parameter of turbulent temperature fluctuations (Ks^{-2})

c Sound speed (m/s)

$\bar{c}$ Average sound speed between the heights h_S and h_R above the ground (m/s)

c_0 Sound speed at the ground in equivalent linear sound speed profile (m/s)

d Distance from source to receiver measured along flat terrain (m)

d_{segm} Length of project of segment onto terrain baseline (m)

d_{SZ} Distance from source to shadow zone measured along terrain segment (m)

d_{refl} Distance from source to reflection point measured along terrain segment (m)

d' Distance between projection of S and R onto a terrain segment (m)

$d_{r,l}$ Distance from reflection point to left edge of reflector (m)

$d_{r,r}$ Distance from reflection point to right edge of reflector (m)

f Frequency (Hz)

F_f Coherence coefficient due to frequency band averaging

$F_{\Delta\tau}$ Coherence coefficient due to fluctuating refraction

F_c Coherence coefficient due to turbulence

F_r Coherence coefficient due to terrain surface roughness

F_s Coherence coefficient due to propagation through scattering zones

F_{λ}	Fraction of the wavelength in Fresnel zone calculations
h_R	Shortest distance from receiver to terrain (m)
h_{Rv}	Height of receiver vertically above terrain (m)
h'_R	Height of R above a terrain segment (m)
h_S	Shortest distance from source to terrain (m)
h_{Sv}	Height of source vertically above terrain (m)
h'_S	Height of S above a terrain segment (m)
h''_{SCR}	Artificial height over screen used when determining the equivalent linear sound speed profile (m)
j	Complex unit
k	Wave number (m^{-1})
k_0	Wave number at the ground corresponding to c_0 (m^{-1})
L_W	Sound power level (dB)
M	Indicates middle part as suffix (between screens or screen edges)
n''	Density of stems, forest (m^{-2})
nxz	Number of points in the terrain (= N_{ts} +1)
N_{ts}	Number terrain segments
$\hat{p}$	Sound pressure with amplitude and phase (complex number)
$\hat{Q}$	Spherical wave reflection coefficient
r	Ground roughness (m)
R	Indicates receiver as suffix
R	Travel distance (m)

$R_{A,B}$ Radius of curvature of ray path (m)

RH Mean relative humidity along propagation path, used for air absorption (%)

$\Re_i$ Incoherent reflection coefficient based on α_{ri}

$\hat{\Re}_P$ Plane wave reflection coefficient

S Indicates source as suffix

s_A Standard deviation of A from short-term meteorological fluctuations (m/s)

s_B Standard deviation of B from short-term meteorological fluctuations (s^{-1})

t_0 Temperature at the ground (°C)

t_{mean} Mean temperature between the heights h_S and h_R above the ground (°C)

t_{air} Mean temperature along propagation path, used for air absorption (°C)

T Edge point of screen

T_1 Edge closest to source

T_2 Edge closest to receiver

w Fresnel-zone weight

x Horizontal position of a ground point (m)

z Vertical position of a ground point (m)

$z_{r,upp}$ Height of upper edge of reflector (m)

$z_{r,low}$ Height of lower edge of reflector (m)

z_0 Roughness length (m)

$\hat{Z}_G$ Normalized ground impedance

α Absorption coefficient

α_{ri} Random incidence absorption coefficient

β Wedge angle (radians)

ΔL_d Propagation effect of spherical divergence of the sound energy (dB)

ΔL_a Propagation effect of air absorption (dB)

ΔL_t Propagation effect of terrain (ground and barriers) (dB)

ΔL_s Propagation effect of scattering zones (dB)

ΔL_r Propagation effect of reflection by an obstacle (dB)

$\Delta\theta$ Change in ray angle (radians)

$\Delta\tau$ Travel time difference for average refraction (s)

$\Delta\tau_+$ Travel time difference for upper refraction (s)

θ_R Diffraction angle of a wedge, receiver side (radians)

θ_S Diffraction angle of a wedge, source side (radians)

θ_r Relection angle between direction from image source S' to receiver R and direction of the reflector (radians)

λ Wavelength (m)

λ_0 Wavelength at the ground corresponding to c_0 (m)

ξ Relative sound speed gradient (m^{-1})

ξ_{ray} Relative sound speed gradient corresponding to $R_{A,B}$ (m^{-1})

ρ Transversal separation between rays (m)

ρ_E Effective energy reflection coefficient ρ_E of a reflector

σ Ground flow resistivity ($Pasm^{-2}$)

τ Travel time for average refraction (s)

τ_+ Travel time for upper refraction(s)

ψ_G Grazing ground reflection angle (radians)

4.3 Coordinates

$O=(x_O,z_O)$ Reflection point coordinates at vertical reflector

$P_S=(x_{SGv},z_{SGv})$ Ground point vertically below source

$P_R=(x_{RGv},z_{RGv})$ Ground point vertically below receiver

$R=(x_R,z_R)$ Receiver coordinates

$R_G=(x_{RG},z_{RG})$ Ground point closest to receiver

$S=(x_S,z_S)$ Source coordinates

$S_G=(x_{SG},z_{SG})$ Ground point closest to source

$T=(x_T,z_T)$ Coordinates of screen edge T

$T_1=(x_{T1},z_{T1})$ Coordinates of screen edge T_1

$T_2=(x_{T2},z_{T2})$ Coordinates of screen edge T_2

4.4 Auxiliary Functions

In order to simplify the description of the method a number of the auxiliary functions have been defined. Most of the functions are described in Section 5.23 where the paragraph headlines correspond to the names of the functions. Other auxiliary functions have been described in different sections throughout the Nordtest standard method. These functions are summarized in Section 5.23.20 with a reference to the section where they have been described.

5. Calculation Method

5.1 Introduction

The method described in Section 5 predicts the attenuation of sound propagating over ground outdoors from a point source to a receiver. The sound pressure level at the receiver is predicted in one-third octave bands from 25 Hz to 10 kHz. The calculated sound pressure levels are short term levels such as instantaneous sound pressure levels or equivalent sound pressure level over a time period without a change in the weather. Short term equivalent sound pressure levels normally have duration of no more than a few hours.

In the method it is assumed that the two-dimensional terrain profile is approximated by a number of straight line segment and that screen and other man-made structure have been made a part of the terrain profile.

In the description of the method a number of auxiliary functions are used which are described in Section 5.23.

5.2 Structure of the Prediction Method

The sound pressure level L_R at the receiver is for each frequency band predicted according to Eq. (1). The equation is used for a direct propagation path from source to receiver as well as for a reflection path via a reflection point.

$$L_R = L_W + \Delta L_d + \Delta L_a + \Delta L_t + \Delta L_s + \Delta L_r \tag{1}$$

where

L_W is the sound power level within the considered frequency band,

ΔL_d is the propagation effect of spherical divergence of the sound energy,

ΔL_a is the propagation effect of air absorption,

ΔL_t is the propagation effect of the terrain (ground and screens),

ΔL_s is the propagation effect of scattering zones,

ΔL_r is the propagation effect of obstacle dimensions and surface properties when calculating a contribution from sound reflected by an obstacle. If the ray path is not a reflection path $\Delta L_r = 0$.

The propagation effects mentioned above are assumed to be independent and can therefore be predicted separately. The only exception is the effect of the terrain ΔL_t and the effect of scattering zones ΔL_s which may interact to some extent as a decrease in coherence introduced by the latter effect may affect the prediction of the former.

5.3 Definition of Input Variables

The input variables can be divided in variables defining the terrain and the weather variables and optionally variables defining a scattering zone.

5.3.1 Terrain Definition Variables

The simplified terrain is defined by the coordinates (x,z) of the points of discontinuity in the terrain profile and the flow resistivity σ and ground roughness r of each terrain segment as shown in Table 1. The number of points in the profile is denoted nxz and the profile therefore contains $N_{ts} = nxz$-1 segments. In the present Nordtest method the x-coordinates has to be in ascending order ($x_i > x_{i-1}$). The numbering of the segments in the terrain profile is from 1 to N_{ts}. Therefore, segment no. i has the end coordinates (x_i,z_i) and (x_{i+1},z_{i+1}) and flow resistivity σ_i and ground roughness r_i. The terrain defined by Table 1 is sometimes denoted a segmented terrain.

Point no.	**Horizontal distance**	**Vertical height**	**Ground flow resistivity**	**Ground roughness**
1	x_1	z_1	σ_1	r_1
2	x_2	z_2	σ_2	r_2
...	...	...	...	...
nxz-1	x_{nxz-1}	z_{nxz-1}	σ_{nxz-1}	r_{nxz-1}
nxz	x_{nxz}	z_{nxz}	NA	NA

Table 1
Terrain profile definition.

The position of the point source S and the receiver R are defined by the vertical source and receiver heights h_{Sv} and h_{Rv}. h_{Sv} is the height of S above the first point (x_1,z_1) in the terrain profile and h_{Rv} is the height above the last point (x_{nxz},z_{nxz}).

5.3.2 Weather Definition Variables

The input variables defining the weather condition are:

z_0 Roughness length (m)

A Coefficient of the logarithmic part of the sound speed profile (m/s)

B Coefficient of the linear part of the sound speed profile (s^{-1})

s_A Standard deviation of A from short-term meteorological fluctuations (m/s)

s_B Standard deviation of B from short-term meteorological fluctuations (s^{-1})

t_0 Temperature at the ground (°C)

C_v^2 Structure parameter of turbulent wind speed fluctuations ($m^{4/3}s^{-2}$)

C_T^2 Structure parameter of turbulent temperature fluctuations (Ks^{-2})

t_{air} Mean temperature along propagation path, used for air absorption (°C)

RH Mean relative humidity along propagation path, used for air absorption (%)

The variables above defines the vertical effective sound speed profile *c(z)* as shown in Eq. (2) where *z* is the height above the ground surface and *C* is the sound speed at the ground determined using the auxiliary function *Coft* as shown in Eq. **(3)**. To avoid numerical problems in the calculation of sound rays (Section 5.5) when z_0 becomes less than 0.001 m, it is recommended to use the value 0.001 m. In the following the effective sound speed will simply be designated the sound speed. In case of segmented terrain z is the perpendicular (slant) distance to each segment.

$$c(z) = A \ln\left(\frac{z}{z_0} + 1\right) + Bz + C \qquad \textbf{(2)}$$

$$C = Coft(t_0) \qquad (3)$$

s_A and s_B include short term fluctuations (without a significant change in the weather) in the sound speed profile in excess what is already covered by the structure parameters C_v^2 and C_T^2. Therefore, when calculating instantaneous noise levels s_A and s_B shall be zero.

The weather coefficients *A* and *B* are determined from weather data available at normal weather stations. When calculating the yearly average of noise levels according to [4] *A* and *B* are directly used to describe the different meteorological classes in [4].

5.3.3 Scattering Zone Variables

The forest (or other kind of dense vegetation) is defined by the following variables.

$x_{i,1}$ X-coordinate of the beginning of belt no. i

$x_{i,2}$ X-coordinate of the end of belt no. i

a Mean stem radius

n'' Density of stems

α Effective absorption coefficent of stems *h* Average height of trees

It is required that $x_{i,1} < x_{i,2} < x_{i+1,1}$. If the belt of trees from a propagation point of view has a limited width perpendicular to the direction of propagation information on the width (in the Y-coordinate direction) has to be included as described in Section 5.19.

5.3.4 Reflection Path Variables

The propagation effect of a reflection path is predicted by the same propagation model used for the direct path on basis of the propagation parameters defined in Sections 5.3.1 to 5.3.3 determined along the reflection path. However, the propagation effects in Eq. (1) will also include a propagation effect ΔL_r which is a correction for the efficiency of the reflection. The reflection path is shown in Figure 1.

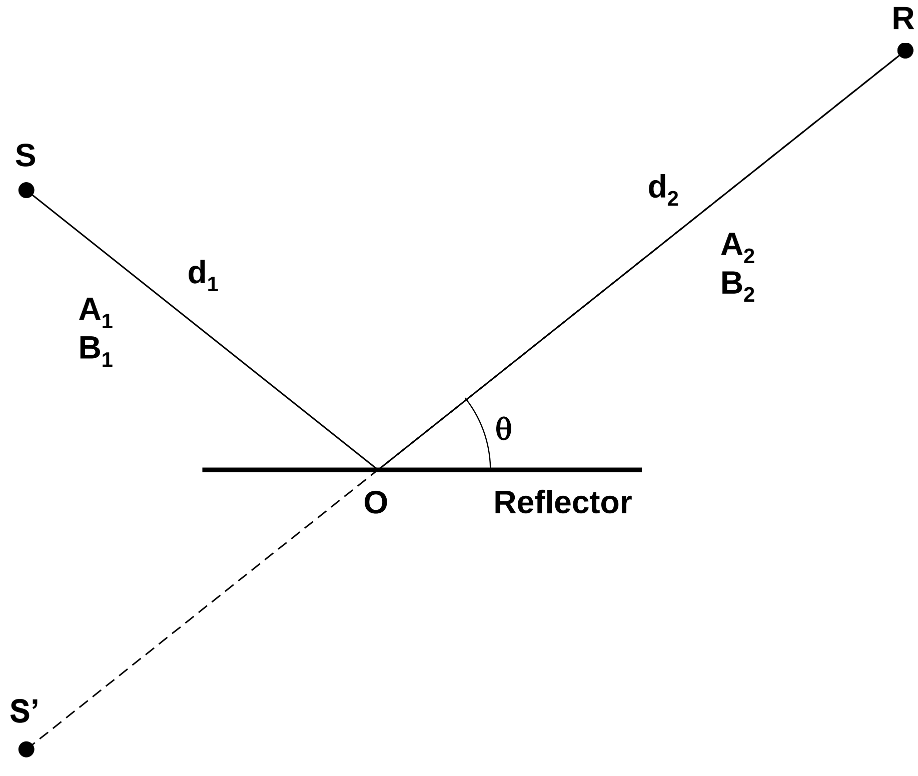

Figure 1
Distances and angles (top view) and weather coefficients in case of a reflection path

For a reflection path separate weather coefficient A and B are given before and after the reflection point and additional input variables are included to define size, orientation and surface properties of the reflector:

A_1 Weather coefficient A before reflection point (m/s)

A_2 Weather coefficient A after reflection point (m/s)

B_1 Weather coefficient B before reflection point (s^{-1})

B_2 Weather coefficient B after reflection point (s^{-1})

d_1 Distance from source to reflection point (m)

d_2 Distance from reflection point to receiver (m)

$z_{r,upp}$ Height of upper edge of reflector (m)

$z_{r,low}$ Height of lower edge of reflector (m)

$d_{r,l}$ Distance from reflection point to left edge of reflector (m)

$d_{r,r}$ Distance from reflection point to right side of reflector (m)

θ_r Angle between direction from image source S' to receiver R and direction of reflector (radians)

ρ_E Effective energy reflection coefficient ρ_E of reflector

5.4 Definition of Auxiliary Variables

5.4.1 Terrain Definition Variables

The first and the last point in the input terrain profile defined in Section 5.3.1 are also denoted $P_S = (x_{SGv},z_{SGv})$ and $P_R = (x_{RGv},z_{RGv})$ as shown in Eq. (4).

$$\begin{aligned} P_S &= \left(x_{SGv}, z_{SGv}\right) = \left(x_1, z_1\right) \\ P_R &= \left(x_{RGv}, z_{RGv}\right) = \left(x_{nxz}, z_{nxz}\right) \end{aligned} \qquad \textbf{(4)}$$

The position of the point source $S = (x_S,z_S)$ and the receiver $R = (x_R,z_R)$ are defined by the vertical source and receiver heights h_{Sv} and h_{Rv}. h_{Sv} is the height of S above P_S and h_{Rv} is the height of R above P_R. If the heights h_{Sv} or h_{Rv} are less than 0.01 m this value is used instead.

The position of S and R are therefore as shown in Eq. (5).

$$S = (x_S, z_S) = (x_1, z_1 + h_{Sv})$$
$$R = (x_R, z_R) = (x_{nxz}, z_{nxz} + h_{Rv}) \qquad \textbf{(5)}$$

Outside the defined terrain profile the surface is assumed to continue with the same slope as the nearest segment.

The source height h_S is defined as the distance from S to the source ground point S_G = (x_{SG},z_{SG}) and the receiver height h_R as the distance from R to the receiver ground point R_G = (x_{RG},z_{RG}), where S_G and R_G are the points on the terrain closest to S and R, respectively. The points S_G and R_G and the heights h_S and h_R can be determined by Eqs. (6) and **(7)** using the auxiliary function *NormLine*.

$$(x_{SG}, z_{SG}, h_S) = NormLine(x_1, z_1, x_2, z_2, x_S, z_S) \qquad \textbf{(6)}$$

$$(x_{RG}, z_{RG}, h_R) = NormLine(x_{nxz-1}, z_{nxz-1}, x_{nxz}, z_{nxz}, x_R, z_R) \qquad (7)$$

The definition of points S, R, S_G, S_R, P_S, and P_R is illustrated in Figure 2 which also shows the terrain baseline defined as the line P_SP_R.

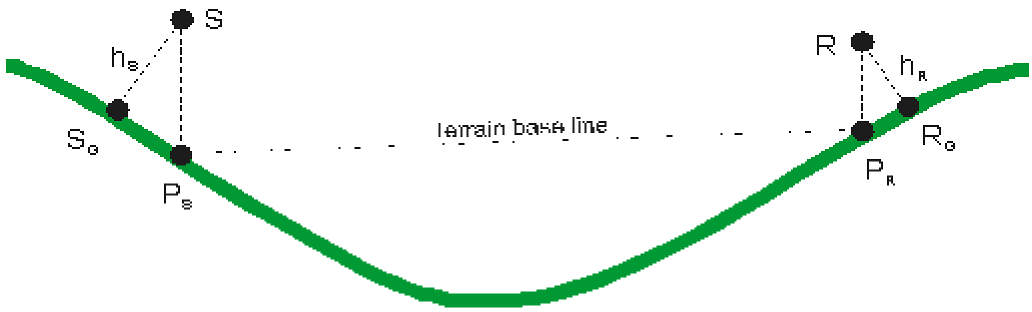

Figure 2
Definition of source points and source ground points.

In the calculation procedure it is required that the terrain is defined from the source ground point S_G to the receiver ground point R_G. Therefore, if $x_{SG} < x_1$ (x_1,z_1) in the terrain profile shall be replaced by (x_{SG},z_{SG}). Likewise, if $x_{RG} > x_{nxz}$ (x_{nxz},z_{nxz}) shall be replaced by (x_{RG},z_{RG}).

The source-receiver distance R_{SR} and the length of the terrain baseline can now be determined used the auxiliary function *Length* as shown in Eqs. (8) and **(9)**.

$$R_{SR} = Length(x_S, z_S, x_R, z_R) \qquad \textbf{(8)}$$

$$d_{base} = Length(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}) \qquad (9)$$

A number of variables are used to define the properties of each point of discontinuity (index i) in the terrain profile. These are:

d_{base}(i) Distance between $P_S = (x_{SGv}, z_{SGv})$ and the projection of point no. i onto terrain baseline ($d_{base}(nxz) = d_{base}$)

h_{base}(i) Shortest distance of terrain point i to terrain baseline

A number of variables are used to define the properties of each segment (index i) in the terrain profile. These are:

h_S'(i) Height of S above segment i

h_R'(i) Height of R above segment i

d'(i) Distance between projection of S and R onto segment i

d_{segm}(i) Length of projection of segments onto terrain baseline

5.4.2 Weather Definition Variables

When the weather coefficient A and B are fluctuating ($s_A > 0$ and $s_B > 0$) upper values of A and B denoted A_+ and B_+ are determined as shown in Eq. (10).

$$\begin{aligned} A_+ &= A + 1.7 s_A \\ B_+ &= B + 1.7 s_B \end{aligned} \qquad \textbf{(10)}$$

The variable t_{mean} is defined as the average temperature between the height h_S and h_R above the ground.

5.4.3 Definition of One-Third Octave Band Centre Frequencies

The centre frequencies of each of the 27 one-third octave bands are determined by Eq. (11).

$$\begin{aligned} &bno = 1, 2, \ldots.., 27 \\ &f(bno) = 10^{\frac{bno+13}{10}} \end{aligned} \qquad \textbf{(11)}$$

5.4.4 Wavelength and Wave Number at the Ground

The wavelength λ_0 and wave number k_0 at the ground are in Eq. **(13)** and **(14)** defined on basis of the sound speed c_0 at the ground in the equivalent linear sound speed profile calculated as shown in Eq. (12) by the function *CalcEqSSP* described in Section 5.5.2.

$$(NA, c_0, NA) = CalcEqSSP(h_{Sv,}, h_{Rv}, z_0, A, B, C) \tag{12}$$

$$\lambda_0 = \frac{c_0}{f} \tag{13}$$

$$k_0 = \frac{2\pi f}{c_0} \tag{14}$$

5.5 Sound Rays and Ray Variables

The calculation of the propagation effect is based on concept of sound rays and the basic approach in the sub-models are to calculate the sound pressure for each ray and add the pressure of all rays to obtain the total sound pressure. In sub-models without screens the rays go from source to receiver and in sub-models with screen from source to receiver via the screen tops. Figure 3 through Figure 6 show examples of such rays in case of downward refraction (the sound speed is increasing with the height) and in case of upward refraction (the sound speed is decreasing with the height).

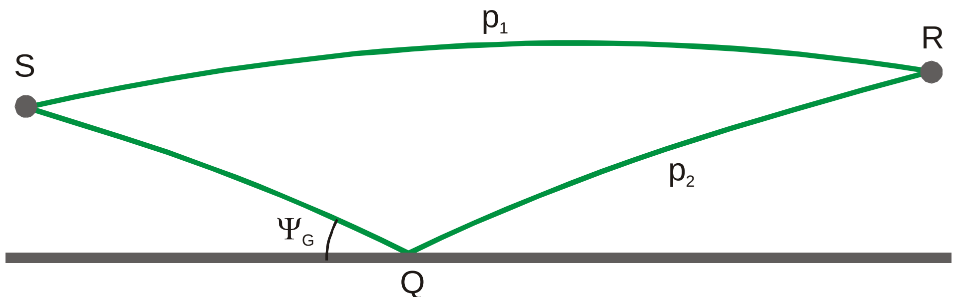

Figure 3
Sound rays for flat terrain in case of downward refraction.

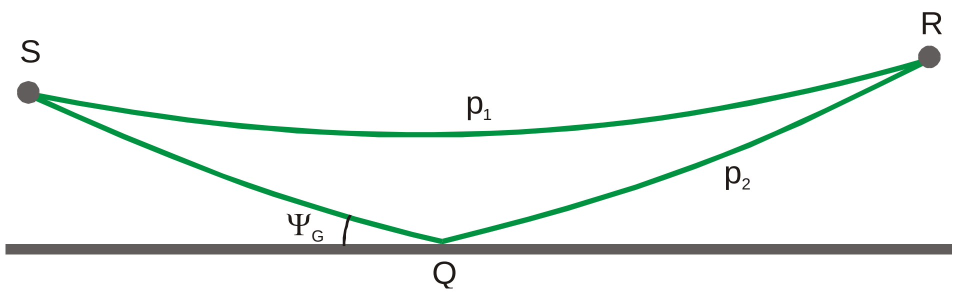

Figure 4
Sound rays for flat terrain in case of upward refraction.

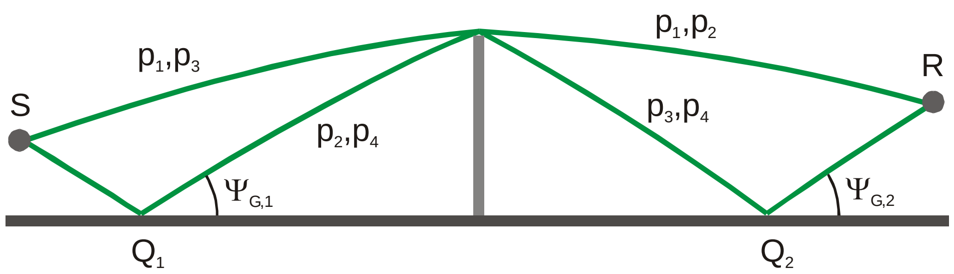

Figure 5
Sound rays for terrain with a screen in case of downward refraction.

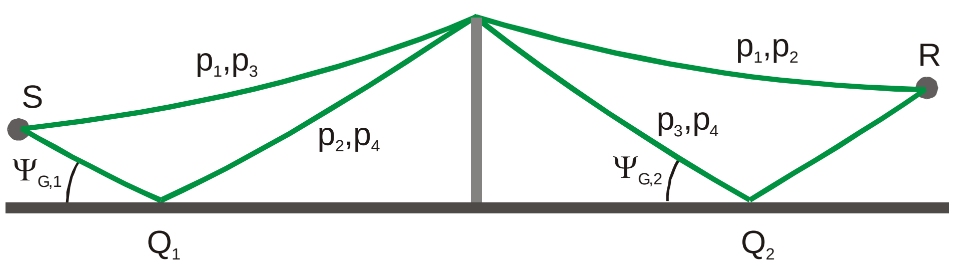

Figure 6
Sound rays for terrain with a screen in case of upward refraction.

In the propagation model the actual position of the ray path (height of the ray along the path) determined as described in Sections 5.5.2 through 5.5.5 is not used directly. Only the calculated ray variables described in Section 5.5.1 are used. However, in a few cases (efficiency of scattering zones and reflecting surfaces) the height of the ray is important. In these cases the ray path is determined using another principle as described in Section 5.5.7.

5.5.1 Ray Variables

The calculation of the effect of sound propagation in the sub-models described in Sections 5.10 through 5.15 is based on a number of propagation variables. The propagation variables depend on whether the sound ray is a direct ray from source to receiver or a ray reflected by the ground.

The variables for the direct ray are:

- The travel time τ along the sound ray from source S to receiver R
- The travel distance R along the sound ray from source S to receiver R
- The change in vertical ray angle $\Delta\theta$ at source and receiver relative to straight line propagation
- Distance d_{SZ} from the source to a possible shadow zone (in upward refraction only)

The variables for the reflected ray are (only relevant if the receiver is not in a shadow zone):

- The travel time τ along the sound ray from source S to receiver R
- The travel distance R along the sound ray from source S to receiver R
- The change in vertical ray angles $\Delta\theta_S$ and $\Delta\theta_R$ at source and receiver relative to straight line propagation
- Ground reflection angle ψ_G (grazing angle) for a ray reflected by the ground

The calculation of propagation variables which is described in Section 5.5 is based on the assumption that ray paths are circular. The vertical log-lin sound speed defined in Section 5.3.2 will not produce circular rays. The first step will therefore be to determine the equivalent linear sound speed profile as shown in Section 5.5.2.

5.5.2 Equivalent Linear Sound Speed Profile

If the sound speed profile is a linear function of the height above ground the propagation the sound rays are circular rays and the propagation variables can be calculated using simple equations for such rays.

The equivalent linear sound speed profile has been introduced to use the simple and fast equations of circular rays. The equivalent linear sound speed profile is the profile leading approximately the same calculated propagation effect as more advanced methods which can take into account non-linear sound speed profiles.

For flat terrain the equivalent sound speed profile depends on the sound speed profile coefficients A, B, C, and z_0 and on the source and receiver heights h_S and h_R.

The equivalent linear sound speed profile is defined by Eq. (15) where z is the height above ground, c_0 is the sound speed at the height 0 and $\Delta c/\Delta z$ is vertical sound speed gradient.

$$c_e(z) = c_0 + \frac{\Delta c}{\Delta z} z \tag{15}$$

When used in the calculations, Eq. (15) is rewritten as shown in Eq. (16) where ξ is the relative sound speed gradient defined by Eq. **(17)**.

$$c_e(z) = c_0(1 + \xi z) \tag{16}$$

$$\xi = \frac{\Delta c / \Delta z}{c_0} \tag{17}$$

$\Delta c/\Delta z$ is determined as the average gradient between the source and receiver heights h_S and h_R by Eq. (18) or if $h_S = h_R$ by the gradient at the height (in this case Eq. (18) can be applied by using the modified source height h_S - 0.005 m and the modified receiver height h_R + 0.005 m).

$$\frac{\Delta c}{\Delta z} = \frac{c(h_R) - c(h_S)}{h_R - h_S} \tag{18}$$

The average sound speed $\bar{c}$ between the heights h_S and h_R is determined by Eq. (19). The integral in the equation is determined as shown in Annex F.

$$\bar{c} = \frac{1}{h_R - h_S} \int_{h_S}^{h_R} c(z)\, dz \tag{19}$$

Finally c_0 is calculated by Eq. (20).

$$c_0 = \bar{c} - \frac{\Delta c}{\Delta z} \frac{h_S + h_R}{2} \tag{20}$$

When using Eqs. (18) to (20) h_S or h_R shall not be less than $h_{min} = 5z_0$ where z_0 is the roughness length.

When $|\xi|$ becomes less than 10^{-6} then the values $\xi = 0$ and $\bar{c} = c_0 = C$ are used instead.

In the following the calculation procedure described above will be referred to by the function *CalcEqSSP* defined in Eq. (21).

$$(\xi, c_0, \bar{c}) = CalcEqSSP(h_{S,}, h_R, z_0, A, B, C) \tag{21}$$

The same method is used in the propagation models containing screens but in this connection separate equivalent profiles are determined between source and the nearest screen, between receiver and the nearest screen and between screens if there are more than two screens. If the ray is starting or ending at a screen top the height of the source or receiver is replaced by an equivalent height denoted h''_{SCR} which depend on the propagation distance. Therefore, in case of screens the equivalent sound speed profile will also depend on the propagation distance.

The height h''_{SCR} is calculated by Eq. (22) on a basis of a modified propagation distance R''_{SCR}. R_{ST} and R_{RT} are the distances from source and receiver to the screen top T, respectively.

$$h''_{scr} = \begin{cases} 4\dfrac{R''_{SCR} - 75}{135} & R''_{SCR} > 75 \\ 0 & R''_{SCR} \le 75 \end{cases} \qquad (22)$$

where

$$R''_{SCR} = R_{SR} + \min(R_{ST}, R_{RT})$$

5.5.3 Modification of the Equivalent Linear Sound Speed Profile for Terrain Effect

For the terrain effect of a hard surface, the diffraction effect of a screen, and when calculating the size of a Fresnel-zone, the equivalent linear sound speed profile defined by ξ and c_0 is independent of the one-third octave band frequency.

However, for the terrain effect of a soft surface (defined as a surface with a flow resistivity σ less than 10,000,000 Pasm^{-2}) an equivalent linear sound speed profile is used that depends on the frequency f.

Above a frequency f_H the variables ξ and c_0 are determined by Eq. (21). Below a frequency f_L $\Delta c/\Delta z$ is assumed to be zero and in the frequency range from f_L to f_H the modified sound speed gradient $\Delta c'/\Delta z$ given by Eq. (23) is used instead of $\Delta c/\Delta z$ when determining ξ and c_0 according to Section 5.5.2.

$$\frac{\Delta c'}{\Delta z} = \frac{\log f - \log f_L}{\log f_H - \log f_L}\frac{\Delta c}{\Delta z} \qquad \mathbf{(23)}$$

The frequencies f_L and f_H are determined on basis of the frequency f_π and $f_{2\pi}$ corresponding to phase differences π and 2π calculated by Eqs. (24) and (25) where *PhaseDiffFreq* is the auxiliary function described in Section 5.23.14. d is the horizontal propagation distance, h_S is the source height, h_R is the receiver height, $Z_G(f)$ is the terrain impedance (complex number) as a function of the one-third octave band frequency from 25 Hz to 10 kHz, and the c_0 is the sound speed at the ground. If d is greater than 400 m the value 400 m is used instead and if h_S or h_R is less 0.5 m the value 0.5 m is used instead when applying Eqs. (24) and **(25)**.

$$f_\pi = PhaseDiffFreq\left(d, h_S, h_R, \hat{Z}_G(f), c_0, \pi\right) \quad \textbf{(24)}$$

$$f_{2\pi} = PhaseDiffFreq\left(d, h_S, h_R, \hat{Z}_G(f), c_0, 2\pi\right) \quad (25)$$

The frequency f_L can now be calculated by Eq. (26) where Δc_{10} is the difference in sound speed 10 m above the ground and at the ground ($\Delta c_{10} = c(10) - c(0)$).

$$f_L = \begin{cases} f_\pi & \Delta c_{10} \le 1 \\ f_\pi \dfrac{43 - 3\Delta c_{10}}{40} & 1 < \Delta c_{10} < 5 \\ 0.7 f_\pi & \Delta c_{10} \ge 5 \end{cases} \quad \textbf{(26)}$$

Finally the frequency f_H can be calculated by Eq. (27).

$$f_H = \max\left(\sqrt{f_L f_{2\pi}}, 1.25 f_L\right) \quad \textbf{(27)}$$

In the following the calculation procedure described above will be referred to by the function *CalcEqSSPGround* defined in Eq. (28). The variables $\xi(f)$ and $c_0(f)$ are the frequency dependent values obtained by the procedure described in this section whereas the variables ξ and c_0 are the frequency independent values obtained by the function *CalcEqSSP* defined in Eq. (21).

$$\left(\xi(f), c_0(f), \bar{c}, \xi, c_0\right) = CalcEqSSPGround\left(h_{S,}, h_R, \hat{Z}_G(f), z_0, A, B, C\right) \quad \textbf{(28)}$$

5.5.4 Calculation of Ray Variables for a Direct Ray

As mentioned in Section 5.5.1 the variables used for the direct ray between source and receiver (or screen tops) when predicting the propagation effect are:

- The travel time τ along the sound ray
- The travel distance R along the sound ray
- The change in vertical ray angle $\Delta\theta$ at the beginning or end of the sound ray relative to straight line propagation
- Distance d_{SZ} from the source, receiver or screen top to a possible shadow zone (in upward refraction only)

In Figure 7 the variables τ, R, and $\Delta\theta$ are defined together with other variables used when calculating the ray variables. In the calculation it is assumed that the sound is propagating along a circular ray from the ray point L to ray point U. L and U can be source, receiver or a screen top and L and U are the lower and upper position, respectively.

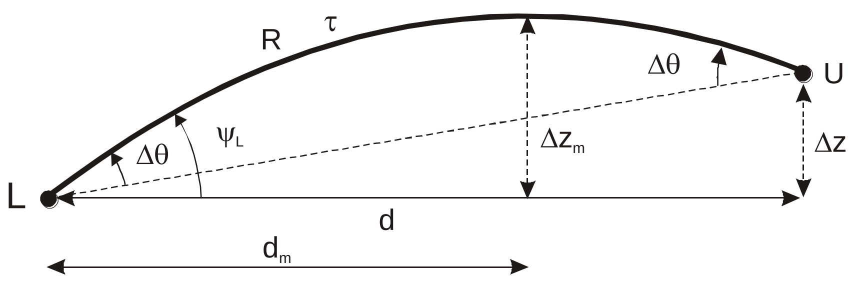

Figure 7
Definition of geometrical parameters for a direct ray.

In order to calculate the ray variables Eq. (16) and **(17)** have to be redefined as shown in Eq. (29) to **(31)** unless the point L is at the ground. z' is the height above the point L ($z' = z - z_L$).

$$c_e(z') = c_0'(1 + \xi' z') \qquad \textbf{(29)}$$

$$\xi' = \frac{\Delta c / \Delta z}{c_0'} = \frac{\xi}{1 + \xi z_L} \qquad (30)$$

$$c_0' = c_0(1 + \xi z_L) \qquad (31)$$

The first step is to calculate the angle ψ_L and horizontal distance d_m from L to the top point of the circle as shown in Figure 7. ψ_L and d_m are calculated by Eqs. (32) and **(33)** where Δz is defined as the height of U above L ($\Delta z = z_U - z_L$) and d is the horizontal distance between L and U.

$$\tan \psi_L = \frac{\xi' d}{2} + \frac{\Delta z\,(2 + \xi' \Delta z)}{2d} \qquad \textbf{(32)}$$

$$d_m = \frac{\tan \psi_L}{\xi'} \qquad (33)$$

If $\xi > 0$ and $d \le d_m$, R and τ are calculated by Eqs. (34) through (37).

$$R(\Delta z) = \frac{1}{\xi' \cos(\psi_L)} \left(\arcsin\left((1+\xi'\Delta z)\cos(\psi_L)\right) - \frac{\pi}{2} + \psi_L\right) \quad \textbf{(34)}$$

$$\tau(\Delta z) = \frac{1}{2\xi' c_0'} \ln\left(\frac{f(0)}{f(\Delta z)}\right) \quad (35)$$

where

$$f(0) = \frac{1+\sin\psi_L}{1-\sin\psi_L} \quad \textbf{(36)}$$

and

$$f(\Delta z) = \frac{1+\sqrt{1-(1+\xi'\Delta z)^2\cos^2\psi_L}}{1-\sqrt{1-(1+\xi'\Delta z)^2\cos^2\psi_L}} \quad \textbf{(37)}$$

If $d > d_m$, R and τ are instead calculated by Eqs. (38) to **(40)** where Δz_m is the height of the ray at the top point of the circle at the horizontal distance d_m. $R(\Delta z_m)$ and $R(\Delta z)$ are calculated by Eq. (34) and $\tau(\Delta z_m)$ and $\tau(\Delta z)$ by Eq. **(35)**.

$$\Delta z_m = \frac{1}{\xi'}\left(\frac{1}{\cos(\psi_L)} - 1\right) \quad \textbf{(38)}$$

$$R = 2\,R(\Delta z_m) - R(\Delta z) \quad (39)$$

$$\tau = 2\,\tau(\Delta z_m) - \tau(\Delta z) \quad (40)$$

Finally the change in ray angle $\Delta\theta$ compared to a straight line ray between L and U can be determined by Eq. (41).

$$\Delta\theta = \psi_L - \arctan\left(\frac{\Delta z}{d}\right) \quad \textbf{(41)}$$

If ξ' is less than zero R, τ and $\Delta\theta$ are also determined by Eqs. (32) through (41) using the absolute value of ξ' ($\xi' = |\xi'|$) but in this case the calculated value of $\Delta\theta$ has to be multiplied by –1 as shown in Eq. (42).

$$\Delta\theta(\xi < 0) = -\Delta\theta(\xi > 0) \quad \textbf{(42)}$$

The equations shown above will when Δz is approaching 0 give rise to numerical problems when being implemented in computer code. Therefore, when Δz becomes less than 0.01 a value of 0.01 should be used instead. Furthermore, the equations cannot be used when ξ becomes 0 (homogeneous atmosphere). Therefore, when $|\xi| < 10^{-10}$, $\xi = 10^{-10}$ has to be used instead.

If ξ is less than zero a part of the ray may be below the ground indicating a shadow zone. The propagation distance d_{SZ} where the ray is just grazing the ground for a given value of ξ is the distance above which shadow zone propagation will occur. d_{SZ} is calculated by Eq. (43).

$$d_{SZ} = \sqrt{z_L\left(\frac{2}{|\xi'|} - z_L\right)} + \sqrt{z_U\left(\frac{2}{|\xi'|} - z_U\right)} \qquad \textbf{(43)}$$

To avoid numerical problems in the calculations, shadow propagation shall be assumed when the horizontal propagation distance d is greater 0.95 d_{SZ}.

The calculation procedure described above will in the following be referred to by the function *DirectRay* defined in Eq. (44). If $\xi \geq 0$, the variable d_{SZ} is fixed at infinity (∞).

$$(\tau, R, \Delta\theta, \bar{c}, d_{SZ}) = DirectRay(d, h_{S,}, h_R, \xi, c_0) \qquad \textbf{(44)}$$

5.5.5 Calculation of Ray Variables for a Ray Reflected by the Ground

If ξ is less than zero and the horizontal propagation distance d is greater than 0.95 d_{SZ} where d_{SZ} has been calculated in the previous section (shadow zone propagation) the ray variables of the reflected ray shall not be determined.

Otherwise, as mentioned in Section 5.5.1 the variables used for the reflected ray between “source” and “receiver” (the beginning and end of the ray may also be a screen edge) when predicting the propagation effect are;

- The travel time τ along the sound ray
- The travel distance R along the sound ray
- The travel distance R_S along the sound ray from source to reflection point
- The travel distance R_R along the sound ray from receiver to reflection point
- The change in vertical ray angles $\Delta\theta_S$ and $\Delta\theta_R$ of the sound ray at the “source”or the “receiver” relative to straight line propagation
- Ground reflection angle ψ_G (grazing angle) for a ray

In Figure 8 the variables $\tau = \tau_S + \tau_R$, $R = R_S + R_R$, $\Delta\theta_S$, $\Delta\theta_R$, and ψ_G are defined together with other variables used when calculating the ray variables.

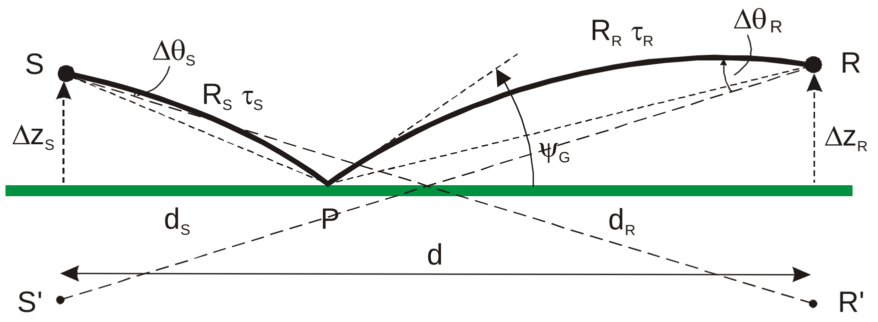

Figure 8
Definition of geometrical parameters for a reflected ray.

For the reflected ray the ray variables are calculated by the equations shown in Section 5.5.4 but the calculation is done separately for part of the ray from the reflection point P to the "source" S and for part of the ray from the reflection point P to the "receiver" R as shown in Eq. (45) and (46). d_S and d_R are the distances from the reflection point to the "source" or "receiver" and NA indicates that the distance d_{SZ} will not be applied (the calculation for reflected ray will not be carried out in case of shadow zone propagation). Also the change in ray angle $\Delta\theta$ cannot be applied as the position of the reflection point P is not the same in the straight line propagation case.

$$\left(\tau_S, R_S, NA, NA, NA\right) = DirectRay\left(d_S, 0, h_S, \xi, c_0\right) \quad \textbf{(45)}$$

$$\left(\tau_R, R_R, NA, NA, NA\right) = DirectRay\left(d_R, 0, h_R, \xi, c_0\right) \quad (46)$$

The grazing reflection angle ψ_G is equal to ψ_L calculated when applying the function *DirectRay* (ψ_L will be the same for the "source" and "receiver" part of the ray) and the change in the ray angles $\Delta\theta_S$ and $\Delta\theta_R$ can be determined by Eqs. (47) and (48).

$$\Delta\theta_S = \psi_G + \arctan\frac{z_S + z_R}{d} - 2\arctan\frac{z_S}{d_S} \quad \textbf{(47)}$$

$$\Delta\theta_R = \psi_G + \arctan\frac{z_S + z_R}{d} - 2\arctan\frac{z_R}{d_R} \quad (48)$$

However, before calculating the ray variables the position of the reflection point P has to be determined.

In downward refraction ($\xi > 0$) the reflection point is determined by finding the roots d_{refl} of the cubic equation in Eq. (49). A method for determining the roots of cubic equation can be found in [5].

$$2d_{refl}^3 - 3dd_{refl}^2 + (b_R^2 + b_S^2 + d^2)d_{refl} - b_S^2 d = 0$$

where

$$b_S^2 = \frac{z_S}{\xi}(2 + \xi z_S) \tag{49}$$

and

$$b_R^2 = \frac{z_R}{\xi}(2 + \xi z_R)$$

Eq. (49) may have up to three real roots for large values of ξ. If the equation has more than one real solution the reflection point closest to the source is used when the source height h_S is less than the receiver height while the reflection point closest to the receiver is used when the source height is greater than the receiver height.

In upward refraction ($\xi > 0$) the reflection point is also determined by Eq. (49) but in this case there will be only one real solution.

The calculation procedure described above will in the following be referred to by the function *Reflected* defined in Eq. (50).

$$(\tau, R, R_S, R_R, \Delta\theta_S, \Delta\theta_R, \psi_G, d_{drefl}) = ReflectedRay(d, h_{S,}, h_R, \xi, c_0) \tag{50}$$

5.5.6 Difference in Travel Time between the Direct and Reflected Ray

In the Nord2000 sub-models described in the following section one of the most important variables is the difference in travel time $\Delta\tau$ between the travel time τ_2 along the reflected ray and the travel time τ_1 along the direct ray as defined in Eq. (51).

$$\Delta\tau = \tau_2 - \tau_1 \tag{51}$$

The travel time difference $\Delta\tau$ determines the phase difference between the direct and reflected sound which is essential to sound interference effects. Therefore, it is very important that $\Delta\tau$ is calculated with the highest possible accuracy. As $\Delta\tau$ normally is the difference between two numbers almost equal ($\tau_2 \approx \tau_1 >> \Delta\tau$) it is recommended to use variables with the highest possible precision for $\tau_2 \approx \tau_1$ when implementing the method into computer code.

For very high sources (or receivers) the calculation of the travel time difference $\Delta\tau$ described above has been found to fail in upward refraction at the edge of a meteorological shadow zone where $\Delta\tau$ has to be zero.

To solve this problem when $\xi < 0$, a maximum travel time difference $\Delta\tau_0$ is calculated by Eq. (52) where C is the sound speed at the ground.

$$\Delta\tau_0 = \frac{\left(1-\left(\frac{d}{d_{SZ}}\right)^2\right)\left(\sqrt{d^2+(h_S+h_R)^2}-\sqrt{d^2+(h_S-h_R)^2}\right)}{C} \quad \textbf{(52)}$$

If $\Delta\tau$ is greater than $\Delta\tau_0$ the latter is used instead. This ensures that $\Delta\tau$ will be zero at the edge of the shadow zone.

The calculation procedure described above will in the following be referred to by the function *TravelTimeDiff* defined in Eq. (53).

$$\Delta\tau = TravelTimeDiff(\tau_1, \tau_2) \quad \textbf{(53)}$$

If the receiver is in a shadow zone ($d > 0.95\, d_{SZ}$ where d_{SZ} is calculated by the function *DirectRay*) $\Delta\tau$ is fixed at a value of zero.

5.5.7 Calculation of the Height of a Ray

As mentioned in the introduction of Section 5.5 the exact the ray path is in most cases not used directly but only for determining the ray variables. However, in a few cases (efficiency of scattering zones and reflecting surfaces) the height of the ray becomes important. In these cases the ray path is determined using another principle as described in this section.

Eq. (54) shows how the ray curvature is determined in case of a log-lin sound speed profile as defined in Eq. (2) by the weather coefficients A, B, and C. The radius of curvature $R_{A,B}$ is determined on basis of radii R_A and R_B of the logarithmic and linear part of the sound speed profile, respectively. d is the horizontal distance.

$$R_A = sign(A)\frac{d}{8}\sqrt{\frac{2\pi C}{|A|}}$$

$$R_B = sign(B)\sqrt{\left(\frac{C}{|B|}\right)^2+\left(\frac{d}{2}\right)^2} \quad \textbf{(54)}$$

$$R_{A,B} = \frac{1}{\frac{1}{R_A}+\frac{1}{R_B}}$$

The relative sound speed gradient ξ_{ray} of the equivalent sound speed profile corresponding to $R_{A,B}$ is determined by Eq. (55) where ψ_S is the start angle of the ray at the source. h_S and h_R is the source and receiver height.

$$\xi_{ray} = \frac{1}{R_{A,B}\cos(\psi_S)}$$
$$\psi_S = \arcsin\left(\frac{\sqrt{d^2 + (h_R - h_S)^2}}{2R_{A,B}}\right) + \arctan\left(\frac{h_R - h_S}{d}\right) \quad \textbf{(55)}$$

The procedure described in this section for calculating position of the circular ray path defined by the radius of curvature $R_{A,B}$ and the corresponding relative sound speed gradient ξ_{ray} is referred to by the function *RayCurvature* defined in Eq. (56).

$$\left(R_{A,B}, \xi_{ray}\right) = RayCurvature(A, B, C, d, h_S, h_R) \quad \textbf{(56)}$$

5.6 Terrain Surface Properties

As mentioned in Section 5.3.1 the surface properties of each segment in the terrain profile is defined by the flow resistivity σ and ground roughness *r*. In the Nord2000 method the flow resistivity used is the effective flow resistivity giving the best fit between calculated impedance applying Delany and Bazley impedance model and the actual impedance of the surface. The effective flow resistivity can be measured according to a Nordtest method [6]. The ground roughness parameter *r* is a variable that quantify the unevenness of the terrain segment if not perfectly flat. The ground roughness is the standard deviation of the random height variations within the segment.

In the following sections the method for calculating the ground impedance on basis of the flow resistivity will be described and a number of reflection coefficients used in Nord2000 will be defined.

The ground roughness will affect the coherence coefficient F_r of the model which is described in Section 0.

5.6.1 Classification of Surface Properties

The method can be used for any value of the flow resistivity σ and ground roughness *r*. However, for practical use a classification has been made which include a number of ground surface types representing typical surfaces.

The classification of flow resistivity which is based on the Nordtest flow resistivity classes [6] is shown in Table 2.

Impedance class	Representative flow resistivity σ (kPasm^{-2})	Range of Nordtest flow resistivity classes	Description
A	12.5	10, 16	Very soft (snow or moss-like)
B	31.5	25, 40	Soft forest floor (short, dense heather-like or thick moss)
C	80	63, 100	Uncompacted, loose ground (turf, grass, loose soil)
D	200	160, 250	Normal uncompacted ground (forest floors, pasture field)
E	500	400, 630	Compacted field and gravel (compacted lawns, park area)
F	2000	2000	Compacted dense ground (gravel road, parking lot, ISO 10844)
G	20000	-	Hard surfaces (most normal asphalt, concrete)
H	200000	-	Very hard and dense surfaces (dense asphalt, concrete, water)

Table 2
Classification of ground impedance types

The classification of ground roughness is shown in Table 3.

Roughness class	Representative σ_r	Range of heights
N: Nil	0	±0.25 m
S: Small	0.25 m	±0.5 m
M: Medium	0.5 m	±1 m
L: Large	1 m	±2 m

Table 3
Classification of ground roughness types.

5.6.2 Ground Impedance

The ground impedance $\hat{Z}_G$ as a function of the frequency is calculated by the Delany and Bazley model as shown in Eq. (57) where σ is the flow resistivity and f is the one-third octave band centre frequency.

$$\hat{Z}_G(f) = 1 + 9.08\left(\frac{1000\ f}{\sigma}\right)^{-0.75} + j\,11.9\left(\frac{1000\ f}{\sigma}\right)^{-0.73} \qquad \textbf{(57)}$$

5.6.3 Spherical-Wave Reflection Coefficient

The spherical wave reflection coefficient Q is a function of the frequency f, the travel time τ_2 along the reflected ray, the grazing reflection angle ψ_G, and the ground impedance Z_G. Q is calculated by Eq. (58) where $\hat{\Re}_p(f,\psi_G)$ is the plane wave reflection coefficient calculated by Eq. (59) and the function $\hat{E}(\hat{\rho})$ is calculated by Eq. (60).

$$\hat{Q}(f,\tau_2,\psi_G,\hat{Z}_G) = \hat{\Re}_p(f,\psi_G) + \left(1-\hat{\Re}_p(f,\psi_G)\right)\hat{E}(\hat{\rho}) \qquad \textbf{(58)}$$

$$\hat{\Re}_p(f,\psi_G) = \frac{\sin(\psi_G) - \dfrac{1}{\hat{Z}_G(f)}}{\sin(\psi_G) + \dfrac{1}{\hat{Z}_G(f)}} \qquad (59)$$

$$\hat{E}(\hat{\rho}) = 1 + j\sqrt{\pi}\,\hat{\rho}\, e^{-\hat{\rho}^2} erfc(-j\hat{\rho})$$
$$where$$
$$\hat{\rho} = \frac{1+j}{2}\sqrt{\omega\tau_2}\left(\sin(\psi_G) + \frac{1}{\hat{Z}_G}\right) \qquad (60)$$

The complex function $w(\hat{\rho}) = e^{-\hat{\rho}^2} erfc(-j\hat{\rho})$ in Eq. **(60)** where *erfc* is the complementary error function extended to complex arguments can be determined by an approximate method as described in the following Eqs. (61) through (74). x and y are the real and imaginary parts of $\hat{\rho} = x + jy$. * denotes complex conjugation and w_+ is calculated by Eq. (61) or **(62)**.

The procedure when $|x| > 3.9 \vee |y| > 3$ is given by Eqs. (61) through (64):

$$\hat{\rho}_+ = |x| + j|y| \qquad \textbf{(61)}$$

$$w(\hat{\rho}) = \begin{cases} w_+(\hat{\rho}) & x > 0 \wedge y > 0 \\ w_+^*(\hat{\rho}_+) & x < 0 \wedge y > 0 \\ 2e^{-(\hat{\rho}_+^*)^2} - w_+^*(\hat{\rho}_+) & y < 0 \end{cases} \qquad (62)$$

$x > 6 \vee y > 6$:

$$w_+(\hat{\rho}) = j\hat{\rho}\left(\frac{0.5124242}{\hat{\rho}^2 - 0.2752551} + \frac{0.05176536}{\hat{\rho}^2 - 2.724745}\right) \quad \textbf{(63)}$$

else

$$w_+(\hat{\rho}) = j\hat{\rho}\left(\frac{0.4613135}{\hat{\rho}^2 - 0.1901635} + \frac{0.09999216}{\hat{\rho}^2 - 1.7844927} + \frac{0.002883894}{\hat{\rho}^2 - 5.5253437}\right) \quad \textbf{(64)}$$

The procedure when $|x| \leq 3.9 \wedge |y| \leq 3$ is given by Eqs. (65) through **(74)**:

$$h = 0.8 \quad \textbf{(65)}$$

$$A_1 = \cos(2xy) \quad (66)$$

$$B_1 = \sin(2xy) \quad (67)$$

$$C_1 = e^{-2y\pi/h} - \cos(2x\pi/h) \quad (68)$$

$$D_1 = \sin(2x\pi/h) \quad (69)$$

$$P_2 = 2e^{-\left(x^2+2y\pi/h-y^2\right)} \frac{A_1C_1 - B_1D_1}{C_1^2 + D_1^2} \quad (70)$$

$$Q_2 = 2e^{-\left(x^2+2y\pi/h-y^2\right)} \frac{A_1D_1 + B_1C_1}{C_1^2 + D_1^2} \quad (71)$$

$$H = \frac{hy}{\pi\left(x^2 + y^2\right)} + \frac{2yh}{\pi} \sum_{n=1}^{5} \frac{e^{-n^2h^2}\left(x^2 + y^2 + n^2h^2\right)}{\left(y^2 - x^2 + n^2h^2\right)^2 + 4x^2y^2} \quad (72)$$

$$K = \frac{hx}{\pi\left(x^2 + y^2\right)} + \frac{2xh}{\pi} \sum_{n=1}^{5} \frac{e^{-n^2h^2}\left(x^2 + y^2 - n^2h^2\right)}{\left(y^2 - x^2 + n^2h^2\right)^2 + 4x^2y^2} \quad (73)$$

$$w(\hat{\rho}) = H + P_2 + j\left(K - Q_2\right) \quad (74)$$

5.6.4 Incoherent Reflection Coefficient

The incoherent reflection coefficient $\Re_i$ which is a function of the frequency and the ground impedance $\hat{Z}_G$ is based on the random incidence absorption coefficient α_{ri} and is defined by Eq. (75).

$$\Re_i\left(f,\hat{Z}_G\right)=\sqrt{1-\alpha_{ri}\left(f,\hat{Z}_G\right)} \qquad \textbf{(75)}$$

α_{ri} is calculated by Eq. (76) where X and Y is the real and imaginary part of the ground impedance $\hat{Z}_G$.

$$\alpha_{ri}\left(f,\hat{Z}_G\right)=8\frac{X}{X^2+Y^2}\left(\begin{array}{l}1-\frac{X}{X^2+Y^2}\ln\left(\left(1+X\right)^2+Y^2\right)\\+\frac{X^2-Y^2}{\left(X^2+Y^2\right)Y}\arctan\left(\frac{Y}{1+X}\right)\end{array}\right) \qquad \textbf{(76)}$$

where

$$\hat{Z}_G(f)=X+jY$$

The advantage of using an incoherent reflection coefficient for the incoherent part of the sound field is that the calculation of $\Re_i$ is faster than the calculation of spherical-wave reflection coefficient Q and because $\Re_i$ is not a function of the ground reflection angle as Q is, it is possible to pre-calculate $\Re_i$ for each impedance type in the prediction model. At high frequencies where the ray contributions become fully incoherent in most cases (coherence coefficient $F = 0$) the calculation time can be reduced considerably as the calculation of the ground reflection coefficient can be replaced by a table look-up.

5.6.5 Plane-Wave Reflection Coefficient

The plane-wave reflection coefficient $\hat{\Re}_p$ is a function of the frequency, the grazing reflection ψ_G and ground impedance $\hat{Z}_G$ and is calculated by Eq. (77). The plane-wave reflection coefficient is used in the multiple ground reflection model.

$$\hat{\Re}_p\left(f,\psi_G,\hat{Z}_G\right)=\frac{\sin\left(\psi_G\right)-\frac{1}{\hat{Z}_G(f)}}{\sin\left(\psi_G\right)+\frac{1}{\hat{Z}_G(f)}} \qquad \textbf{(77)}$$

5.7 Propagation Effect of a Wedge-Shaped Screen

This section contains procedures used when calculating the propagation effects of a wedge shaped-screen in the sub-models described in Sections 5.13 to 5.15.

5.7.1 Diffraction of a Wedge with Finite Surface Impedance

This section describes the procedure used in the Nord2000 method to calculate the sound pressure at the receiver when sound propagates from a point source over a finite impedance wedge.

The input variables in the model are:

- The travel time τ_S from source S to the top of the wedge T
- The travel time τ_R from T to receiver R
- The travel time τ from S to R over T (normally $\tau = \tau_S + \tau_R$ but when used in the procedure for a two-edge screen τ may be defined otherwise)
- The travel distance R_S from S to T
- The travel distance R_R from T to R
- The travel distance ℓ from S to R over T (normally $\ell = R_S + R_R$ but when used in the procedure for a two-edge screen R may be defined otherwise)
- The source diffraction angle θ_S re. receiver wedge face
- The receiver diffraction angle θ_R re. receiver wedge face
- Wedge angle β
- Surface impedance Z_S of source wedge face
- Surface impedance Z_R of receiver wedge face

In the presentation of the solution shown in the following it is assumed that $0 \le \theta_R \le \theta_S \le \beta \le 2\pi$. If this is not the case the angles have to be modified as described in the end of the section.

The input variables are illustrated in Figure 9 for a non-refracting atmosphere. For a refracting atmosphere The refraction-modified geometrical parameters used in the diffraction solution the rays S-T and R-T will be arcs instead.

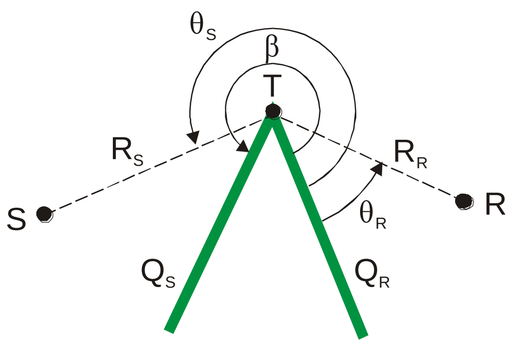

Figure 9
Definition of variables used when calculating of the sound pressure level behind a wedge-shaped screen with finite surface impedances.

The sound pressure level at the receiver p_{diffr} is calculated by Eq. (78) where ω is the angular frequency (=2π*f*)

$$\hat{p}_{diffr}(f) = -\frac{1}{\pi}\sum_{n=1}^{4}\hat{Q}_n A(\theta_n)\hat{E}_\nu(A(\theta_n))\frac{e^{j\omega\tau}}{\ell} \qquad \textbf{(78)}$$

The angle θ_n in Eq. (78) is defined by Eq. (79).

$$\begin{aligned}\theta_1 &= \theta_S - \theta_R \\ \theta_2 &= \theta_S + \theta_R \\ \theta_3 &= 2\beta - (\theta_S + \theta_R) \\ \theta_4 &= 2\beta - (\theta_S - \theta_R)\end{aligned} \qquad \textbf{(79)}$$

The "reflection coefficient" Q_n in Eq. (78) is calculated by Eq. (80).

$$\begin{aligned}Q_1 &= 1 \\ Q_2 &= Q_S\left(f, \tau_S + \tau_R, \min(\beta - \theta_S, \pi/2), \hat{Z}_S\right) \\ Q_3 &= Q_R\left(f, \tau_S + \tau_R, \min(\theta_R, \pi/2), \hat{Z}_R\right) \\ Q_4 &= Q_S\left(f, \tau_S + \tau_R, \min(\beta - \theta_S, \pi/2), \hat{Z}_S\right)Q_R\left(f, \tau_S + \tau_R, \min(\theta_R, \pi/2), \hat{Z}_R\right)\end{aligned} \qquad \textbf{(80)}$$

The function $\hat{E}_\nu(A(\theta_n))$ is calculated by Eq. (81) where $\nu = \pi/\beta$ is the wedge index. The solution is only valid for $\beta > \pi$.

$$\hat{E}_\nu\left(A(\theta_n)\right) = \frac{\pi}{\sqrt{2}} \frac{\sin|A(\theta_n)|}{|A(\theta_n)|} \frac{e^{j\pi/4}}{\sqrt{1+\left(\frac{2\tau_S\tau_R}{\tau^2}+\frac{1}{2}\right)\frac{\cos^2|A(\theta_n)|}{\nu^2}}} \hat{A}_D(B) \qquad \textbf{(81)}$$

In Eq. (81) $A(\theta_n)$ is given by Eq. (82), B by Eq. **(83)** and $A_D(B)$ by Eq. **(84)**. In Eq. (82) *H(x)* is Heavisides' step function calculated by the auxiliary function *H* and in Eq. **(84)** *Sign*(*x*) is the Signum function calculated by the auxiliary function *Sign*.

$$A(\theta_n) = \frac{\nu}{2}\left(-\beta - \pi + \theta_n\right) + \pi H\left(\pi - \theta_n\right) \qquad \textbf{(82)}$$

$$B = \sqrt{\frac{4\omega\tau_S\tau_R}{\pi\tau}} \frac{\cos|A(\theta_n)|}{\sqrt{\nu^2 + \left(\frac{2\tau_S\tau_R}{\tau^2}+\frac{1}{2}\right)\cos^2|A(\theta_n)|}} \qquad (83)$$

$$\hat{A}_D(B) = Sign(B)\left(f(|B|) - jg(|B|)\right) \qquad (84)$$

In Eq. **(84)** the functions $f(x)$ and $g(x)$ are the auxiliary Fresnel-functions calculated as shown in Eqs. (85) and **(86)**. If $x < 5$ $f(x)$ and $g(x)$ is calculated by a polynomial fit. The constants a_0 to a_{12} are defined in Table 4 and Table 5 for $f(x)$ and $g(x)$, respectively.

$$f(x) = \begin{cases} \dfrac{1}{\pi x} & x \ge 5 \\ \displaystyle\sum_{n=0}^{12} a_n x^n & x < 5 \end{cases} \qquad \textbf{(85)}$$

$$g(x) = \begin{cases} \dfrac{1}{\pi^2 x^3} & x \ge 5 \\ \displaystyle\sum_{n=0}^{12} a_n x^n & x < 5 \end{cases} \qquad (86)$$

a_{12}	0.00000019048125
a_{11}	-0.00000418231569
a_{10}	0.00002262763737
a_9	0.00023357512010
a_8	-0.00447236493671
a_7	0.03357197760359
a_6	-0.15130803310630
a_5	0.44933436012454
a_4	-0.89550049255859
a_3	1.15348730691625
a_2	-0.80731059547652
a_1	0.00185249867385
a_0	0.49997531354311

Table 4
Constants in polynomial fit of f(x) for x < 5.

a_{12}	-0.00000151974284
a_{11}	0.00005018358067
a_{10}	-0.00073624261723
a_9	0.00631958394266
a_8	-0.03513592318103
a_7	0.13198388204736
a_6	-0.33675804584105
a_5	0.55984929401694
a_4	-0.50298686904881
a_3	-0.06004025873978
a_2	0.80070190014386
a_1	-1.00151717179967
a_0	0.50002414586702

Table 5
Constants in polynomial fit of g(x) for x < 5.

If $\theta_n = \pi$ numerical problems will occur when calculating the diffracted sound pressure by Eq. (78). This can be fixed by subtracting a small quantity ε from θ_n when $|\theta_n - \pi| < \varepsilon$. $\varepsilon = 10^{-8}$ has been found suitable but may depend on the implementation in program code.

If $\theta_1 > \pi$ (wedge edge is above the line from the source to the receiver) the sound pressure at the receiver is determined by $\hat{p}_{diffr}$ as shown in Eq. (87).

$$\hat{p} = \hat{p}_{diffr} \quad \textbf{(87)}$$

If $\theta_1 < \pi$ (wedge edge is below the line from the source to the receiver) the contribution from the direct ray shall be added to the solution as shown in Eq. (88).

$$\begin{aligned} &\hat{p} = \hat{p}_{diffr} + \frac{e^{j\omega\tau_1}}{R_1} \\ &\textit{where} \\ &R_1 = \sqrt{R_S^2 + R_R^2 - 2R_S R_R \cos(\theta_1)} \\ &\tau_1 = \sqrt{\tau_S^2 + \tau_R^2 - 2\tau_S \tau_R \cos(\theta_1)} \end{aligned} \quad \textbf{(88)}$$

If $\theta_3 < \pi$ (wedge edge is below the line from the image source mirrored in source wedge leg to the receiver) the contributions from the direct ray as well as the ray reflected in the soource face of the wedge shall be added to the solution as shown in Eq. (89). R_1 and τ_1 are defined in Eq. (88). Q_R is the spherical-wave reflection coefficient calculated as shown in 5.6.3.

$$\begin{aligned} &\hat{p}(f) = \hat{p}_{diffr}(f) + \frac{e^{j\omega\tau_1}}{R_1} + \hat{Q}_R\left(f, \tau_2, \psi_{G,R}, \hat{Z}_R\right)\frac{e^{j\omega\tau_2}}{R_2} \\ &\textit{where} \\ &R_2 = \sqrt{R_S^2 + R_R^2 - 2R_S R_R \cos(\theta_2)} \\ &\tau_2 = \sqrt{\tau_S^2 + \tau_R^2 - 2\tau_S \tau_R \cos(\theta_2)} \\ &\psi_{G,R} = \arcsin\left(\frac{R_S \sin\theta_S + R_R \sin\theta_R}{R_2}\right) \end{aligned} \quad \textbf{(89)}$$

If $\theta_2 < \pi$ (wedge edge is below the line from the source to the image receiver mirrored in receiver wedge leg) the contributions from the direct ray as well as the ray reflected in the receiver face of the wedge shall be added to the solution as shown in Eq. (90). R_1 and τ_1 are defined in Eq. (88). Q_S is the spherical-wave reflection coefficient calculated as shown in 5.6.3.

$$\hat{p}(f) = \hat{p}_{diffr}(f) + \frac{e^{j\omega\tau_1}}{R_1} + \hat{Q}_S\left(f, \tau_3, \psi_{G,S}, \hat{Z}_S\right)\frac{e^{j\omega\tau_3}}{R_3}$$

$$\begin{aligned} &where \\ &R_3 = \sqrt{R_S^2 + R_R^2 - 2R_S R_R \cos(\theta_3)} \\ &\tau_3 = \sqrt{\tau_S^2 + \tau_R^2 - 2\tau_S \tau_R \cos(\theta_3)} \\ &\psi_{G,S} = \arcsin\left(\frac{R_S \sin(\beta - \theta_S) + R_R \sin(\beta - \theta_R)}{R_3}\right) \end{aligned} \qquad \textbf{(90)}$$

In cases where the source and receiver are reflected by a ground surface before and after the wedge the calculation will also be carried out for the image source and receiver as described in Sections 5.13 to 5.15. In such cases the "source" or "receiver" may be inside the wedge. The same may happen when for the source and receiver in case of upward refraction. This is in both cases taken care of by modifying the angles according to the following scheme where θ'_R, θ'_S and β' are the modified angles.

$0 > \theta_R > \beta - 2\pi$:

$\theta'_R = 0$

$\theta'_S = \theta_S - \theta_R$

$\beta' = \beta - \theta_R$

$\theta_R \leq \beta - 2\pi$:

$\theta'_R = 0$

$\theta'_S = 2\pi - (\beta - \theta_S)$

$\beta' = 2\pi$

$\beta < \theta_S < 2\pi$ (θ'_S and β' are used instead of θ_S and β when modified above):

$\beta' = \theta_S$

$\theta_S \geq 2\pi$ (θ'_S is used instead θ_S when modified above):

$\theta'_S = 2\pi$

$\beta' = 2\pi$

The procedure described above in this section will be referred to by the function pwedge as defined in Eq. (91).

$$\hat{p}(f) = pwedge\left(f, \beta, \theta_S, \theta_R, \tau, \tau_S, \tau_R, \ell, R_S, R_R, \hat{Z}_S, \hat{Z}_R\right) \tag{91}$$

5.7.2 Diffraction Coefficient

The diffraction coefficient $\hat{D}$ is defined by Eq. (92). $\hat{p}$ is calculated as described in Section 5.7.1 where τ and ℓ are defined.

$$\hat{p}(f) = \hat{D}(f)\frac{e^{j\omega\tau}}{\ell} \tag{92}$$

Therefore, the diffraction coefficient can be calculated by Eq. (93).

$$\hat{D}(f) = \frac{\ell}{e^{j\omega\tau}} pwedge\left(f, \beta, \theta_S, \theta_R, \tau, \tau_S, \tau_R, \ell, R_S, R_R, \hat{Z}_S, \hat{Z}_R\right) \tag{93}$$

The procedure described this section will be referred to by the function *Dwedge* as defined in Eq. (94).

$$\hat{D}(f) = Dwedge\left(f, \beta, \theta_S, \theta_R, \tau, \tau_S, \tau_R, \ell, R_S, R_R, \hat{Z}_S, \hat{Z}_R\right) \tag{94}$$

5.7.3 Diffraction of Two Wedge-Shaped Screens

This section describes the procedure used in the Nord2000 method to calculate the sound pressure at the receiver when sound propagates from a point source over two finite impedance wedges as shown in Figure 10. The wedge closest to the source is designated the first wedge (top edge T_1) and the wedge closest to the receiver is designated the second wedge (top edge T_2). In the following R_1, R_2 and R_3 in the figure are designated R_S, R_M, and R_R.

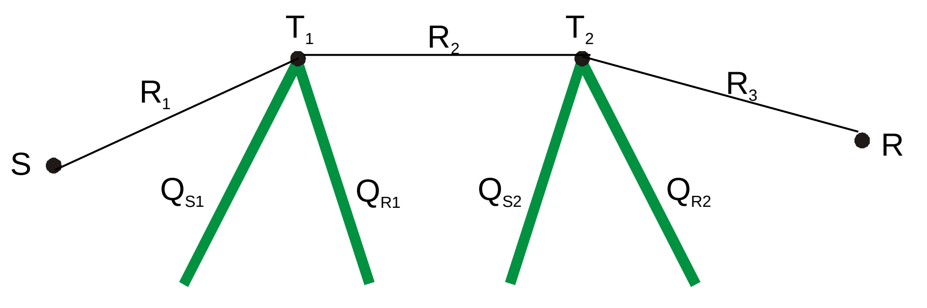

Figure 10
Propagation over two wedge-shaped screens.

The input variables in the model are:

- The travel time τ_S from source S to T_1
- The travel time τ_M from T_1 to T_2
- The travel time τ_R from receiver R to T_2
- The travel distance R_S from S to T_1
- The travel distance R_M from T_1 to T_2
- The travel distance R_R from R to T_2
- The source diffraction angle θ_{1S} of the first wedge
- The “receiver” diffraction angle θ_{1R} of the first wedge. If T_2 is above the line from T_1 to R, θ_{1R} is the angle between the receiver wedge face and the line T_1T_2. Otherwise θ_{1R} is the angle between the receiver wedge face and the line T_1R
- Wedge angle β_1 of the first wedge
- Surface impedance Z_{1S} of source face of the first wedge
- Surface impedance Z_{1R} of receiver face of first wedge
- The “source” diffraction angle θ_{2S} of the second wedge. If T_1 is above the line from T_2 to S, θ_{2S} is the angle between the receiver wedge face and the line T_2T_1. Otherwise θ_{2R} is the angle between the receiver wedge face and the line T_2S
- The receiver diffraction angle θ_{2R} of the second wedge
- Wedge angle β_2 of the second wedge
- Surface impedance Z_{2S} of source face of the second wedge
- Surface impedance Z_{2R} of receiver face of second wedge

The total travel time τ and distance ℓ is defined in by Eqs. (95) and **(96)**.

$$\tau = \tau_S + \tau_M + \tau_R \qquad \textbf{(95)}$$

$$\ell = R_S + R_M + R_R \qquad (96)$$

If the first wedge is the most important wedge the sound pressure at the receiver $\hat{p}$ is calculated by Eq. (97). The most important wedge in the terrain is determined in Section 5.21.

$$\begin{aligned}
&\hat{p}(f) = \hat{D}_1(f)\hat{D}_2(f)\frac{e^{j2\pi f\tau}}{\ell} \\
&where \\
&\hat{D}_1(f) = Dwedge\left(f, \beta_1, \theta_{1S}, \theta_{1R}, \tau, \tau_S, \tau_M + \tau_R, \ell, R_S, R_M + R_R, \hat{Z}_{1S}, \hat{Z}_{1R}\right) \\
&\hat{D}_2(f) = Dwedge\left(f, \beta_2, \theta_{2S}, \theta_{2R}, \tau_M + \tau_R, \tau_M, \tau_R, R_M + R_R, R_M, R_R, \hat{Z}_{2S}, \hat{Z}_{2R}\right)
\end{aligned} \tag{97}$$

If the second wedge is the most important wedge the sound pressure at the receiver $\hat{p}$ is calculated by Eq. (98).

$$\begin{aligned}
&\hat{p}(f) = \hat{D}_1(f)\hat{D}_2(f)\frac{e^{j2\pi f\tau}}{\ell} \\
&where \\
&\hat{D}_1(f) = Dwedge\left(f, \beta_1, \theta_{1S}, \theta_{1R}, \tau_S + \tau_M, \tau_S, \tau_M, R_S + R_M, R_S, R_M, \hat{Z}_{1S}, \hat{Z}_{1R}\right) \\
&\hat{D}_2(f) = Dwedge\left(f, \beta_2, \theta_{2S}, \theta_{2R}, \tau, \tau_S + \tau_M, \tau_R, \ell, R_S + R_M, R_R, \hat{Z}_{2S}, \hat{Z}_{2R}\right)
\end{aligned} \tag{98}$$

The procedure described in this section for calculating the sound pressure at the receiver from sound propagation over two wedge-shaped screens will be referred to by the function *p2wedge* as defined in Eq. (99).

$$\hat{p}(f) = p2wedge\begin{pmatrix} f, \beta_1, \theta_{1S}, \theta_{1R}, \beta_2, \theta_{2S}, \theta_{2R}, \\ \tau_S, \tau_M, \tau_R, R_S, R_M, R_R, \hat{Z}_{1S}, \hat{Z}_{1R}, \hat{Z}_{2S}, \hat{Z}_{2R} \end{pmatrix} \tag{99}$$

5.7.4 Diffraction of a Thick Screen

This section describes the procedure used in the Nord2000 method to calculate the sound pressure at the receiver when sound propagates from a point source over a sceeen with two edges and finite impedance surfaces as shown in Figure 11. The edge closest to the source is designated the first edge T_1 and the edge closest to the receiver is designated the second edge T_2 in the description of the method. In the following R_1, R_2 and R_3 in the figure will be designated R_S, R_M, and R_R. The procedure described in this section is based on the diffraction of two wedges. The first and second wedge is formed by the segments on each side of the top points T_1 and T_2, respectively. Therefore, T_1T_2 is included in both wedges.

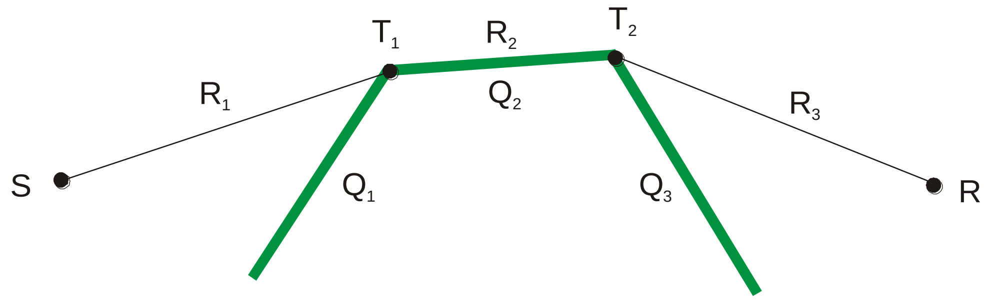

Figure 11
Propagation over a thick screen.

The input variables in the model are:

- The travel time τ_S from source S to T_1
- The travel time τ_M from T_1 to T_2
- The travel time τ_R from receiver R to T_2
- The travel distance R_S from S to T_1
- The travel distance R_M from T_1 to T_2
- The travel distance R_R from R to T_2
- The source diffraction angle θ_{1S} of the first wedge
- The "receiver" diffraction angle θ_{1R} of the first wedge. If T_2 is above the line from T_1 to R, then $\theta_{1R} = 0$. Otherwise θ_{1R} is the angle between the line T_1T_2 and the line T_1R
- Wedge angle β_1 of the first wedge
- Surface impedance Z_{1S} of source face of the first wedge
- The "source" diffraction angle θ_{2S} of the second wedge. If T_1 is above the line from T_2 to S, then $\theta_{1S} = \beta_2$. Otherwise θ_{1S} is the angle between the receiver side face of the second wedge and the line T_2S
- The receiver diffraction angle θ_{2R} of the second wedge
- Wedge angle β_2 of the second wedge
- Surface impedance Z_{2R} of receiver face of second wedge

In the method finite impedance at the top of the thick screen are ignored by assuming a hard top ($Z = \infty$).

The total travel time τ and distance ℓ is defined in by Eqs. (100) and **(101)**.

$$\tau = \tau_S + \tau_M + \tau_R \qquad \textbf{(100)}$$

$$\ell = R_S + R_M + R_R \qquad (101)$$

If the first edge is the most important edge the sound pressure at the receiver $\hat{p}$ is calculated by Eq. (102).

$$\begin{aligned}
&\hat{p}(f) = 0.5\hat{D}_1(f)\hat{D}_2(f)\frac{e^{j2\rho f\tau}}{\ell} \\
&where \\
&\hat{D}_1(f) = Dwedge\left(f, \beta_1, \theta_{1S}, \theta_{1R}, \tau, \tau_S, \tau_M + \tau_R, \ell, R_S, R_M + R_R, \hat{Z}_{1S}, \infty\right) \\
&\hat{D}_2(f) = Dwedge\left(f, \beta_2, \theta_{2S}, \theta_{2R}, \tau_M + \tau_R, \tau_M, \tau_R, R_M + R_R, R_M, R_R, \infty, \hat{Z}_{2R}\right)
\end{aligned} \qquad \textbf{(102)}$$

If the second edge is the most important edge the sound pressure at the receiver $\hat{p}$ is calculated by Eq. (103).

$$\begin{aligned}
&\hat{p}(f) = 0.5\hat{D}_1(f)\hat{D}_2(f)\frac{e^{j2\rho f\tau}}{\ell} \\
&where \\
&\hat{D}_1(f) = Dwedge\left(f, \beta_1, \theta_{1S}, \theta_{1R}, \tau_S + \tau_M, \tau_S, \tau_M, R_S + R_M, R_S, R_M, \hat{Z}_{1S}, \infty\right) \\
&\hat{D}_2(f) = Dwedge\left(f, \beta_2, \theta_{2S}, \theta_{2R}, \tau, \tau_S + \tau_M, \tau_R, \ell, R_S + R_M, R_R, \infty, \hat{Z}_{2R}\right)
\end{aligned} \qquad \textbf{(103)}$$

The procedure described in this section for calculating the sound pressure at the receiver from sound propagation over a thick screen will be referred to by the function *p2edge* as defined in Eq. (104).

$$\hat{p}(f) = p2edge\left(f, \beta_1, \theta_{1S}, \theta_{1R}, \beta_2, \theta_{2S}, \theta_{2R}, \tau_S, \tau_M, \tau_R, R_S, R_M, R_R, \hat{Z}_{1S}, \hat{Z}_{2R}\right) \qquad \textbf{(104)}$$

5.7.5 Wedge with a Non-Reflecting Surface

In the some cases where the wedge faces are assumed to be non-reflecting (shadow zone shielding, finite screens) the method described in Section 5.7.1 will be simplified. The diffracted sound pressure given by Eq. (78) will change to Eq. (105) and the possible contribution from a reflection in a wedge face given by either Eq. (89) or (90) disappears.

$$\hat{p}_{diffr}(f) = -\frac{1}{\pi} A(\theta_1) \hat{E}_\nu (A(\theta_1)) \frac{e^{j\omega\tau}}{\ell} \qquad \textbf{(105)}$$

The procedure for calculating the sound pressure and the diffraction coefficient of a non-reflecting wedge are referred to by the functions *pwedge0* and *Dwedge0* defined in Eqs. (106) and (107).

$$\hat{p}(f) = pwedge0(f, \beta, \theta_S, \theta_R, \tau, \tau_S, \tau_R, \ell, R_S, R_R) \qquad \textbf{(106)}$$

$$\hat{D}(f) = Dwedge0(f, \beta, \theta_S, \theta_R, \tau, \tau_S, \tau_R, \ell, R_S, R_R) \qquad (107)$$

5.8 Fresnel Zones, Fresnel-Zone Weights and Freznel-Zone Interpolation

The concept of Fresnel-zones is widely used in the Nord2000 propagation model. Particularly when sound is reflected by a plane surface the efficiency of the reflection is quantified by the ratio between the area of the surface within the Fresnel-zone and the area of the entire Fresnel-zone. This ratio is called the Fresnel-zone weight.

The Fresnel ellipsoid is defined by the locus of the points P defined by Eq. (108) where S is the source point, R is the receiver point, and F_λ is a fraction of the wavelength λ. The foci of the ellipsoid are placed at S and R.

$$|SP| + |RP| - |SR| = F_\lambda \lambda \qquad \textbf{(108)}$$

When the sound field is reflected by a plane surface, the Fresnel-zone is defined by the intersection between the plane and the Fresnel ellipsoid with foci at the image source point S' and the receiver R as shown in Figure 12.

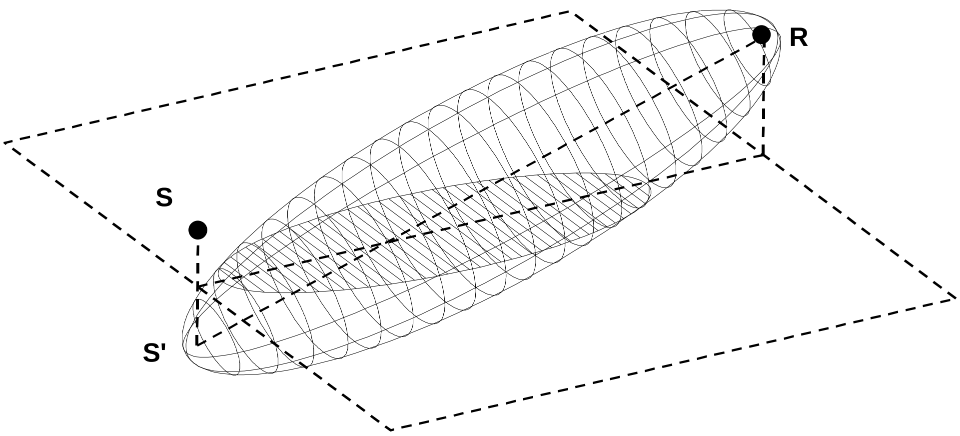

Figure 12
Definition of Fresnel ellipsoid and Fresnel-zone.

For practical purposes the elliptical shape is very inconvenient to work with when calculating sub-areas within the Fresnel-zone. In the Nord2000 method the Fresnel-zone is therefore defined to be the circumscribed rectangle instead. The size of the rectangle is determined by the size of the ellipse along the major and minor axes (in the direction of propagation and perpendicular to the direction). Another practical modification of the Fresnel-zone definition is that only the part of the Fresnel-zone area between source and receiver is included.

As the propagation model is two-dimensional in most of the Nord2000 method the Fresnel-zone becomes one-dimensional as shown in Figure 13.

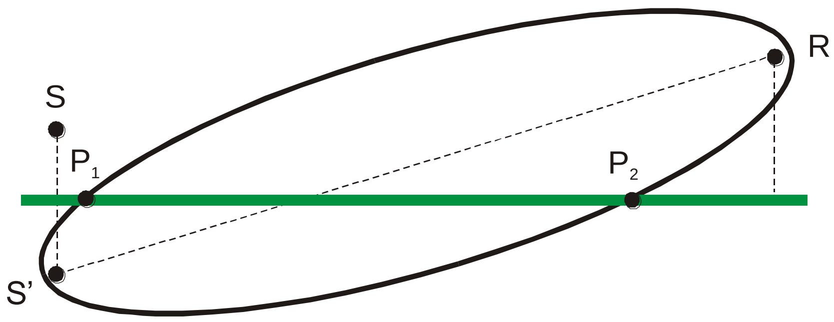

Figure 13
Definition of the one-dimensional Fresnel-zone (P_1P_2) in the two-dimensional part of the propagation model.

The position of the Fresnel-zone and the Fresnel-zone weights can be determined by a number of auxiliary functions *CalcFZd*, *FresnelZoneSize*, *FresnelZoneW*, and *FresnelZoneWm*.

The fraction F_λ used when calculating the Fresnel-zone weight depends on the sub-model. When calculating terrain effects $F_\lambda = 1/16$ is used except in the flat terrain model with more than one ground type where $F_\lambda = 1/4$ is used. In case of reflections by vertically erected surfaces and when determining the efficiency of a scattering zone with finite size $F_\lambda = 1/8$ is used.

In several of the sub-models in the Nord2000 method for calculating terrain effects, a principle has been used which is denoted Fresnel-zone interpolation. In the Fresnel-zone intepolation principle it is assumed that the overall terrain effect can be determined on basis of the terrain effect $\Delta L_i(f)$ calculated for each segment separately disregarding the finite size of the segment. The overall effect $\Delta L(f)$ is determined by adding the terrain effects of all segments weighted by the Fresnel-zone weight $w_i(f)$ of the segment as shown in Eq. (109).

$$\Delta L(f) = \sum_{i}^{N_{ts}} w_i(f) \Delta L_i(f) \qquad \textbf{(109)}$$

In Sub-model 3 (non-flat terrain without screening effects) described in Section 5.12 the Fresnel-zone weight in a frequency band $w_i(f)$ is normalized to a sum of 2 if the sum exceeds 2. The weight in a frequency band is also normalized in case of large attenuation (small values of ΔL) as described in Section 5.12.

In Sub-models 4-6 (terrain with one or two screens) described in Sections 5.13 through 5.15 the Fresnel-zone weight in a frequency band $w_i(f)$ is again normalized if the sum of weigts exceeds a given value in the same way as in sub-model 3. However, in this case the normalization is based on the sum of weights in excess of 1 in each terrain region (before, after or between screens). If the sum of excess values exceeds 1 the weights are normalized as described in Sections 5.13 through 5.15.

5.9 Coherence Coefficients

The coherence between two rays in propagation model is determined by a frequency dependent variable denoted a coherence coefficient. Coherence coefficients are denoted F and is for each frequency band a real number between 0 and 1. The value 1 is indicating full coherence and the value 0 is indicating no coherence. The overall coherence coefficient F is a combination of different coherence effects as shown in Eq. (110).

$$F = F_f F_{\Delta\tau} F_c F_r F_s \qquad \textbf{(110)}$$

where

- F_f is a coherence coefficient due to averaging within the one-third octave band
- $F_{\Delta\tau}$ is a coherence coefficient due to fluctuating refraction ($s_A > 0$ or $s_B > 0$)
- F_c is a coherence coefficient due to turbulence ($C_v^2 > 0$ or $C_T^2 > 0$)
- F_r is a coherence coefficient due to ground surface roughness ($r > 0$)
- F_s is a coherence coefficient due to propagation through scattering zones

Calculation of F_f, $F_{\Delta\tau}$, F_c, and F_r are described in the following section whereas the calculation of F_s is described in Section 5.19.

5.9.1 Coherence Coefficient due to Frequency Band Averaging

The value of coherence F_f due to frequency band averaging depends on the travel time difference $\Delta\tau(f)$ (≥ 0) between the secondary ray and the primary ray and on the frequency f ans is calculated as shown in Eq. (111).

$$F_f\left(f,\Delta\tau\right)=\begin{cases}1 & x=0\\ \dfrac{\sin x}{x} & 0<x<\pi\\ 0 & x\geq\pi\end{cases}\qquad \textbf{(111)}$$

$$\textit{where}$$

$$x=0.23\pi\, f\,\Delta\tau\left(f\right)$$

5.9.2 Coherence Coefficient due to Fluctuating Refraction

The value of coherence due to fluctuating refraction $F_{\Delta\tau}$ depends on the travel time difference $\Delta\tau(f)$ (≥ 0) in case of average refraction (based on weather variables A and B) and on the travel time difference $\Delta\tau_+(f)$ (≥ 0) in case of upper refraction (based on A_+ and B_+) between the secondary ray and the primary ray and on the frequency f and is calculated as shown in Eq. (112).

$$F_{\Delta\tau}\left(f,\Delta\tau,\Delta\tau_+\right)=\begin{cases}1 & x=0\\ \dfrac{\sin x}{x} & 0<x<\pi\\ 0 & x\geq\pi\end{cases}\qquad \textbf{(112)}$$

$$\textit{where}$$

$$x=2\pi\, f\left|\Delta\tau_+\left(f\right)-\Delta\tau\left(f\right)\right|$$

5.9.3 Coherence Coefficient due to Turbulence

The value of coherence due to turbulence F_c depends on the turbulence variables C_v^2 and C_T^2, the average temperature $\bar{t}$, the average sound speed $\bar{c}$, the transversal separation ρ, the horizontal distance d, and the frequency f and is calculated as shown in Eq. (113). *exp'* is the auxiliary function defined in Section 5.23.3.

$$F_c\left(f,C_v^2,C_T^2,\bar{t},\bar{c},\rho,d\right)=\exp'(x)$$

$$\textit{where}$$

$$x=-5.3888\left(\frac{C_T^2}{\left(\bar{t}+273.15\right)}+\frac{22}{3}\frac{C_v^2}{\bar{c}^2}\right)\left(\frac{f}{\bar{c}}\right)^2\rho^{5/3}d\qquad \textbf{(113)}$$

5.9.4 Coherence Coefficient due to Ground Surface Roughness

The value of coherence due to ground surface roughness F_r depends on the wave number k, the grazing reflection angle ψ_G, and the ground surface roughness r and is calculated as shown in Eq. (114). *exp'* is the auxiliary function defined in Section 5.23.3.

$$F_r(k,\psi_G,r) = \exp'(0.5\,g(X))$$

where

$$g(X) = \begin{cases} 0 & X \le 0.026686 \\ 0.55988\,(0.115448 - X) - 0.049696 & 0.026686 < X < 0.115448 \\ -0.066 + 1.066X - 8.543X^2 + 4.71X^3 - 0.83X^4 & X \ge 0.115448 \end{cases} \quad \textbf{(114)}$$

and

$$X = k\,r\sin(\psi_G)$$

5.10 Sub-Model 1: Flat Terrain with One Type of Surface

The geometrical setup in case of flat terrain with one type of surface is shown in Figure 14. The rays shown in the figure are straight line corresponding to a non-refracting atmosphere ($\xi = 0$). For refracting atmospheres the rays will be arcs of circles instead as described in Section 5.5.

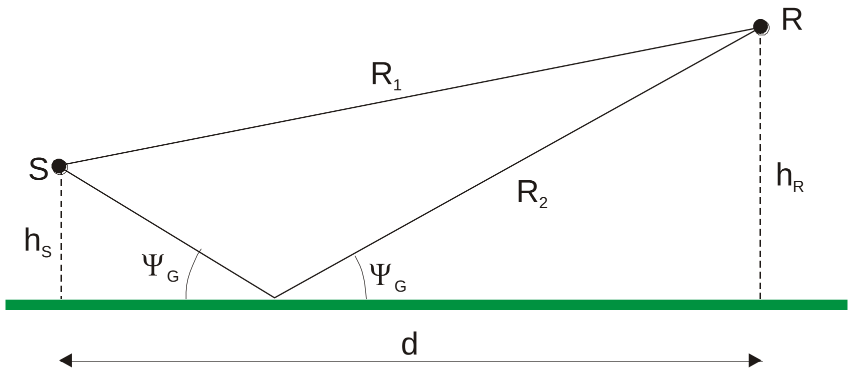

Figure 14
Geometrical variables for flat terrain.

The input variables of the sub-model are:

- Shortest distance h_S from the source S to the ground surface
- Shortest distance h_R from the receiver R to the ground surface
- Distance d from S to R measured along the ground surface
- Flow resistivity σ of the ground
- Roughness r of the ground
- Roughness length z_0

- Weather variables A, B, C, s_A, s_B
- Turbulence variables C_v^2, C_T^2

First the modified frequency dependent equivalent linear sound speed profile is determined by the function *CalcEqSSPGround* described in Section 5.5.3 as shown in Eq. (115) for average refraction and for upper refraction (indicates by +).

$$\begin{aligned}(\xi(f), c_0(f), \bar{c}, \xi, c_0) &= CalcEqSSPGround\left(h_{S,}, h_R, \hat{Z}_G(f), z_0, A, B, C\right)\\ (\xi_+(f), c_{0+}(f), NA, NA, NA) &= CalcEqSSPGround\left(h_{S,}, h_R, \hat{Z}_G(f), z_0, A_+, B_+, C\right)\end{aligned} \qquad \textbf{(115)}$$

The ray variables are determined for the direct ray and the reflected ray in Eq. (116) for average refraction and upper refraction using the procedures *DirectRay* and *ReflectedRay* described in Sections 5.5.4 and 5.5.5. NA indicates that a calculated variable is not used. If the calculation by *DirectRay* shows that the receiver is in a shadow zone ($\xi < 0$ and $d > 0.95\, d_{SZ}$ where d_{SZ} is defined in Section 5.5.4) calculations by *ReflectedRay* are not carried out. The variables ξ, c_0, τ, R, ψ_G, and $\Delta\tau$ are in the following equations of this section a function of the frequency.

$$\begin{aligned}(\tau_1, R_1, NA, \bar{c}, d_{SZ}) &= DirectRay(d, h_{S,}, h_R, \xi, c_0)\\ (\tau_{1+}, NA, NA, NA, NA) &= DirectRay(d, h_{S,}, h_R, \xi_+, c_{0+})\\ (\tau_2, R_2, NA, NA, NA, NA, \psi_G, NA) &= ReflectedRay(d, h_{S,}, h_R, \xi, c_0)\\ (\tau_{2+}, NA, NA, NA, NA, NA, NA, NA) &= ReflectedRay(d, h_{S,}, h_R, \xi_+, c_{0+})\end{aligned} \qquad \textbf{(116)}$$

The travel time differences $\Delta\tau$ and $\Delta\tau_+$ for average and upper refraction are determined by Eq. (117).

$$\begin{aligned}\Delta\tau &= TravelTimeDiff(\tau_2, \tau_1)\\ \Delta\tau_+ &= TravelTimeDiff(\tau_{2+}, \tau_{1+})\end{aligned} \qquad \textbf{(117)}$$

The coherence coefficients F is calculated by Eq. (118) where the coherence coefficients F_f, $F_{\Delta\tau}$, F_c, and F_r are calculated as described in Section 0. ρ is the transversal separation calculated by Eq. **(119)** and k_0 is the wave number at the ground. In case of propagation through a scattering zone the coherence coefficient F_s is calculated as described in Section 5.19. Otherwise $F_s = 1$.

$$F(f) = F_f(f, \Delta\tau) F_{\Delta\tau}(f, \Delta\tau, \Delta\tau_+) F_c\left(f, C_v^2, C_T^2, t_{mean}, \bar{c}, \rho, d\right) F_r(k_0, \psi_G, r) F_s(f) \qquad \textbf{(118)}$$

$$\rho = \frac{2 h_S h_R}{h_S + h_R} \qquad (119)$$

If the receiver is not in a shadow zone the ground effect ΔL_{flat} is calculated by Eq. (120).

$$\Delta L_{flat}(f) = \left(\left| 1 + F\frac{R_1}{R_2} e^{j2\pi f\Delta\tau} \hat{Q}\left(f, \tau_2, \psi_G, \hat{Z}_G\right) \right|^2 + \left(1 - F^2\right) \left(\frac{R_1}{R_2} \Re_i\left(f, \hat{Z}_G\right) \right)^2 \right) \quad \textbf{(120)}$$

Otherwise, if the receiver is in a shadow zone the ground effect ΔL_{flat} is calculated by Eq. (121).

$$\Delta L_1(f) = \left(\left| 1 + F\hat{Q}\left(f, 0, 0, \hat{Z}_G\right) \right|^2 + \left(1 - F^2\right) \left(\Re_i\left(f, \hat{Z}_G\right)\right)^2 \right) + \Delta L_{SZ}(f) \quad \textbf{(121)}$$

In Eq. (121) the term ΔL_{SZ} is the part of the shadow zone attenuation that is called the shadow zone shielding in the Nord2000 method. ΔL_{SZ} is calculated as shown in Eq. (122) by the auxiliary function *ShadowZoneShielding* based on the variables d, h_S, h_R, ξ, c_0 and d_{SZ}. ξ and c_0 are the frequency independent variables obtained by the function *CalcEqSSPGround*.

$$\Delta L_{SZ}(f) = ShadowZoneShielding\left(f, d, h_S, h_R, \xi, c_0, d_{SZ}\right) \quad \textbf{(122)}$$

If Sub-model 1 is applied for a non-flat terrain the values of h_{Se}, h_{Re} and d_e measured relative to the equivalent flat terrain and calculated as shown in Eq. (316) are used instead of h_S, h_R and d.

Sub-model 1 is used by other sub-models of the Nordtest standard method. In these cases Sub-model 1 is referred to by the function *SubModel1* as defined in Eq. (123).

$$\Delta L_i(f) = SubModel1\left(d'_i, h'_{S,i}, h'_{R,i}, \sigma_i, r_i, z_0, A, B, C, s_A, s_B, C_v^2, C_T^2\right) \quad \textbf{(123)}$$

5.11 Sub-Model 2: Flat Terrain with more than One Type of Surface

If the terrain is flat but have more than one type of ground surface (combination of flow resistivity σ and roughness r) Sub-model 1 cannot be used. In this case the ground effect ΔL_2 is calculated by Sub-model 2. The input variables of Sub-model 2 are:

- Shortest distance h_S from the source S to the ground surface
- Shortest distance h_R from the receiver R to the ground surface
- Distance d_i from S to the end point of ground segment no. i measured along the ground surface (d_{i-1} is the distance from S to the starting point of the segment, and $d_0 = 0$)
- Flow resistivity σ_i of ground segment no. i
- Roughness r_i of ground segment no. i

- Roughness length z_0
- Weather variables A, B, C, s_A, s_B
- Turbulence variables C_v^2, C_T^2

The ground effect according to Sub-model 2 is determined by Eq. (124) where N_σ is the number of impedances and N_r is the number of roughness types. $\Delta L_{ii,ir}(f)$ is the ground effect for each combination of σ and r calculated by Sub-model 1 as described in Section 5.10 and $w'_{ii,ir}(f)$ is a modified Fresnel-zone weight quantifying the relative importance of each ground type in this sub-model.

$$\Delta L_2(f) = \sum_{ii}^{N_\rho} \sum_{ir}^{N_r} w'_{ii,ir}(f) \Delta L_{ii,ir}(f) \qquad \textbf{(124)}$$

The geometrical variables used to calculate the modified Fresnel-zone weight $w_{ii,ir}(f)$ for each ground segment are defined in Figure 15. Other variables used in the calculation are the product $F_\lambda \lambda$ (where F_λ in this submodel is equal 0.25 and λ is the wavelength) and the relative sound speed gradient ξ and the sound speed at the ground c_0 in the equivalent linear sound speed profile.

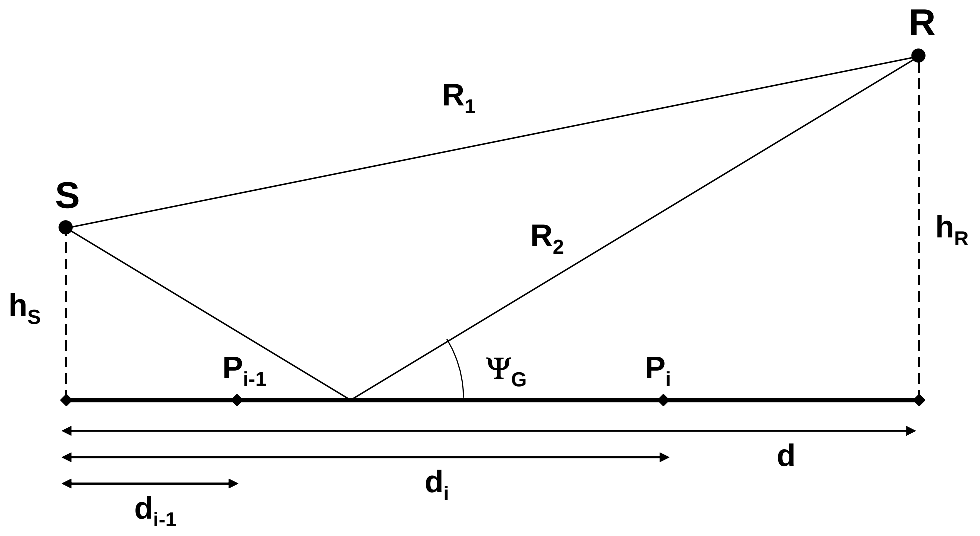

Figure 15
Geometrical variables used in the calculation of the Fresnel-zone weight for one ground segment.

The Fresnel-zone weight $w_i(f)$ for the i'the ground segment (out of N_{ts}) to be used at low frequencies is calculated by Eq. (125) based on the auxiliary function *FresnelZoneW*. The function also calculates the horizontal distance and the source and receiver heights corresponding to the refraction modified source and receiver positions defined in Section 5.23.7. The correction for refraction is indicated by placing the symbol ∪ over the variables.

$$\left(w_i(f), \breve{d}, \breve{h}_S, \breve{h}_R, NA\right) = FresnelZoneW\left(d, h_S, h_R, d_{i-1}, d_i, 0.25\lambda, \xi, c_0\right) \tag{125}$$

A speciel Fresnel-zone weight $r_i(f)$ to be used at high frequencies is calculated by the function *FresnelZoneWm* as shown in Eq. (126).

$$r_i(f) = FresnelZoneWm\left(d, h_S, h_R, d_{i-1}, d_i, 0.25\lambda, \xi, c_0\right) \tag{126}$$

For each type of surface (each combination of flow resistivity *ii* and ground roughness *ir*) the weights from all segments are added as shown in Eq. (127). The weight $w_{ii,ir,L}$ is the Fresnel-zone weight in the low frequency range whereas $r_{ii,ir}$ is a weight used to calculate the Fresnel-zone weight $w_{ii,ir,H}$ in the high frequency range.

$$\begin{aligned} w_{ii,ir,L}(f) &= \sum_i^{N_{ts}} \begin{cases} w_i(f) & if\ \#of\ \sigma = ii \wedge \#of\ r = ir \\ 0 & otherwise \end{cases} \\ r_{ii,ir}(f) &= \sum_i^{N_{ts}} \begin{cases} r_i(f) & if\ \#of\ \sigma = ii \wedge \#of\ r = ir \\ 0 & otherwise \end{cases} \end{aligned} \tag{127}$$

On basis of $r_{ii,ir}$ the weight $w_{ii,ir,H}$ in the high frequency range can be calculated by Eq. (128) where ψ_G is the grazing reflection angle. Most of the variables in the equation are a function of the frequency although not indicated.

$$\begin{aligned} r_{ii} &= \sum_{ir}^{N_r} r_{ii,ir} \\ r_{ii}'' &= 8.78\, r_{ii}^5 - 21.95\, r_{ii}^4 + 21.76\, r_{ii}^3 - 10.69\, r_{ii}^2 + 3.1\, r_{ii} \\ r_{ii,ir}' &= \frac{r_{ii}''}{\sum_{ii}^{N_\sigma} r_{ii}''} \frac{r_{ii,ir}}{r_{ii}} \\ r_h &= \begin{cases} 1 & \tan\psi_G \geq 0.04 \\ \dfrac{\log\left(200\tan\psi_G\right)}{\log(8)} & 0.005 < \tan\psi_G < 0.04 \\ 0 & \tan\psi_G \leq 0.005 \end{cases} \\ w_{ii,ir,H}(f) &= \left(r_{ii,ir} - r_{ii,ir}'\right) r_h + r_{ii,ir}' \end{aligned} \tag{128}$$

Then the modified Fresnel-zone weight $w'_{ii,ir}(f)$ is calculated in the whole frequency by Eq. (129).

$$w'_{ii,ir}(f)=\begin{cases} w_{ii,ir,L}(f) & f \le f_L \\ \dfrac{\log f_H - \log f}{\log f_H - \log f_L}\left(w_{ii,ir,L}(f) - w_{ii,ir,H}(f)\right) + w_{ii,ir,H}(f) & f_L < f < f_H \\ w_{ii,ir,H}(f) & f \ge f_H \end{cases} \quad \textbf{(129)}$$

The frequencies f_L and f_H are determined on basis of phase differences α_L and π between the direct and reflected ray as shown in Eqs. (130) and **(131)**. The calculation is carried using the auxiliary function *PhaseDiffFreq* described in Section 5.23.12. $Z_{G,min}(f)$ is the terrain impedance corresponding the smallest flow resistivity in the terrain profile and the c_0 is the sound speed at the ground in the equivalent linear sound speed profile.

$$f_L = PhaseDiffFreq\left(\breve{d}, \breve{h}_S, \breve{h}_R, \hat{Z}_{G,\min}(f), c_0, \alpha_L\right) \quad \textbf{(130)}$$

$$f_H = PhaseDiffFreq\left(\breve{d}, \breve{h}_S, \breve{h}_R, \hat{Z}_{G,\min}(f), c_0, \pi\right) \quad (131)$$

The phase difference α_L is determined by Eq.(132).

$$\begin{aligned} &\Delta\alpha_L = \pi - \left(1.9483 \ln\left(h_{\min}\right) + 18.052\right)\tan\psi_G \\ &where \\ &h_{\min} = \max\left(\min(\breve{h}_S, \breve{h}_R), 0.01\right) \end{aligned} \quad \textbf{(132)}$$

If $f_L > 0.8\, f_H$, $f_L = 0.8\, f_H$ is used instead.

If Sub-model 2 is applied for a non-flat terrain the values of h_{Se}, h_{Re} and d_e measured relative to the equivalent flat terrain and calculated as shown in Eq. (316) are used instead of h_S, h_R and d. The value $d_{e,i}$ determined by Eq. (133) for the projection of ground point no. i onto the equivalent flat terrain is used instead of d_i (other variables in Eq. (133) correspond to Eq. (316)). If $d_{i+1} \le d_i$ segment no. i is not included in the Sub-model 2 calculations.

$$\begin{aligned} &\left(x'_{Ge,i}, z'_{Ge,i}, NA\right) = NormLine\left(x_{SGe}, z_{SGe}, x_{RGe}, z_{RGe}, x_i, z_i\right) \\ &d_{e,i} = Length\left(x'_{SGe}, z'_{SGe}, x'_{Ge,i}, z'_{Ge,i}\right) \end{aligned} \quad \textbf{(133)}$$

5.12 Sub-Model 3: Non-Flat Terrain without Screening Effects

If the terrain is non-flat but contains neither screens nor parts of the terrain that can cause screening effects, the terrain effect is calculated by Sub-model 3 described in this section. When to use Sub-model 3 is described in Sections 5.21 and 5.21.6. An example of such a terrain which in most cases will form a “valley-shape” is shown in Figure 16. The figure also shows the source and receiver heights h_S and h_R.

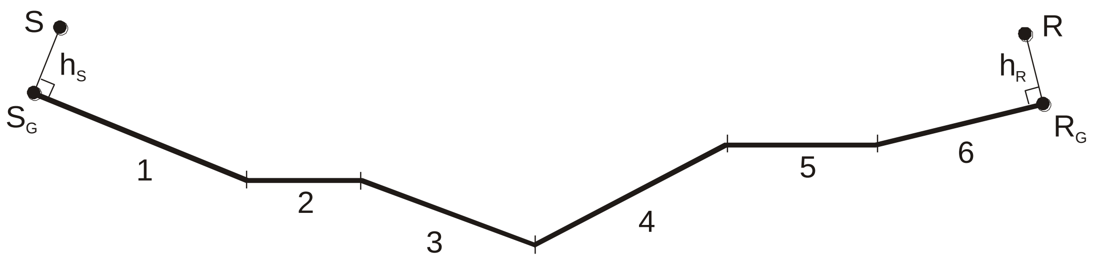

Figure 16
Example of a segmented terrain without screening effects.

The input variables of the sub-model correspond to the input variables defined in Sections 5.3.1 and 5.3.2.

In Sub-model 3 it is assumed that the overall terrain effect can be determined by calculating the terrain effect for each segment separately and then adding them according to the Fresnel-zone interpolation principle described in Section 5.8.

When calculating the terrain effect of each segment it is necessary to distinguish between three types of terrain segments:

- Concave segments
- Convex segments
- Transition segments

The type of segment is determined on basis of the source and receiver heights h'_S and h'_R measured relative to the extended segment. If the source or receiver is below the segment this is indicated by a negative value. Figure 17 shows examples of the three types of segments taken from Figure 16 and shows how the variables h'_S and h'_R and the horizontal distance d' are defined. These variables are used when calculating the terrain effect of each segment. The variables h'_S and h'_R relative to h_S and h_R defined in Section 5.4.1 are used to define the type of terrain segment as described below.

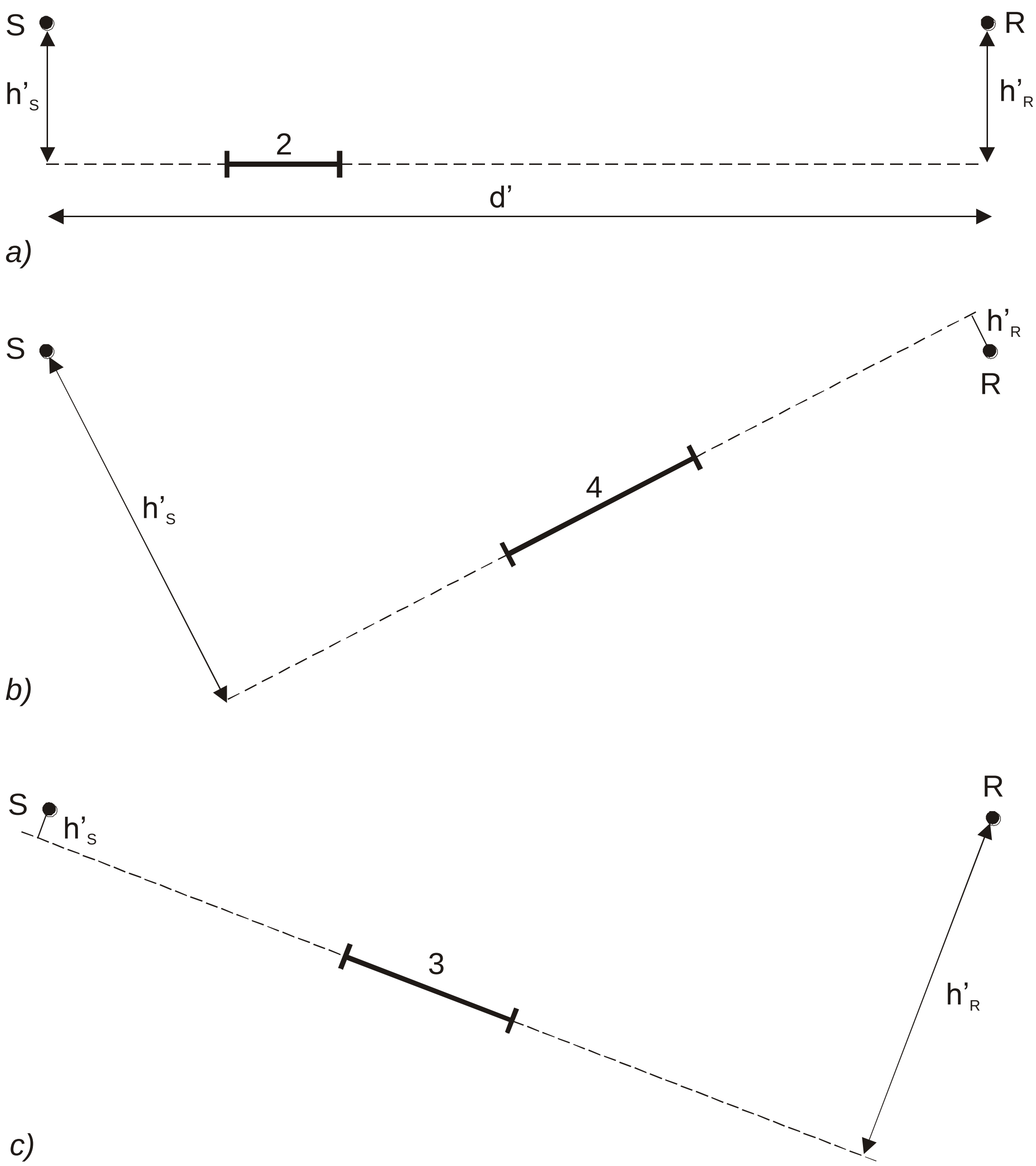

Figure 17
Definition of source and receiver heights h'_S and h'_R relative to the extended segment for ***a)*** *a concave segment where $h'_S > h_S$ and $h'_R > h_R$,* ***b)*** *a convex segment where $h'_S > h_S$ and $h'_R < 0$ and* ***c)*** *a transition segment where $0 < h'_S < h_S$ and $h'_R > h_R$.*

The type of segment is determined on basis of the so-called relative source and receiver height $h_{S,rel}(f)$ and $h_{R,rel}(f)$ which will be defined in the following. The relative heights are a function of the frequency. These heights are in case of a concave or transition segment calculated on basis of the refraction corrected source and receiver height. The refraction corrected variables are indicated by the symbol ◡ over the variables and are calculated by the function *FresnelZoneW* as shown in Eq. (134). d_{i-1} and d_i are the distances from the source to the start and end point of the segment measured along the segment as shown in Figure 15. The Fresnel-zone weight $w_i(f)$ also calculated by the function *FresnelZoneW* is used only for a concave and a transition segment. λ is the wavelength and ξ and c_0 defining the equivalent linear sound speed profile are calculated by Eq. **(135)**.

$$\left(w_i(f), \breve{d}', \breve{h}'_S, \breve{h}'_R, \breve{d}_{refl}\right) = FresnelZoneW\left(d', h'_S, h'_R, d_{i-1}, d_i, 1/16\,\lambda, \xi, c_0\right) \qquad \textbf{(134)}$$

$$\left(\xi, c_0, NA\right) = CalcEqSSP\left(h'_{S,}, h'_R, z_0, A, B, C\right) \qquad (135)$$

The type of segment is determined on basis of the relative source height $h_{S,rel}$ and the relative receiver height $h_{R,rel}$ defined as shown in Eqs. (136) and **(137)**. If the segment is a convex segment $\breve{h}'_S = h'_S$ and $\breve{h}'_R = h'_R$. If the heights h''_S and h''_R are the minimum allowable heights of a concave segment. h''_S is determined by the smallest value of the source height h_S and a height called $h_{S,Fz}$ and in the same way h''_R is determined by the smallest value of the receiver height h_R and a height called $h_{R,Fz}$. The heights $h_{S,Fz}$ and $h_{R,Fz}$ are calculated by the auxiliary function *MinConcaveHeight* as shown in Eq. **(138)** and **(139)**. d_{refl} is the distance from source to reflection point measured along the segment.

$$h_{S,rel}(f) = \begin{cases} 1 & \breve{h}'_S \geq h''_S \\ \dfrac{\breve{h}'_S}{h''_S(f)} & 0 < \breve{h}'_S < h''_S \\ 0 & \breve{h}'_S \leq 0 \end{cases} \qquad \textbf{(136)}$$

where

$$h''_S(f) = \min\left(h_S, h_{S,Fz}(f)\right)$$

$$h_{R,rel}(f) = \begin{cases} 1 & \breve{h}'_R \geq h''_R \\ \dfrac{\breve{h}'_R}{h''_R(f)} & 0 < \breve{h}'_R < h''_R \\ 0 & \breve{h}'_R \leq 0 \end{cases} \qquad (137)$$

where

$$h''_R(f) = \min\left(h_R, h_{R,Fz}(f)\right)$$

$$h_{S,Fz}(f) = MinConcaveHeight\left(\breve{h}'_R, \breve{d}_x, \breve{d}, \lambda\right)$$

where (138)

$$\breve{d}_x = d_{i-1} - d_{refl} + \breve{d}_{refl}$$

$$h_{R,Fz}(f) = MinConcaveHeight\left(h'_S, \breve{d}_x, \breve{d}, \lambda\right)$$
$$where$$
$$\breve{d}_x = d - d_i + d_{refl} - \breve{d}_{refl} \tag{139}$$

The type of segments can now be determined on basis of $h_{S,rel}$ and $h_{R,rel}$:

- Concave segment: $h_{S,rel}(f) = 1 \wedge h_{R,rel}(f) = 1$
- Convex segment: $h_{S,rel}(f) = 0 \vee h_{R,rel}(f) = 0$
- Transition: if neither concave nor convex

If the ground segment is a concave segment the terrain effect is calculated by Eq. (140) where the function *SubModel1* designates Sub-model 1 described in Section 5.10 and the Fresnel-zone weight $w_i(f)$ of the segment is calculated as shown in Eq. (134).

$$\Delta L_i(f) = SubModel1\left(d'_i, h'_{S,i}, h'_{R,i}, \sigma_i, r_i, z_0, A, B, C, s_A, s_B, C_v^2, C_T^2\right) \tag{140}$$

If the ground segment is a convex segment the terrain effect has to be calculated using the diffraction solution described in Section 5.7.1. The convex segment will constitute of one of the wedge faces or be a part of one of the wedge faces which is denoted the primary wedge face. The secondary wedge face will geometrically be determined by another segment in the terrain profile as described in the following but will in the calculation be assigned the same impedance.

If $h_{S,rel} < h_{R,rel}$, the secondary wedge face will be determined by a secondary ground segment between the source and the convex segment under consideration. The secondary ground segment to be used is the segment closest the convex segment where $h'_{Sv} \geq h_{Sv}$. h'_{Sv} is the source height measured vertically about the secondary segment.

If $h_{S,rel} \geq h_{R,rel}$, the secondary wedge face will be determined by a secondary ground segment between the receiver and the convex segment under consideration. The secondary ground segment to be used is the segment closest the convex segment where $h'_{Rv} \geq h_{Rv}$. h'_{Rv} is the receiver height measured vertically about the secondary segment.

If the two segments are not adjacent, an equivalent wedge is determined. The top of the wedge is determined by the intersection between the primary and secondary segment as shown in Figure 18. The coordinates of the top point (x_T,z_T) are calculated by the auxiliary function *WedgeCross* as shown in Eq. (141). (x_1,z_1) and (x_2,z_2) are the start and end coordinates of the segment closest to the source and (x_3,z_3) and (x_4,z_4) are the start and end coordinates of the segment closest to the receiver $(x_1<x_2<x_3<x_4)$.

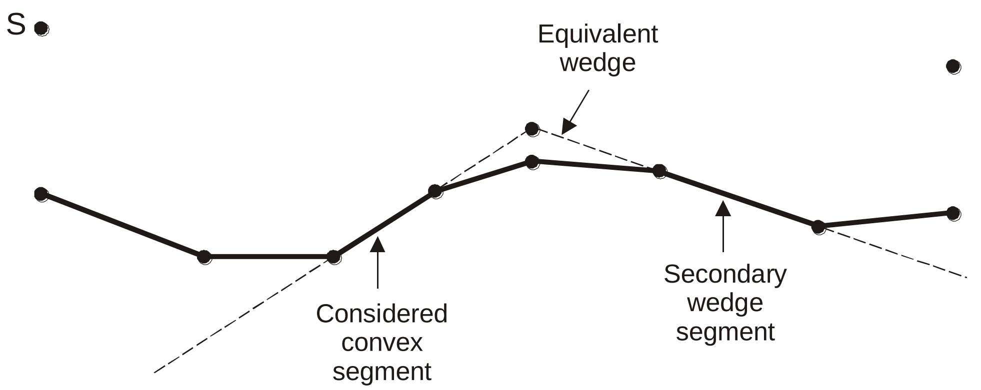

Figure 18
Definition of an equivalent wedge used for predicting the ground effect of a convex segment.

$$(x_T, z_T) = WedgeCross(x_1, z_1, x_2, z_2, x_3, z_3, x_4, z_4) \quad \textbf{(141)}$$

If the two segments are adjacent, the wedge is directly determined by the primary and secondary segment and $x_T = x_2 = x_3$ and $z_T = z_2 = z_3$.

In order to determine the diffraction angles of the wedge, the height of the source h'_{S1} above the source side wedge face and the distance d'_1 from source to the top of the wedge measured along the wedge face are determined by Eqs. (142) and **(143)**. In the same way the height of the receiver h'_{R2} above the receiver side wedge face and the distance d'_2 from receiver to the top of the wedge measured along the wedge face are determined by Eqs. **(144)** and **(145)**. Also the equivalent screen height h''_{SCR} is determined by Eq. **(22)** in Section 5.5.2.

$$(x'_S, z'_S, h'_{S1}) = NormLine(x_1, z_1, x_T, z_T, x_S, z_S) \quad \textbf{(142)}$$

$$d'_1 = Length(x'_S, z'_S, x_T, z_T) \quad (143)$$

$$(x'_R, z'_R, h'_{R2}) = NormLine(x_T, z_T, x_4, z_4, x_R, z_R) \quad (144)$$

$$d'_2 = Length(x'_R, z'_R, x_T, z_T) \quad (145)$$

The next step is to calculate the wedge angle β and the diffraction angles θ_S and θ_R as shown in Eq. (146). The variables $\Delta\theta_S$ and $\Delta\theta_R$ which are the change in diffraction angles due to refraction are calculated in Eq **(148)** and **(150)**.

$$\beta_1 = \arctan\left(\frac{z_1 - z_T}{x_T - x_1}\right) + \frac{\pi}{2}$$
$$\beta_2 = \arctan\left(\frac{z_2 - z_T}{x_2 - x_T}\right) + \frac{\pi}{2}$$
$$\theta_1 = \arctan\left(\frac{z_S - z_T}{x_T - x_S}\right) + \frac{\pi}{2} \qquad \mathbf{(146)}$$
$$\theta_2 = \arctan\left(\frac{z_R - z_T}{x_R - x_T}\right) + \frac{\pi}{2}$$
$$\beta = 2\pi - \beta_1 - \beta_2$$
$$\theta_S = 2\pi - \theta_1 - \beta_2 - \Delta\theta_S$$
$$\theta_R = \theta_2 - \beta_2 + \Delta\theta_R$$

The travel time τ_S between source and wedge top and τ_R between receiver and wedge top and the corresponding travel distances R_S and R_R are calculated by Eqs. (147) to **(150)**.

$$\left(\xi_S, c_{0S}, NA\right) = CalcEqSSP\left(h'_{S1,}, h''_{SCR}, z_0, A, B, C\right) \qquad \mathbf{(147)}$$

$$\left(\tau_S, R_S, \Delta\theta_S, NA, NA\right) = DirectRay\left(d'_1, h'_{1,}, 0, \xi_S, c_{0S}\right) \qquad (148)$$

$$\left(\xi_R, c_{0R}, NA\right) = CalcEqSSP\left(h''_{SCR}, h'_{R1,}, z_0, A, B, C\right) \qquad (149)$$

$$\left(\tau_R, R_R, \Delta\theta_R, NA, NA\right) = DirectRay\left(d'_2, 0, h'_R, \xi_S, c_{0S}\right) \qquad (150)$$

The terrain effect of a convex segment can finally be calculated by Eq. (151) using the auxiliary function *pwedge*. R_{SR} is the source-receiver distance and $\hat{Z}_i(f)$ is the impedance of the convex segment.

$$\Delta L_i(f) = 20\log\left(\left|\hat{p}(f)\right| R_{SR}\right)$$
$$where \qquad \mathbf{(151)}$$
$$\hat{p}(f) = pwedge\left(f, \beta, \theta_S, \theta_R, \tau_S + \tau_R, \tau_S, \tau_R, R_S + R_R, R_S, R_R, \hat{Z}_i(f), \hat{Z}_i(f)\right)$$

For a convex segment the Fresnel-zone weight $w_i(f)$ cannot be calculated by the procedure described in 5.8 as the source or the receiver is below the segment. Instead a modified principle is applied. If the top point of the wedge is at or above the terrain base line defined in Section 5.3.1, the projection of the convex segment onto the base line is used when determining the Fresnel-zone weight (similar to a concave segment). If the top point is below the base line the projection on a line parallel with the base line through the top point is used instead as shown in Figure 19. If the considered segment is P_1P_0 the segment used in the determination of the Fresnel-zone weight is P'_1P_0 and if the considered segment is P_0P_2 the segment to be used is $P_0P'_2$.

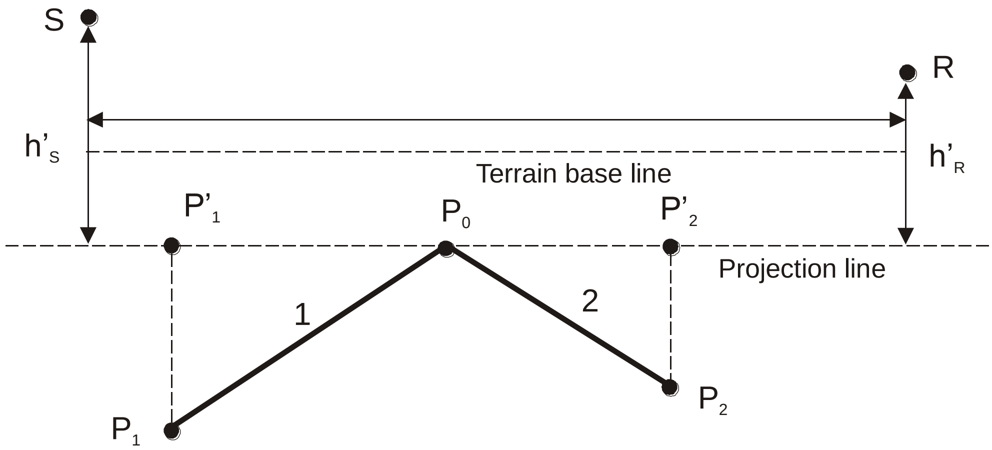

Figure 19
Definition of the Fresnel-zone weighting principle for convex segments.

The geometrical variables in the modified Fresnel-zone principle described above can be calculated as shown in Eq. (152).

$$\begin{aligned}
&(x'_S, z'_S, h'_{Sb}) = NormLine(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}, x_S, z_S) \\
&(NA, NA, h'_{Rb}) = NormLine(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}, x_R, z_R) \\
&(x'_1, z'_1, h'_1) = NormLine(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}, x_i, z_i) \\
&(x'_2, z'_2, h'_2) = NormLine(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}, x_{i+1}, z_{i+1}) \\
&d'_{i-1} = Length(x'_S, z'_S, x'_1, z'_1) \\
&d'_i = Length(x'_S, z'_S, x'_2, z'_2) \\
&d' = Length(x'_S, z'_S, x'_R, z'_R) \\
&h'_m = \max(h'_1, h'_2) \\
&\Delta h = \begin{cases} |h'_m| & h'_m < 0 \\ 0 & h'_m \geq 0 \end{cases} \\
&h'_S = h'_{Sb} + \Delta h \\
&h'_R = h'_{Rb} + \Delta h
\end{aligned} \qquad \textbf{(152)}$$

Accordingly the Fresnel-zone weight $w_i(f)$ can be calculated by Eqs. (153) where the Fresnel-zone weight is further modified if both $h_{S,rel}$ and $h_{R,rel}$ are less than one. λ is the wavelength and ξ' and c'_0 defining the equivalent linear sound speed profile are calculated by Eq. **(154)**.

$$\begin{aligned}&\left(w_{x,i}(f), NA, NA, NA, NA\right) = FresnelZoneW\left(d', h'_S, h'_R, d'_{i-1}, d'_i, 1/16\,\lambda, \xi', c'_0\right)\\&w_i(f) = w_{x,i}(f) Max(h_{S,rel}(f), h_{R,rel}(f))\end{aligned} \quad \textbf{(153)}$$

$$\left(\xi', c'_0, NA\right) = CalcEqSSP\left(h'_{S,}, h'_R, z_0, A, B, C\right) \quad (154)$$

If the segment is a transition segment the terrain effect and the Fresnel-zone weight is calculated by the method for a concave as well as a convex segment and the results is obtained by interpolation between the two results as shown in Eq. (155). $w_{i,concave}$ and $\Delta L_{i,concave}$ are determined by Eqs. (134) and (140), respectively and $w_{i,convex}$ and $\Delta L_{i,convex}$ by Eqs. (153) and (151).

$$\begin{aligned}&w_i(f)\Delta L_i(f) = w_{i,concave}(f)\Delta L_{i,concave}(f) r(f) + w_{i,convex}(f)\Delta L_{i,convex}(f)(1 - r(f))\\&where\\&r(f) = Min(h_{S,rel}(f), h_{R,rel}(f))\end{aligned} \quad \textbf{(155)}$$

Finally, the over-all terrain effect ΔL_3 for Sub-model 3 of the N_{ts} terrain segments can be calculated by Eq. (156) using a modified Fresnel-zone interpolation principle. The modified principle is based on the original Fresnel-zone interpolation result ΔL_0 calculated as described in Section 5.8. When ΔL_0 is greater than zero the modified principle is identical to the original principle but the effect of the modification increases with a decreasing value of ΔL_0.

$$
\begin{aligned}
& w_t(f) = \sum_i^{N_{ts}} w_i(f) \\
& w_i'(f) = \begin{cases} \dfrac{2w_i(f)}{w_t(f)} & \text{if } w_t(f) > 2 \\ w_i(f) & \text{if } w_t(f) \le 2 \end{cases} \\
& \Delta L_0(f) = \sum_i^{N_{ts}} w_i'(f) \Delta L_i(f) \\
& r'(f) = \begin{cases} 0 & \Delta L_0(f) \ge 0 \\ -\Delta L_0(f)/20 & -20 < \Delta L_0(f) < 0 \\ 1 & \Delta L_0(f) \le -20 \end{cases} \\
& \Delta L_3(f) = \Delta L_0(f) \left(1 - r'(f) + \frac{r'(f)}{\sum_i^{N_{ts}} w_i'(f)} \right)
\end{aligned}
\qquad \textbf{(156)}
$$

5.13 Sub-Model 4: Terrain with One Screen Having One Edge

If the terrain has been found to contain one screen with one significant diffracting edge, the terrain effect is calculated by Sub-model 4 described in this section. The description has been divided into two parts. In Section 5.13.1 the base model is described where there is one reflecting surface before the screen and one after the screen. In Section 5.13.2 the general model is described which can have any number of segments before and after the screen.

5.13.1 Base Model

In the base model there is one reflecting surface on each side of a wedge-shaped screen as shown in Figure 20. The wedge is defined by the points W_1, T_1, and W_2 and reflecting surfaces by $P_{S1}P_{S2}$ on the source side of the screen and by $P_{R1}P_{R2}$ on the receiver side. S_i and R_i are the image of the source S and receiver R, respectively. The rays shown in the figure are straight line rays corresponding to a non-refracting atmosphere. For refracting atmospheres the rays will be arcs of circles instead as described in Section 5.5.

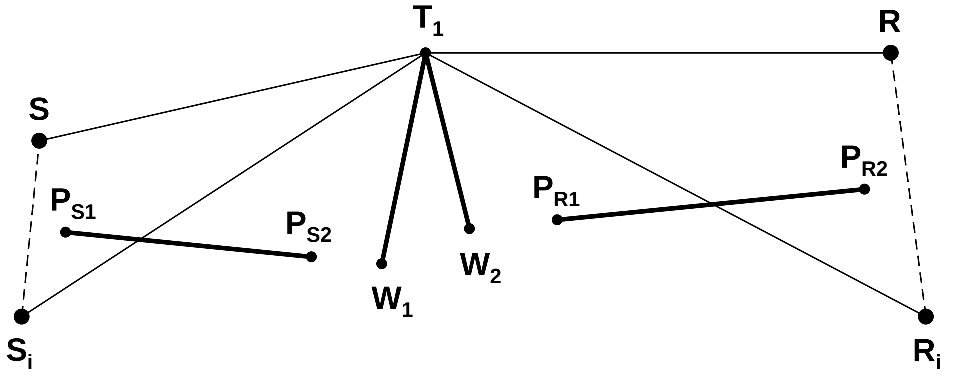

Figure 20
Definition of geometry for the base model.

In the base model the so-called the image method is used where the sound pressure at the receiver is the sum of coherent contributions from four rays as expressed by Eq. (157). p_1 is the diffracted sound pressure at the receiver from the source. p_2 is the diffracted sound pressure at the receiver from the image source, p_3 is the diffracted sound pressure at the image receiver from the source and p_4 is the diffracted sound pressure at the image receiver from the image source. The spherical wave reflection coefficients Q_1 and Q_2 on the source and receiver side of the screen, respectively, are calculated as if the receiver when calculating Q_1 or the source when calculating Q_2 is located at the screen top.

$$\hat{p} = \hat{p}_1 + \hat{Q}_1 \hat{p}_2 + \hat{Q}_2 \hat{p}_3 + \hat{Q}_1 \hat{Q}_2 \, \hat{p}_4 \quad \textbf{(157)}$$

In order to apply the Fresnel-zone interpolation principle described in Section 5.8 the propagation effect is obtained by expressing the sound pressure relative to the free-field sound pressure p_0 and screen effect and ground effect are separated as shown in Eq.(158). Allthough not indicated all variables in the equation are a function of the frequency. In this equation $p_{1,ff}/p_0$ is the effect of the screen in free space and the term in brackets is the effect of the ground in excess of the screen effect. The reason for denoting the diffracted sound pressure from source to receiver $p_{1,ff}$ in the screen effect part of the equation and p_1 in ground effect is that different equivalent sound speed profiles are used in the two cases. The linearization used to calculate $p_{1,ff}$ is independent of the position of the reflecting ground surfaces before and after the screen.

$$\frac{\hat{p}}{\hat{p}_0} = \frac{\hat{p}_{1,ff}}{\hat{p}_0} \left(1 + \hat{Q}_1 \frac{\hat{p}_2}{\hat{p}_1} + \hat{Q}_2 \frac{\hat{p}_3}{\hat{p}_1} + \hat{Q}_1 \hat{Q}_2 \frac{\hat{p}_4}{\hat{p}_1} \right) \quad \textbf{(158)}$$

If case of reduced efficiency of the ground reflection on the source or receiver side of the screen it may be necessary to modify Q_1 and Q_2. In Eq. (159) the modified values are denoted Q'_1 and Q'_2 and are obtained by multiplying the original values by a real number w_Q between 0 and 1. The value 1 indicates a fully efficient ground reflection while 0 indicates no reflection at all. The calculation of w_{Q1} and w_{Q2} will be described in the general model in Section 5.13.2. As mentioned above the term outside the brackets is the effect of the screen in free space and is denoted p_{SCR} while the term inside the brackets is the effect of the ground and is denoted p_G.

$$\frac{\hat{p}}{\hat{p}_0} = \frac{\hat{p}_{1,ff}}{\hat{p}_0}\left(1 + \hat{Q}_1'\frac{\hat{p}_2}{\hat{p}_1} + \hat{Q}_2'\frac{\hat{p}_3}{\hat{p}_1} + \hat{Q}_1'\hat{Q}_2'\frac{\hat{p}_4}{\hat{p}_1}\right) = \hat{p}_{SCR}\hat{p}_G$$
$$\text{where}$$
$$\hat{Q}_1' = w_{Q1}\hat{Q}_1 \qquad (159)$$
$$\text{and}$$
$$\hat{Q}_2' = w_{Q2}\hat{Q}_2$$

The first step is to determine the variables that have to be used to calculate the diffracted sound pressures $p_{1,ff}$, p_1, p_2, p_3 and p_4 by the auxiliary function *pwedge* as shown in Eq. (160). $Z_S(f)$ and $Z_R(f)$ are the impedance of the source and receiver side wedge face.

$$\hat{p}(f) = pwedge\left(f, \beta, \theta_S, \theta_R, \tau, \tau_S, \tau_R, \ell, R_S, R_R, \hat{Z}_S(f), \hat{Z}_R(f)\right) \qquad (160)$$

To calculate the diffracted sound pressure the input variables in Eq. (160) which are defined in Section 5.7.1 have to be determined. The wedge-shaped screen are defined by the diffracting edge $T_1 = (x_T, x_T)$, the start of the wedge $W_1 = (x_1, z_1)$ closest to source and the end of the wedge $W_2 = (x_2, z_2)$ closest to receiver. The ground segment is defined by the end points $P_{S1} = (x_{S1}, z_{S1})$ and $P_{S2} = (x_{S2}, z_{S2})$ and the ground impedance $Z_{G1}(f)$ on the source side of the screen and by the end points $P_{R1} = (x_{R1}, z_{R1})$ and $P_{R2} = (x_{R2}, z_{R2})$ and the ground impedance $Z_{G2}(f)$ on the receiver side of the screen.

The variables used to calculate $p_{1,ff}$ is determined according to Eqs. (161) and (162). d_{base} is defined in Eq. **(9)** and h''_{SCR} is determined by Eq. **(22)**. When calculating $p_{1,ff}$ the equivalent linear sound speed profile is independent of the frequency.

$$\begin{aligned}
&(x_T', z_T', h_{SCR}) = NormLine(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}, x_T, z_T)\\
&d_{SCR1} = Length(x_{SGv}, z_{SGv}, x_T', z_T')\\
&d_{SCR2} = d_{base} - d_{SCR1}\\
&(\xi_S, c_{0S}, NA) = CalcEqSSP(h_{Sv,}, h''_{SCR}, z_0, A, B, C)\\
&(\tau_S, R_S, \Delta\theta_S, NA, d_{SZ,S})) = DirectRay(d_{SCR1}, h_{S,}, h_{SCR}, \xi_S, c_{0S})\\
&(\xi_R, c_{0R}, NA) = CalcEqSSP(h_{Rv,}, h''_{SCR}, z_0, A, B, C)\\
&(\tau_R, R_R, \Delta\theta_R, NA, d_{SZ,R}) = DirectRay(d_{SCR2}, h_{R,}, h_{SCR}, \xi_R, c_{0R})\\
&\tau = \tau_S + \tau_R\\
&\ell = R_S + R_R
\end{aligned} \qquad (161)$$

The wedge angle β and diffraction angles θ_S and θ_R can now be determined by Eq. (162) on basis of the wedge coordinates.

$$\begin{aligned}
\beta_1 &= \arctan\left(\frac{z_1 - z_T}{x_T - x_1}\right) + \frac{\pi}{2} \\
\beta_2 &= \arctan\left(\frac{z_2 - z_T}{x_2 - x_T}\right) + \frac{\pi}{2} \\
\theta_1 &= \arctan\left(\frac{z_S - z_T}{x_T - x_S}\right) + \frac{\pi}{2} \\
\theta_2 &= \arctan\left(\frac{z_R - z_T}{x_R - x_T}\right) + \frac{\pi}{2} \\
\beta &= 2\pi - \beta_1 - \beta_2 \\
\theta_S &= 2\pi - \theta_1 - \beta_2 - \Delta\theta_S \\
\theta_R &= \theta_2 - \beta_2 + \Delta\theta_R
\end{aligned} \tag{162}$$

The numerical value of the screen effect $|p_{SCR}|$ is now determined by Eq. (163) where $p_{1,ff}(f)$ is calculated by Eq. (160) using the values of the input variables given in Eqs. (161) and (162). R_{SR} is the source-receiver distance

$$\left|\hat{p}_{SCR}(f)\right| = \left|\hat{p}_{1,ff}(f)\right| R_{SR} \tag{163}$$

In the calculation of p_1 to p_4 the linearization of the sound speed profile used to determine the diffraction angles will still be independent of the frequency in the same way as described for $p_{1,ff}$ but the travel times and travel distances in the ground effect calculation will depend on the frequency as described in Section 5.5.3.

To calculate the sound pressures p_1 to p_4 in the ground attenuation part of Eq. (159) the first step is to determine the height h'_{S1} of the source S and the height h'_{R1} of the screen edge T_1 above the terrain segment on the source side of the screen, and the distances d'_1 from S to T_1, d'_{11} from S to the start of the segment, and d'_{12} from S to the end of the segment measured along the terrain segment. This is done by the auxiliary function *SegmentVariables* described in Section 5.23.15 as shown in Eq. (164). In the same way the height h'_{S2} of the screen edge S and the height h'_{R2} of the receiver R above the terrain segment on the receiver side of the screen, and the distances d'_2 from T_1 to R, d'_{21} from T to the start of the segment, and d'_{22} from T_1 to the end of the segment measured along the terrain segment. This is also shown in Eq. (164).

$$\begin{aligned}
(d'_1, h'_{S1}, h'_{R1}, d'_{11}, d'_{12}) &= SegmentVariables(x_S, z_S, x_T, z_T, x_{S1}, z_{S1}, x_{S2}, z_{S2}) \\
(d'_2, h'_{S2}, h'_{R2}, d'_{21}, d'_{22}) &= SegmentVariables(x_T, z_T, x_R, z_R, x_{R1}, z_{R1}, x_{R2}, z_{R2})
\end{aligned} \tag{164}$$

When calculating the sound pressure p_1 the diffraction angles are the same as used $p_{1,ff}$. When calculating the sound pressures p_2 to p_4 diffraction angles θ_{Si} and θ_{Ri} for the image source and receiver have to be determined as shown in Eq. (165). The angles β, β_1, and β_2 are the same as calculated in Eq. (162). Due to numerical difficulties in strong upward refraction cases the image point angles θ_1 and θ_2 in Eq. (165) may become larger than corresponding angles of the direct ray defined in Eq. (162). This may lead to erroneuos results and in such cases the image point angle shall be set equal to the direct ray angle.

$$\begin{aligned}
&(NA, NA, NA, NA, NA, \Delta\theta_{Si}, NA, NA) = ReflectedRay(d'_1, h'_{S1,}, h'_{R1}, \xi_S, c_{0S}) \\
&(NA, NA, NA, NA, \Delta\theta_{Ri}, NA, NA, NA) = ReflectedRay(d'_2, h'_{S2,}, h'_{R2}, \xi_R, c_{0R}) \\
&(x_{Si}, z_{Si}) = ImagePoint(x_{S1}, z_{S1}, x_{S2}, z_{S2}, x_S, z_S) \\
&(x_{Ri}, z_{Ri}) = ImagePoint(x_{R1}, z_{R1}, x_{R2}, z_{R2}, x_R, z_R) \\
&\theta_1 = \arctan\left(\frac{z_{Si} - z_T}{x_T - x_{Si}}\right) + \frac{\pi}{2} \\
&\theta_2 = \arctan\left(\frac{z_{Ri} - z_T}{x_{Ri} - x_T}\right) + \frac{\pi}{2} \\
&\theta_{Si} = 2\pi - \theta_1 - \beta_2 - \Delta\theta_{Si} \\
&\theta_{Ri} = \theta_2 - \beta_2 + \Delta\theta_{Ri}
\end{aligned} \tag{165}$$

The travel times and travel distances used to calculate the sound pressures p_2 to p_4 are based on a frequency dependent linear sound speed profile and will therefore be a function of the frequency.

For the variables of the source side of the screen the modified frequency dependent equivalent linear sound speed profile is determined by the function *CalcEqSSPGround* described in Section 5.5.3 as shown in Eq. (166) for average refraction and for upper refraction (indicates by +).

$$\begin{aligned}
&(\xi_S(f), c_{0S}(f), \bar{c}_S, \xi_S, c_{0S}) = CalcEqSSPGround(h'_{S1,}, h'_{R1}, \hat{Z}_{G1}(f), z_0, A, B, C) \\
&(\xi_{S+}(f), c_{0S+}(f), NA, NA, NA) = \\
&\qquad CalcEqSSPGround(h'_{S1,}, h'_{R1}, \hat{Z}_{G1}(f), z_0, A_+, B_+, C)
\end{aligned} \tag{166}$$

The ray variables on the source side of the screen are determined for the direct ray and the reflected ray in Eq. (167) for average refraction and upper refraction using the procedures *DirectRay* and *ReflectedRay* described in Sections 5.5.4 and 5.5.5. NA indicates that a calculated variable is not used. If the calculation by *DirectRay* shows that the receiver is in a shadow zone ($\xi_S < 0$ and $d'_1 > 0.95\, d_{SZ,1}$ where $d_{SZ,1}$ is the distance to the shadow zone as defined in Section 5.5.4) calculations by ReflectedRay are not carried out. The variables τ, R, ψ_G, and $\Delta\tau$ are in the following equations of this section a function of the frequency.

$$
\begin{aligned}
&\left(\tau_{1S}, R_{1S}, NA, NA, d_{SZ,1}\right) = DirectRay\left(d_1', h_{S1,}', h_{R1}', \xi_S(f), c_{0S}(f)\right)\\
&\left(\tau_{1S+}, NA, NA, NA, NA\right) = DirectRay\left(d_1', h_{S1,}', h_{R1}', \xi_{S+}(f), c_{0S+}(f)\right)\\
&\left(\tau_{2S}, R_{2S}, NA, NA, NA, NA, \psi_{GS}, NA\right) =\\
&\qquad ReflectedRay\left(d_1', h_{S1,}', h_{R1}', \xi_S(f), c_{0S}(f)\right)\\
&\left(\tau_{2S+}, NA, NA, NA, NA, NA, NA, NA\right) =\\
&\qquad ReflectedRay\left(d_1', h_{S1,}', h_{R1}', \xi_{S+}(f), c_{0S+}(f)\right)
\end{aligned}
\tag{167}
$$

The travel time differences $\Delta\tau_S$ and $\Delta\tau_{S+}$ for average and upper refraction are determined by Eq. (168).

$$
\begin{aligned}
\Delta\tau_S &= TravelTimeDiff\,(\tau_{2S}, \tau_{1S})\\
\Delta\tau_{S+} &= TravelTimeDiff\,(\tau_{2S+}, \tau_{1S+})
\end{aligned}
\tag{168}
$$

The spherical-wave reflection coefficent Q_1 for the terrain reflection on the source side of the screen is calculated by Eq. (169).

$$
\hat{Q}_1 = \hat{Q}\left(f, \tau_{2S}, \psi_{GS}, \hat{Z}_{G1}\right)
\tag{169}
$$

For the variables of the receiver side of the screen the modified frequency dependent equivalent linear sound speed profile is determined by Eq. (170) for average refraction and for upper refraction (indicates by +).

$$
\begin{aligned}
&\left(\xi_R(f), c_{0R}(f), \bar{c}_R, \xi_R, c_{0R}\right) = CalcEqSSPGround\left(h_{S2,}', h_{R2}', \hat{Z}_{G2}(f), z_0, A, B, C\right)\\
&\left(\xi_{R+}(f), c_{0R+}(f), NA, NA, NA\right) =\\
&\qquad CalcEqSSPGround\left(h_{S2,}', h_{R2}', \hat{Z}_{G2}(f), z_0, A_+, B_+, C\right)
\end{aligned}
\tag{170}
$$

The ray variables on the receiver side are determined for the direct ray and the reflected ray in Eq. (171) for average and upper refraction using the procedures *DirectRay* and *ReflectedRay* described in Sections 5.5.4 and 5.5.5. NA indicates that a calculated variable is not used. If the calculation by *DirectRay* shows that the receiver is in a shadow zone (ξ_R < 0 and $d'_2 > 0.95\, d_{SZ,2}$ where $d_{SZ,2}$ is the distance to the shadow zone as defined in Section 5.5.4) calculations by *ReflectedRay* are not carried out. The variables τ, R, ψ_G, and $\Delta\tau$ are in the following equations of this section a function of the frequency.

$$
\begin{aligned}
&\left(\tau_{1R}, R_{1R}, NA, NA, d_{SZ,2}\right) = DirectRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_R(f), c_{0R}(f)\right) \\
&\left(\tau_{1R+}, NA, NA, NA, NA\right) = DirectRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_{R+}(f), c_{0R+}(f)\right) \\
&\left(\tau_{2R}, R_{2R}, NA, NA, NA, NA, \psi_{GR}, NA\right) = \\
&\qquad ReflectedRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_R(f), c_{0R}(f)\right) \\
&\left(\tau_{2R+}, NA, NA, NA, NA, NA, NA, NA\right) = \\
&\qquad ReflectedRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_{R+}(f), c_{0R+}(f)\right)
\end{aligned}
\tag{171}
$$

The travel time differences $\Delta\tau_R$ and $\Delta\tau_{R+}$ for average and upper refraction are determined by Eq. (172).

$$
\begin{aligned}
\Delta\tau_R &= TravelTimeDiff\,(\tau_{2R}, \tau_{1R}) \\
\Delta\tau_{R+} &= TravelTimeDiff\,(\tau_{2R+}, \tau_{1R+})
\end{aligned}
\tag{172}
$$

The spherical-wave reflection coefficent Q_2 for the terrain reflection on the receiver side of the screen is calculated by Eq. (173).

$$
\hat{Q}_2 = \hat{Q}\left(f, \tau_{2R}, \psi_{GR}, \hat{Z}_{G2}\right)
\tag{173}
$$

If the size of terrain segment on the source and receiver side is not sufficient large the ground attenuation part $|p_G|$ of the propagation effect has to be corrected for the limited size of the segments. This is done by calculating the Fresnel-zone weights of each segment w_1 and w_2 as shown in Eq. (174). Subsequently the weights are modified when source or receiver is close to the extension of the segment. The modified weights are denoted w''_1 and w''_2. The modifiers r_{S1}, r_{R1}, r_{S2}, and r_{R2} are calculated as shown in Eq. **(175)** and **(176)**. If source or receiver is below the extension of the segment the product of the modifiers becomes 0 which eliminates the problem of the Fresnel-zone weights w_1 and w_2 being undefined in this case. The Fresnel-zone weights are used in the general model described in Section 5.13.2.

$$
\begin{aligned}
&\left(w_1(f), NA, NA, NA, NA\right) = FresnelZoneW\left(d'_1, h'_{S1}, h'_{R1}, d_{11}, d_{12}, 1/16\,\lambda, \xi_S, c_{0S}\right) \\
&\left(w_2(f), NA, NA, NA, NA\right) = FresnelZoneW\left(d'_2, h'_{S2}, h'_{R2}, d_{21}, d_{22}, 1/16\,\lambda, \xi_R, c_{0R}\right) \\
&w''_1(f) = w_1(f)\, r_{S1} r_{R1} \\
&w''_2(f) = w_2(f)\, r_{S2} r_{R2}
\end{aligned}
\tag{174}
$$

$$
\begin{aligned}
&h_{\max,1} = Min(0.0005(x_T - x_S),0.2)\\
&h_1'' = Min(h_S, h_{\max,1})\\
&r_{S1} = \begin{cases} 1 & h_{S1}' \geq h_1'' \\ \dfrac{h_{S1}'}{h_1''} & 0 < h_{S1}' < h_1'' \\ 0 & h_{S1}' \leq 0 \end{cases}\\
&r_{R1} = \begin{cases} 1 & h_{R1}' \geq h_{\max,1} \\ \dfrac{h_{R1}'}{h_{\max,1}} & 0 < h_{R1}' < h_{\max,1} \\ 0 & h_{R1}' \leq 0 \end{cases}
\end{aligned}
\tag{175}
$$

$$
\begin{aligned}
&h_{\max,2} = Min(0.0005(x_R - x_T),0.2)\\
&h_2'' = Min(h_R, h_{\max,2})\\
&r_{R2} = \begin{cases} 1 & h_{R2}' \geq h_2'' \\ \dfrac{h_{R2}'}{h_2''} & 0 < h_{R2}' < h_2'' \\ 0 & h_{R2}' \leq 0 \end{cases}\\
&r_{S2} = \begin{cases} 1 & h_{S2}' \geq h_{\max,2} \\ \dfrac{h_{S2}'}{h_{\max,2}} & 0 < h_{S2}' < h_{\max,2} \\ 0 & h_{S2}' \leq 0 \end{cases}
\end{aligned}
\tag{176}
$$

If the propagation of the four rays in the image model was fully coherent the propagation effect could be determined by Eq. (158) but in order to take into account averaging and incoherent effects as described in Section 0, the coherence coefficient F_2, F_3, and F_4 describing the coherence between ray no. 2, 3, and 4 respectively and the direct ray have to be determined.

The coherence coefficient F_2 of ray no. 2 is calculated by Eq. (177) where the coherence coefficients F_f, $F_{\Delta\tau}$, F_c, and F_r are calculated as described in Section 0. ρ_1 is the transversal separation calculated by Eq. **(178)**, k_0 is the wave number at the ground and r_2 is the roughness of the source side terrain segment. In case of propagation through a scattering zone F_s is the coherence coefficient calculated as described in Section 5.19. Otherwise F_s = 1.

$$
\begin{aligned}
F_2(f) = F_f(f,\Delta\tau_S)F_{\Delta\tau}(f,\Delta\tau_S,\Delta\tau_{S+})F_c\left(f,C_v^2,C_T^2,t_{mean},\bar{c}_S,\rho_1,d_1'\right)\\
F_r(k_0,\psi_{GS},r_1)F_s(f)
\end{aligned}
\tag{177}
$$

$$\rho_1 = \frac{2h'_{S1}h'_{R1}}{h'_{S1}+h'_{R1}} \tag{178}$$

The coherence coefficient F_3 of ray no. 3 is calculated by Eq. (179) where the coherence coefficients F_f, $F_{\Delta\tau}$, F_c, and F_r are calculated as described in Section 0. ρ_2 is the transversal separation calculated by Eq. **(180)**, k_0 is the wave number at the ground and r_2 is the roughness of the receiver side terrain segment.

$$F_3(f) = F_f(f,\Delta\tau_R)F_{\Delta\tau}(f,\Delta\tau_R,\Delta\tau_{R+})F_c\left(f,C_v^2,C_T^2,t_{mean},\bar{c}_R,\rho_2,d'_2\right) F_r(k_0,\psi_{GR},r_2)F_s(f) \tag{179}$$

$$\rho_2 = \frac{2h'_{S2}h'_{R2}}{h'_{S2}+h'_{R2}} \tag{180}$$

The coherence coefficient F_4 of ray no. 4 is calculated by Eq. (181).

$$\begin{aligned} F_4(f) = {} & F_f(f,\Delta\tau_S+\Delta\tau_R)F_{\Delta\tau}(f,\Delta\tau_S+\Delta\tau_R,\Delta\tau_{S+}+\Delta\tau_{R+}) \\ & F_c\left(f,C_v^2,C_T^2,t_{mean},\bar{c}_S,\rho_1,d'_1\right)F_c\left(f,C_v^2,C_T^2,t_{mean},\bar{c}_R,\rho_2,d'_2\right) \\ & F_r(k_0,\psi_{GS},r_1)F_r(k_0,\psi_{GR},r_2)F_s(f) \end{aligned} \tag{181}$$

Now the propagation effect can be determined by Eq. (182) if shadow zone effects occur neither on the source side of the screen nor on the receiver side.

$$|\hat{p}_G| = \sqrt{\begin{aligned} & \left|1+F_2\frac{w_{Q1}\hat{Q}_1\hat{p}_2}{\hat{p}_1}+F_3\frac{w_{Q2}\hat{Q}_2\hat{p}_3}{\hat{p}_1}+F_4\frac{w_{Q1}\hat{Q}_1w_{Q2}\hat{Q}_2\hat{p}_4}{\hat{p}_1}\right|^2 + \\ & \left(1-F_2^2\right)\left|\frac{w_{Q1}\Re_1\hat{p}_2}{\hat{p}_1}\right|^2 + \left(1-F_3^2\right)\left|\frac{w_{Q2}\Re_2\hat{p}_3}{\hat{p}_1}\right|^2 + \\ & \left(1-F_4^2\right)\left|\frac{w_{Q1}\Re_1w_{Q2}\Re_2\hat{p}_4}{\hat{p}_1}\right|^2 \end{aligned}} \tag{182}$$

The incoherent reflection coefficients $\Re_1$ and $\Re_2$ in Eq. (182) are determined by Eq. (183).

$$\begin{aligned} \Re_1 &= \Re\left(f,\hat{Z}_{G1}\right) \\ \Re_2 &= \Re\left(f,\hat{Z}_{G2}\right) \end{aligned} \tag{183}$$

If $d'_1 > 0.95d_{SZ,1}$ and $d'_2 \le 0.95d_{SZ,2}$ shadow zone effects will occur on the source side of the screen and $|p_G|$ has to be calculated by Eq. (184) where $|p_G|^{\text{Eq.182}}$ indicates the value calculated by Eq. (182) with modified values of Q_1, p_2 and p_4.

$$\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,1}(f)}{20}} \left|\hat{p}_G\right|^{Eq.182}$$
$$where$$
$$\Delta L_{SZ,1}(f) = ShadowZoneShielding\left(f, d_1', h_{S1}', h_{R1}', \xi_S, c_{0S}, d_{SZ,1}\right)$$
$$\hat{Q}_1(f) = \hat{Q}\left(f, \tau_{1S}, 0, \hat{Z}_{G1}(f)\right)$$
$$\hat{p}_2 = \hat{p}_1$$
$$\hat{p}_4 = \hat{p}_3 \qquad \textbf{(184)}$$

If $d'_2 > 0.95 d_{SZ,2}$ and $d'_1 \le 0.95 d_{SZ,1}$ shadow zone effects will occur on the receiver side of the screen and $|p_G|$ has to be calculated by Eq. (185) where $|p_G|^{\text{Eq.182}}$ indicates the value calculated by Eq. (182) with modified values of Q_2, p_3 and p_4.

$$\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,2}(f)}{20}} \left|\hat{p}_G\right|^{Eq.182}$$
$$where$$
$$\Delta L_{SZ,2}(f) = ShadowZoneShielding\left(f, d_2', h_{S2}', h_{R2}', \xi_R, c_{0R}, d_{SZ,2}\right)$$
$$\hat{Q}_2(f) = \hat{Q}\left(f, \tau_{1R}, 0, \hat{Z}_{G2}(f)\right)$$
$$\hat{p}_3 = \hat{p}_1$$
$$\hat{p}_4 = \hat{p}_2 \qquad \textbf{(185)}$$

If $d'_1 > 0.95 d_{SZ,1}$ and $d'_2 > 0.95 d_{SZ,2}$ shadow zone effects will occur on both sides of the screen and $|p_G|$ has to be calculated by Eq. (186) where $|p_G|^{\text{Eq.182}}$ indicates the value calculated by Eq. (182) with modified values of Q_1, Q_2 ,p_2 , p_3, and p_4.

$$\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,1}(f)}{20}} 10^{\frac{\Delta L_{SZ,2}(f)}{20}} \left|\hat{p}_G\right|^{Eq.182}$$
$$where$$
$$\Delta L_{SZ,1}(f) = ShadowZoneShielding\left(f, d_1', h_{S1}', h_{R1}', \xi_S, c_{0S}, d_{SZ,1}\right)$$
$$\Delta L_{SZ,2}(f) = ShadowZoneShielding\left(f, d_2', h_{S2}', h_{R2}', \xi_R, c_{0R}, d_{SZ,2}\right)$$
$$\hat{Q}_1(f) = \hat{Q}\left(f, \tau_{1S}, 0, \hat{Z}_{G1}(f)\right)$$
$$\hat{Q}_2(f) = \hat{Q}\left(f, \tau_{1R}, 0, \hat{Z}_{G2}(f)\right)$$
$$\hat{p}_4 = \hat{p}_1$$
$$\hat{p}_3 = \hat{p}_1$$
$$\hat{p}_2 = \hat{p}_1 \qquad \textbf{(186)}$$

5.13.2 General Model

If the terrain has been found to contain one screen with one significant diffracting edge, the terrain effect is calculated by Sub-model 4 described in this section. An example of such a terrain is shown in Figure 21 where the two segments denoted 4 and 5 form a wedge-shaped screen. The remaining five segments will be considered reflecting surfaces. Segments 1–3 will form the surface on the source side of the screen while segments 6–7 form the surface on the receiver side.

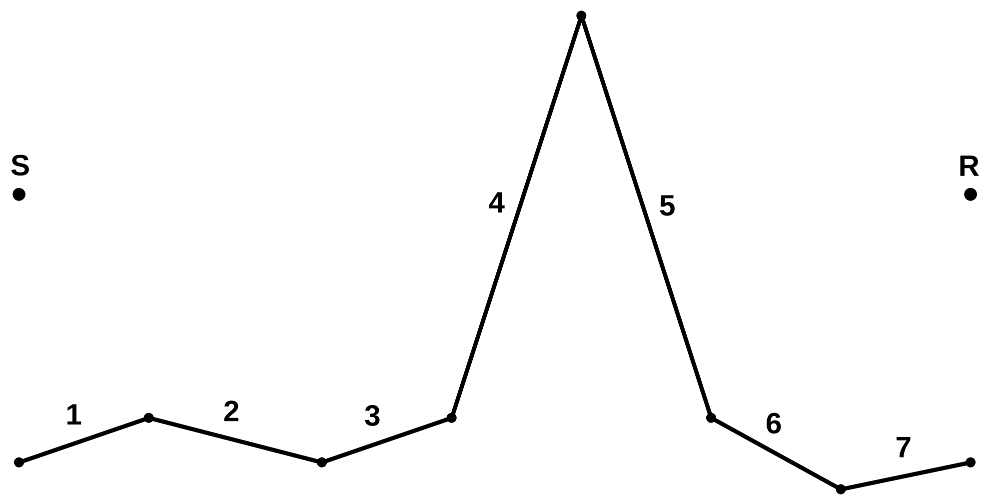

Figure 21
Example of a segmented terrain with one screen having one diffracting edge

At this point it is assumed that the screen part of the terrain profile has already been identified and therefore that the number of segments before and after the screen which are considered reflecting segments are known. If the part of the input terrain forming the screen shape contains more than three ground points the screen shape is reduced to three points as described in Section 5.21.

The screen is defined by the following point numbers in the terrain profile (numbered 1 to N_{ts}+1 where N_{ts} is the number of segments in the terrain profile).

- *iSCR,1* terrain point number closest to the source
- *iSCR,2* terrain point number closest to the receiver
- *iSCR,T* terrain point number of the diffracting edge

Therefore, the line segment representing the wedge face closest to the source has the end coordinates $W_1 = (x_{iSCR,1},z_{iSCR,1})$ and $T_1 = (x_{iSCR,T},z_{iSCR,T})$ while the line segment representing the wedge face closest to the receiver has the end coordinates $W_1 = (x_{iSCR,2},z_{iSCR,2})$ and $T_1 = (x_{iSCR,T},z_{iSCR,T})$. Possible terrain points between point no. *iSCR,1* and *iSCR,T* and between point no. *iSCR,2* and *iSCR,T* are ignored. In this case the flow resistivity $\sigma_{iSCR,T-1}$ is used as representative to the source side wedge face and $\sigma_{iSCR,T}$ is used as representative to the receiver side wedge face. In the example in Figure 21 *iSCR,1* = 4, *iSCR,2* = 6 and *iSCR,S* = 5.

The number of reflecting segments before the screen will therefore be *iSCR,1*-1 numbered from $N_{S1} = 1$ to $N_{S2} = iSCR,1\text{-}1$ while the number of reflecting segments after the screen will be N_{ts}+1-*iSCR,2* numbered from $N_{R1} = iSCR,2$ to $N_{R2} = N_{ts}$.

The base model will now used for all combinations of segments of the source side ($i_1 = N_{S1}$ to N_{S2}) and on the receiver side ($i_2 = N_{R1}$ to N_{R2}). For each case of *i1* and *i2* the coordinates to use in the base model are:

- $T_1 = (x_T,z_T) = (x_{iSCR,T},z_{iSCR,T})$
- $W_1 = (x_1,z_1) = (x_{iSCR,1},z_{iSCR,1})$
- $W_2 = (x_2,x_2) = (x_{iSCR,2},z_{iSCR,2})$
- $Z_S = Z_{iSCR,T-1}$
- $Z_R = Z_{iSCR,T}$
- $P_{S1} = (x_{S1},z_{S1}) = (x_{i1},z_{i1})$
- $P_{S2} = (x_{S2},z_{S2}) = (x_{i1+1},z_{i1+1})$
- $Z_{G1} = Z_{i1}$
- $w''_1(f) = w''_{i1}(f)$
- $P_{R1} = (x_{R1},z_{R1}) = (x_{i2},z_{i2})$
- $P_{R2} = (x_{R2},z_{R2}) = (x_{i2+1},z_{i2+1})$
- $Z_{G2} = Z_{i2}$
- $w''_2(f) = w''_{i2}(f)$

The base model is used to calculate the screen effect $|p_{SCR}|$ and the ground effect $|p_G|$. The former will be identical for all combinations of terrain segment and has to be calculated only once while the latter will vary for each combination of terrain terrain segments and will be denoted $|p_{G,i1,i2}|$ for segment *i1* on the source side of the screen and *i2* on the receiver side.

Based on the sum of Fresnel-zone weights $w''_{i1}(f) = w''_1(f)$ and $w''_{i2}(f) = w''_2(f)$ on each side of the screen the Fresnel-zone weights are normalized as shown in Eq. (187) and the weights w_{Q1} and w_{Q2} used the base model are determined.

$$
\begin{aligned}
&w_{1t}(f) = \sum_{i1=N_{S1}}^{N_{S2}} w''_{i1}(f) \\
&w_{2t}(f) = \sum_{i2=N_{R1}}^{N_{R2}} w''_{i2}(f) \\
&\Delta w_{1t}(f) = \begin{cases} w_{1t}(f) - 1 & \text{if } w_{1t}(f) > 1 \\ 0 & \text{if } w_{1t}(f) \le 1 \end{cases} \\
&\Delta w_{2t}(f) = \begin{cases} w_{2t}(f) - 1 & \text{if } w_{2t}(f) > 1 \\ 0 & \text{if } w_{2t}(f) \le 1 \end{cases} \\
&\Delta w_t(f) = \Delta w_{1t}(f) + \Delta w_{2t}(f) \\
&w'_{i1}(f) = \begin{cases} \dfrac{w''_{i1}(f)}{w_{1t}(f)}\left(\dfrac{\Delta w_{1t}(f)}{\Delta w_t(f)} + 1\right) & \text{if } w_{1t}(f) > 1 \\ \dfrac{w''_{i1}(f)}{w_{1t}(f)} & \text{if } 0 < w_{1t}(f) \le 1 \\ 0 & \text{if } w_{1t}(f) = 0 \end{cases} \\
&w'_{i2}(f) = \begin{cases} \dfrac{w''_{i2}(f)}{w_{2t}(f)}\left(\dfrac{\Delta w_{2t}(f)}{\Delta w_t(f)} + 1\right) & \text{if } w_{2t}(f) > 1 \\ \dfrac{w''_{i2}(f)}{w_{2t}(f)} & \text{if } 0 < w_{2t}(f) \le 1 \\ 0 & \text{if } w_{2t}(f) = 0 \end{cases} \\
&w_{Q1}(f) = \begin{cases} 1 & \text{if } w_{1t}(f) \ge 1 \\ w_{1t}^2(f) & \text{if } w_{1t}(f) < 1 \end{cases} \\
&w_{Q2}(f) = \begin{cases} 1 & \text{if } w_{2t}(f) \ge 1 \\ w_{2t}^2(f) & \text{if } w_{2t}(f) < 1 \end{cases}
\end{aligned}
\qquad \textbf{(187)}
$$

Finally the sound pressure level ΔL_4 of Sub-model 4 for a terrain with one screen having one edge is calculated according to Eq. (188).

$$\Delta L_4 = 20\log\left(\left|\hat{p}_{SCR}(f)\right| \prod_{i1=N_{S1}}^{N_{R1}} \prod_{i2=N_{R1}}^{N_{R2}} \left|\hat{p}_{G,i1,i2}\right|^{w'_{i1}(f)w'_{i2}(f)} \right) \quad \textbf{(188)}$$

5.14 Sub-Model 5: Terrain with One Screen Having Two Edges

If the terrain has been found to contain one screen with two significant diffracting edges, the terrain effect is calculated by Sub-model 5 described in this section. The description has been divided into two parts. In Section 5.14.1 the base model is described where there is one reflecting surface before the screen and one after the screen. In Section 5.14.2 the general model is described which can have any number of segments before and after the screen.

5.14.1 Base Model

In the base model there is one reflecting surface on each side of a wedge-shaped screen as shown in Figure 22. The wedge is defined by the points W_1, T_1, T_2, and W_2 and reflecting surfaces by $P_{S1}P_{R1}$ on the source side of the screen and by $P_{S2}P_{R2}$ on the receiver side. S_i and R_i are the image of the source S and receiver R, respectively. T_1 and T_2 are the two diffracting edges. The rays shown in the figure are straight line rays corresponding to a non-refracting atmosphere. For refracting atmospheres the rays will be arcs of circles instead as described in Section 5.5.

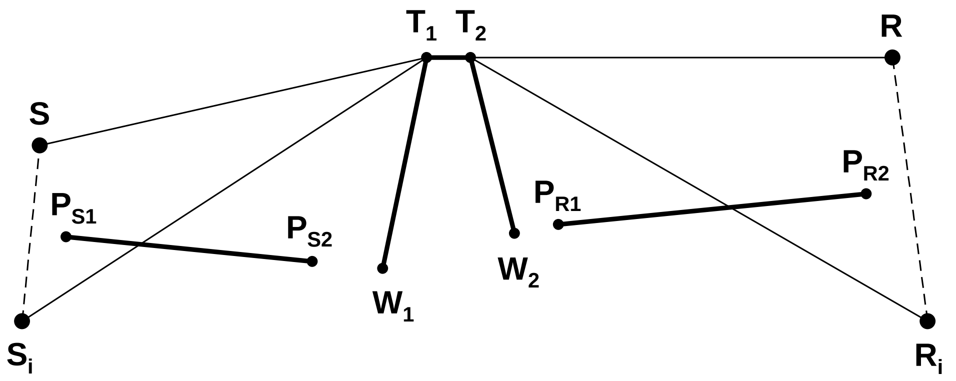

Figure 22
Definition of geometry for the base model.

In the base model the image method is used where the sound pressure at the receiver is the sum of coherent contributions from four rays as expressed by Eq. (189). p_1 is the diffracted sound pressure at the receiver from the source. p_2 is the diffracted sound pressure at the receiver from the image source, p_3 is the diffracted sound pressure at the image receiver from the source and p_4 is the diffracted sound pressure at the image receiver from the image source. The spherical wave reflection coefficients Q_1 and Q_2 on the source and receiver side of the screen, respectively, are calculated as if the receiver is located at T_1 when calculating Q_1 or the source is located at T_2 when calculating Q_2.

$$\hat{p} = \hat{p}_1 + \hat{Q}_1 \hat{p}_2 + \hat{Q}_2 \hat{p}_3 + \hat{Q}_1 \hat{Q}_2 \, \hat{p}_4 \tag{189}$$

In order to apply the Fresnel-zone interpolation principle described in Section 5.8 the propagation effect is obtained by expressing the sound pressure relative to the free-field sound pressure p_0 and screen effect and ground effect are separated as shown in Eq.(190). Allthough not indicated all variables in the equation is a function of the frequency. In this equation $p_{1,ff}/p_0$ is the effect of the screen in free space and the term in brackets is the effect of the ground in excess of the screen effect. The reason for denoting the diffracted sound pressure from source to receiver $p_{1,ff}$ in the screen effect part of the equation and p_1 in ground effect is that different equivalent sound speed profiles are used in the two cases. The linearization used to calculate $p_{1,ff}$ is independent of the position of the reflecting ground surfaces before and after the screen.

$$\frac{\hat{p}}{\hat{p}_0} = \frac{\hat{p}_{1,ff}}{\hat{p}_0} \left(1 + \hat{Q}_1 \frac{\hat{p}_2}{\hat{p}_1} + \hat{Q}_2 \frac{\hat{p}_3}{\hat{p}_1} + \hat{Q}_1 \hat{Q}_2 \frac{\hat{p}_4}{\hat{p}_1} \right) \tag{190}$$

If case of reduced efficiency of the ground reflection on the source or receiver side of the screen it may be necessary to modify Q_1 and Q_2. In Eq. (191) the modified values are denoted Q'_1 and Q'_2 and are obtained by multiplying the original values by a real number w_Q between 0 and 1. The value 1 indicates a fully efficient ground reflection while 0 indicates no reflection at all. The calculation of w_{Q1} and w_{Q2} will be described in the general model in Section 5.14.2. As mentioned above the term outside the brackets is the effect of the screen in free space and is denoted p_{SCR} while the term inside the brackets is the effect of the ground and is denoted p_G.

$$\frac{\hat{p}}{\hat{p}_0} = \frac{\hat{p}_{1,ff}}{\hat{p}_0} \left(1 + \hat{Q}'_1 \frac{\hat{p}_2}{\hat{p}_1} + \hat{Q}'_2 \frac{\hat{p}_3}{\hat{p}_1} + \hat{Q}'_1 \hat{Q}'_2 \frac{\hat{p}_4}{\hat{p}_1} \right) = \hat{p}_{SCR} \hat{p}_G$$
$$\textit{where} \quad \hat{Q}'_1 = w_{Q1} \hat{Q}_1 \quad \textit{and} \quad \hat{Q}'_2 = w_{Q2} \hat{Q}_2 \tag{191}$$

The first step is to determine the variables that have to be used to calculate the diffracted sound pressures $p_{1,ff}$, p_1, p_2, p_3 and p_4 by the auxiliary function *p2edge* as shown in Eq. (192). $Z_S(f)$ and $Z_R(f)$ are the impedance of the source and receiver side wedge face.

$$\hat{p}(f) = p2edge\left(f, \beta_1, \theta_{1S}, \theta_{1R}, \beta_2, \theta_{2S}, \theta_{2R}, \tau_S, \tau_M, \tau_R, R_S, R_M, R_R, \hat{Z}_S(f), \hat{Z}_R(f)\right) \quad \textbf{(192)}$$

To calculate the diffracted sound pressure the input variables in Eq. (192) which are defined in Section 5.7.4 have to be determined. The screen is defined by the diffracting edge $T_1 = (x_{T1},x_{T1})$ and $T_2 = (x_{T1},x_{T1})$, the start of the wedge $W_1 = (x_1,z_1)$ closest to source and the end of the wedge $W_2 = (x_2,z_2)$ closest to receiver. The ground segment is defined by the end points $P_{S1} = (x_{S1},z_{S1})$ and $P_{S2} = (x_{S2},z_{S2})$ and the ground impedance $Z_{G1}(f)$ on the source side of the screen and by the end points $P_{R1} = (x_{R1},z_{R1})$ and $P_{R2} = (x_{R2},z_{R2})$ and the ground impedance $Z_{G2}(f)$ on the receiver side of the screen.

The variables used to calculate $p_{1,ff}$ is determined according to Eqs. (193) through (195). d_{base} is defined in Eq. **(9)** and h''_{SCR} is by determined by Eq. **(22)**. When calculating $p_{1,ff}$ the equivalent linear sound speed profile is independent of the frequency.

$$\begin{aligned}
&(x'_{T1}, z'_{T1}, h_{SCR1}) = NormLine(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}, x_{T1}, z_{T1}) \\
&(x'_{T2}, z'_{T2}, h_{SCR2}) = NormLine(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}, x_{T2}, z_{T2}) \\
&d_{SCR1} = Length(x_{SGv}, z_{SGv}, x'_{T1}, z'_{T1}) \\
&d_{SCR2} = Length(x_{SGv}, z_{SGv}, x'_{T2}, z'_{T2}) - d_{SCR1} \\
&d_{SCR3} = d_{base} - d_{SCR2} - d_{SCR1} \\
&(\xi_S, c_{0S}, NA) = CalcEqSSP(h_{Sv,}, h''_{SCR}, z_0, A, B, C) \\
&(\tau_S, R_S, \Delta\theta_S, NA, d_{SZ,S})) = DirectRay(d_{SCR1}, h_{S,}, h_{SCR1}, \xi_S, c_{0S}) \\
&(\xi_M, c_{0M}, NA) = CalcEqSSP(h''_{SCR}, h''_{SCR}, z_0, A, B, C) \\
&(\tau_M, R_M, \Delta\theta_M, NA, NA)) = DirectRay(|d_{SCR2}|, h_{SCR1,}, h_{SCR2}, \xi_M, c_{0M}) \\
&(\xi_R, c_{0R}, NA) = CalcEqSSP(h_{Rv,}, h''_{SCR}, z_0, A, B, C) \\
&(\tau_R, R_R, \Delta\theta_R, NA, d_{SZ,R}) = DirectRay(d_{SCR3}, h_{R,}, h_{SCR2}, \xi_R, c_{0R})
\end{aligned} \quad \textbf{(193)}$$

The wedge angle β_1 and diffraction angles θ_{1S} and θ_{1R} of the first wedge (T_1) can now be determined by Eq. (194) on basis of the screen coordinates.

$$\beta_{11} = \arctan\left(\frac{z_1 - z_{T1}}{x_{T1} - x_1}\right) + \frac{\pi}{2}$$
$$\beta_{12} = \arctan\left(\frac{z_{T2} - z_{T1}}{x_{T2} - x_{T1}}\right) + \frac{\pi}{2}$$
$$\theta_{11} = \arctan\left(\frac{z_S - z_{T1}}{x_{T1} - x_S}\right) + \frac{\pi}{2} \qquad \textbf{(194)}$$
$$\theta_{12} = Max\left(\arctan\left(\frac{z_{T2} - z_{T1}}{x_{T2} - x_{T1}}\right), \arctan\left(\frac{z_R - z_{T1}}{x_R - x_{T1}}\right)\right)\arctan\left(\frac{z_{T2} - z_{T1}}{x_{T2} - x_{T1}}\right) + \frac{\pi}{2}$$
$$\beta_1 = 2\pi - \beta_{11} - \beta_{12}$$
$$\theta_{1S} = 2\pi - \theta_{11} - \beta_{12} - \Delta\theta_S$$
$$\theta_{1R} = \theta_{12} - \beta_{12} + \Delta\theta_M$$

The wedge angle β_2 and diffraction angles θ_{2S} and θ_{2R} of the second wedge (T_2) can be determined by Eq. (195) on basis of the screen coordinates.

$$\beta_{21} = \arctan\left(\frac{z_{T1} - z_{T2}}{x_{T2} - x_{T1}}\right) + \frac{\pi}{2}$$
$$\beta_{22} = \arctan\left(\frac{z_2 - z_{T2}}{x_2 - x_{T2}}\right) + \frac{\pi}{2}$$
$$\theta_{21} = Max\left(\arctan\left(\frac{z_{T1} - z_{T2}}{x_{T2} - x_{T1}}\right), \arctan\left(\frac{z_S - z_{T2}}{x_{T2} - x_S}\right)\right) + \frac{\pi}{2} \qquad \textbf{(195)}$$
$$\theta_{22} = \arctan\left(\frac{z_R - z_{T2}}{x_R - x_{T2}}\right) + \frac{\pi}{2}$$
$$\beta_2 = 2\pi - \beta_{21} - \beta_{22}$$
$$\theta_{2S} = 2\pi - \theta_{21} - \beta_{22} - \Delta\theta_M$$
$$\theta_{2R} = \theta_{22} - \beta_{22} + \Delta\theta_R$$

The numerical value of the screen effect $|p_{SCR}|$ is now determined by Eq. (196) where $p_{1,ff}(f)$ is calculated by Eq. (192) using the values of the input variables given in Eqs. (193) through (195). R_{SR} is the source-receiver distance

$$\left|\hat{p}_{SCR}(f)\right| = \left|\hat{p}_{1,ff}(f)\right| R_{SR} \qquad \textbf{(196)}$$

In the calculation of p_1 to p_4 the linearization of the sound speed profile used to determine the diffraction angles will still be independent of the frequency in the same way as described for $p_{1,ff}$ but the travel times and travel distances in the ground effect calculation will depend on the frequency as described in Section 5.5.3.

To calculate the sound pressures p_1 to p_4 in the ground attenuation part of Eq. (191) the first step is to determine the height h'_{S1} of the source S and the height h'_{R1} of the screen edge T above the terrain segment on the source side of the screen, and the distances d'_1 from S to T, d'_{11} from S to the start of the segment, and d'_{12} from S to the end of the segment measured along the terrain segment. This is done by the auxiliary function *SegmentVariables* described in Section 5.23.15 as shown in Eq. (197). In the same way the height h'_{S2} of the screen edge S and the height h'_{R2} of the receiver R above the terrain segment on the receiver side of the screen, and the distances d'_2 from T to R, d'_{21} from T to the start of the segment, and d'_{22} from T to the end of the segment measured along the terrain segment. This is also shown in Eq. (197).

$$\begin{aligned}(d'_1, h'_{S1}, h'_{R1}, d'_{11}, d'_{12}) &= SegmentVariables(x_S, z_S, x_{T1}, z_{T1}, x_{S1}, z_{S1}, x_{S2}, z_{S2})\\(d'_2, h'_{S2}, h'_{R2}, d'_{21}, d'_{22}) &= SegmentVariables(x_{T2}, z_{T2}, x_R, z_R, x_{R1}, z_{R1}, x_{R2}, z_{R2})\end{aligned} \qquad \textbf{(197)}$$

When calculating the sound pressure p_1 the diffraction angles are the same as used $p_{1,ff}$. When calculating the sound pressures p_2 to p_4 diffraction angles θ_{1Si} and θ_{2Ri} for the image source and receiver have to be determined as shown in Eq. (198). The β angles are the same as calculated in Eqs. (194) and (195). Due to numerical difficulties in strong upward refraction cases the image point angles θ_{11} and θ_{22} in Eq. (198) may become larger than corresponding angles of the direct ray defined in Eqs. (194) and (195). This may lead to erroneuos results and in such cases the image point angle shall be set equal to the direct ray angle.

$$\begin{aligned}
&(NA, NA, NA, NA, NA, \Delta\theta_{Si}, NA, NA) = ReflectedRay(d'_1, h'_{S1,}, h'_{R1}, \xi_S, c_{0S})\\
&(NA, NA, NA, NA, \Delta\theta_{Ri}, NA, NA, NA) = ReflectedRay(d'_2, h'_{S2,}, h'_{R2}, \xi_R, c_{0R})\\
&(x_{Si}, z_{Si}) = ImagePoint(x_{S1}, z_{S1}, x_{S2}, z_{S2}, x_S, z_S)\\
&(x_{Ri}, z_{Ri}) = ImagePoint(x_{R1}, z_{R1}, x_{R2}, z_{R2}, x_R, z_R)\\
&\theta_{11} = \arctan\left(\frac{z_{Si} - z_{T1}}{x_{T1} - x_{Si}}\right) + \frac{\pi}{2}\\
&\theta_{22} = \arctan\left(\frac{z_{Ri} - z_{T2}}{x_{Ri} - x_{T2}}\right) + \frac{\pi}{2}\\
&\theta_{1Si} = 2\pi - \theta_{11} - \beta_{12} - \Delta\theta_{Si}\\
&\theta_{2Ri} = \theta_{22} - \beta_{22} + \Delta\theta_{Ri}
\end{aligned} \qquad \textbf{(198)}$$

The travel times and travel distances used to calculate the sound pressures p_2 to p_4 are based on a frequency dependent linear sound speed profile and will therefore be a function of the frequency.

For the variables of the source side of the screen the modified frequency dependent equivalent linear sound speed profile is determined by the function *CalcEqSSPGround* described in Section 5.5.3 as shown in Eq. (199) for average refraction and for upper refraction (indicates by +).

$$\begin{aligned} &\left(\xi_S(f), c_{0S}(f), \bar{c}_S, \xi_S, c_{0S}\right) = CalcEqSSPGround\left(h'_{S1,}, h'_{R1}, \hat{Z}_{G1}(f), z_0, A, B, C\right) \\ &\left(\xi_{S+}(f), c_{0S+}(f), NA, NA, NA\right) = \\ &\qquad CalcEqSSPGround\left(h'_{S1,}, h'_{R1}, \hat{Z}_{G1}(f), z_0, A_+, B_+, C\right) \end{aligned} \quad \textbf{(199)}$$

The ray variables on the source side of the screen are determined for the direct ray and the reflected ray in Eq. (200) for average refraction and upper refraction using the procedures *DirectRay* and *ReflectedRay* described in Sections 5.5.4 and 5.5.5. NA indicates that a calculated variable is not used. If the calculation by *DirectRay* shows that the receiver is in a shadow zone ($\xi_S < 0$ and $d'_1 > 0.95\ d_{SZ,1}$ where $d_{SZ,1}$ is the distance to the shadow zone as defined in Section 5.5.4) calculations by ReflectedRay are not carried out. The variables τ, R, ψ_G, and Δτ are in the following equations of this section a function of the frequency.

$$\begin{aligned} &\left(\tau_{1S}, R_{1S}, NA, NA, d_{SZ,1}\right) = DirectRay\left(d'_1, h'_{S1,}, h'_{R1}, \xi_S(f), c_{0S}(f)\right) \\ &\left(\tau_{1S+}, NA, NA, NA, NA\right) = DirectRay\left(d'_1, h'_{S1,}, h'_{R1}, \xi_{S+}(f), c_{0S+}(f)\right) \\ &\left(\tau_{2S}, R_{2S}, NA, NA, NA, NA, \psi_{GS}, NA\right) = \\ &\qquad ReflectedRay\left(d'_1, h'_{S1,}, h'_{R1}, \xi_S(f), c_{0S}(f)\right) \\ &\left(\tau_{2S+}, NA, NA, NA, NA, NA, NA, NA\right) = \\ &\qquad ReflectedRay\left(d'_1, h'_{S1,}, h'_{R1}, \xi_{S+}(f), c_{0S+}(f)\right) \end{aligned} \quad \textbf{(200)}$$

The travel time differences $\Delta\tau_S$ and $\Delta\tau_{S+}$ for average and upper refraction are determined by Eq. (201).

$$\begin{aligned} \Delta\tau_S &= TravelTimeDiff\,(\tau_{2S}, \tau_{1S}) \\ \Delta\tau_{S+} &= TravelTimeDiff\,(\tau_{2S+}, \tau_{1S+}) \end{aligned} \quad \textbf{(201)}$$

The spherical-wave reflection coefficent Q_1 for the terrain reflection on the source side of the screen is calculated by Eq. (202).

$$\hat{Q}_1 = \hat{Q}\left(f, \tau_{2S}, \psi_{GS}, \hat{Z}_{G1}\right) \quad \textbf{(202)}$$

For the variables of the receiver side of the screen the modified frequency dependent equivalent linear sound speed profile is determined by Eq. (203) for average refraction and for upper refraction (indicates by +).

$$\begin{aligned}&\left(\xi_R(f), c_{0R}(f), \bar{c}_R, \xi_R, c_{0R}\right) = CalcEqSSPGround\left(h'_{S2,}, h'_{R2}, \hat{Z}_{G2}(f), z_0, A, B, C\right)\\&\left(\xi_{R+}(f), c_{0R+}(f), NA, NA, NA\right) =\\&\qquad CalcEqSSPGround\left(h'_{S2,}, h'_{R2}, \hat{Z}_{G2}(f), z_0, A_+, B_+, C\right)\end{aligned} \tag{203}$$

The ray variables on the receiver side are determined for the direct ray and the reflected ray in Eq. (204) for average and upper refraction using the procedures *DirectRay* and *ReflectedRay* described in Sections 5.5.4 and 5.5.5. NA indicates that a calculated variable is not used. If the calculation by *DirectRay* shows that the receiver is in a shadow zone (ξ_R < 0 and $d'_2 > 0.95\, d_{SZ,2}$ where $d_{SZ,2}$ is the distance to the shadow zone as defined in Section 5.5.4) calculations by ReflectedRay are not carried out. The variables τ, R, ψ_G, and Δτ are in the following equations of this section a function of the frequency.

$$\begin{aligned}&\left(\tau_{1R}, R_{1R}, NA, NA, d_{SZ,2}\right) = DirectRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_R(f), c_{0R}(f)\right)\\&\left(\tau_{1R+}, NA, NA, NA, NA\right) = DirectRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_{R+}(f), c_{0R+}(f)\right)\\&\left(\tau_{2R}, R_{2R}, NA, NA, NA, NA, \psi_{GR}, NA\right) =\\&\qquad ReflectedRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_R(f), c_{0R}(f)\right)\\&\left(\tau_{2R+}, NA, NA, NA, NA, NA, NA, NA\right) =\\&\qquad ReflectedRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_{R+}(f), c_{0R+}(f)\right)\end{aligned} \tag{204}$$

The travel time differences $\Delta\tau_R$ and $\Delta\tau_{R+}$ for average and upper refraction are determined by Eq. (205).

$$\begin{aligned}\Delta\tau_R &= TravelTimeDiff\,(\tau_{2R}, \tau_{1R})\\\Delta\tau_{R+} &= TravelTimeDiff\,(\tau_{2R+}, \tau_{1R+})\end{aligned} \tag{205}$$

The spherical-wave reflection coefficent Q_2 for the terrain reflection on the receiver side of the screen is calculated by Eq. (206).

$$\hat{Q}_2 = \hat{Q}\left(f, \tau_{2R}, \psi_{GR}, \hat{Z}_{G2}\right) \tag{206}$$

If the size of terrain segment on the source and receiver side is not sufficient large the ground attenuation part $|p_G|$ of the propagation effect has to be corrected for the limited size of the segments. This is done by calculating the Fresnel-zone weights of each segment w_1 and w_2 as shown in Eq. (207). Subsequently the weights are modified when source or receiver is close to the extension of the segment. The modified weights are denoted w''_1 and w''_2. The modifiers r_{S1}, r_{R1}, r_{S2}, and r_{R2} are calculated as shown in Eq. **(208)** and **(209)**. If source or receiver is below the extension of the segment the product of the modifiers becomes 0 which eliminates the problem of the Fresnel-zone weights w_1 and w_2 being undefined in this case. The Fresnel-zone weights are used in the general model described in Section 5.13.2.

$$\begin{aligned}
&(w_1(f), NA, NA, NA, NA) = FresnelZoneW(d_1', h_{S1}', h_{R1}', d_{11}, d_{12}, 1/16\,\lambda, \xi_S, c_{0S})\\
&(w_2(f), NA, NA, NA, NA) = FresnelZoneW(d_2', h_{S2}', h_{R2}', d_{21}, d_{22}, 1/16\,\lambda, \xi_R, c_{0R})\\
&w_1''(f) = w_1(f) r_{S1} r_{R1}\\
&w_2''(f) = w_2(f) r_{S2} r_{R2}
\end{aligned} \qquad \mathbf{(207)}$$

$$\begin{aligned}
&h_{\max,1} = Min(0.0005(x_T - x_S), 0.2)\\
&h_1'' = Min(h_S, h_{\max,1})\\
&r_{S1} = \begin{cases} 1 & h_{S1}' \geq h_1'' \\ \dfrac{h_{S1}'}{h_1''} & 0 < h_{S1}' < h_1'' \\ 0 & h_{S1}' \leq 0 \end{cases}\\
&r_{R1} = \begin{cases} 1 & h_{R1}' \geq h_{\max,1} \\ \dfrac{h_{R1}'}{h_{\max,1}} & 0 < h_{R1}' < h_{\max,1} \\ 0 & h_{R1}' \leq 0 \end{cases}
\end{aligned} \qquad (208)$$

$$\begin{aligned}
&h_{\max,2} = Min(0.0005(x_R - x_T), 0.2)\\
&h_2'' = Min(h_R, h_{\max,2})\\
&r_{R2} = \begin{cases} 1 & h_{R2}' \geq h_2'' \\ \dfrac{h_{R2}'}{h_2''} & 0 < h_{R2}' < h_2'' \\ 0 & h_{R2}' \leq 0 \end{cases}\\
&r_{S2} = \begin{cases} 1 & h_{S2}' \geq h_{\max,2} \\ \dfrac{h_{S2}'}{h_{\max,2}} & 0 < h_{S2}' < h_{\max,2} \\ 0 & h_{S2}' \leq 0 \end{cases}
\end{aligned} \qquad (209)$$

If the propagation of the four rays in the image model was fully coherent the propagation effect could be determined by Eq. (191) but in order to take into account averaging and incoherent effects as described in Section 0, the coherence coefficient F_2, F_3, and F_4 describing the coherence between ray no. 2, 3, and 4 respectively and the direct ray have to be determined.

The coherence coefficient F_2 of ray no. 2 is calculated by Eq. (210) where the coherence coefficients F_f, $F_{\Delta\tau}$, F_c, and F_r are calculated as described in Section 0. ρ_1 is the transversal separation calculated by Eq. **(211)**, k_0 is the wave number at the ground and r_2 is the roughness of the source side terrain segment. In case of propagation through a scattering zone F_s is the coherence coefficient calculated as described in Section 5.19. Otherwise F_s = 1.

$$F_2(f) = F_f(f, \Delta\tau_S) F_{\Delta\tau}(f, \Delta\tau_S, \Delta\tau_{S+}) F_c\left(f, C_v^2, C_T^2, t_{mean}, \bar{c}_S, \rho_1, d_1'\right) F_r(k_0, \psi_{GS}, r_1) F_s(f) \quad \textbf{(210)}$$

$$\rho_1 = \frac{2h_{S1}' h_{R1}'}{h_{S1}' + h_{R1}'} \quad (211)$$

The coherence coefficient F_3 of ray no. 3 is calculated by Eq. (212) where the coherence coefficients F_f, $F_{\Delta\tau}$, F_c, and F_r are calculated as described in Section 0. ρ_2 is the transversal separation calculated by Eq. **(213)**, k_0 is the wave number at the ground and r_2 is the roughness of the receiver side terrain segment.

$$F_3(f) = F_f(f, \Delta\tau_R) F_{\Delta\tau}(f, \Delta\tau_R, \Delta\tau_{R+}) F_c\left(f, C_v^2, C_T^2, t_{mean}, \bar{c}_R, \rho_2, d_2'\right) F_r(k_0, \psi_{GR}, r_2) F_s(f) \quad \textbf{(212)}$$

$$\rho_2 = \frac{2h_{S2}' h_{R2}'}{h_{S2}' + h_{R2}'} \quad (213)$$

The coherence coefficient F_4 of ray no. 4 is calculated by Eq. (214).

$$\begin{aligned} F_4(f) = {} & F_f(f, \Delta\tau_S + \Delta\tau_R) F_{\Delta\tau}(f, \Delta\tau_S + \Delta\tau_R, \Delta\tau_{S+} + \Delta\tau_{R+}) \\ & F_c\left(f, C_v^2, C_T^2, t_{mean}, \bar{c}_S, \rho_1, d_1'\right) F_c\left(f, C_v^2, C_T^2, t_{mean}, \bar{c}_R, \rho_2, d_2'\right) \\ & F_r(k_0, \psi_{GS}, r_1) F_r(k_0, \psi_{GR}, r_2) F_s(f) \end{aligned} \quad \textbf{(214)}$$

Now the propagation effect can be determined by Eq. (215) if shadow zone effects occur neither on the source side of the screen nor on the receiver side.

$$\left|\hat{p}_G\right| = \sqrt{\begin{aligned} & \left|1 + F_2 \frac{w_{Q1}\hat{Q}_1 \hat{p}_2}{\hat{p}_1} + F_3 \frac{w_{Q2}\hat{Q}_2 \hat{p}_3}{\hat{p}_1} + F_4 \frac{w_{Q1}\hat{Q}_1 w_{Q2}\hat{Q}_2 \hat{p}_4}{\hat{p}_1}\right|^2 + \\ & \left(1 - F_2^2\right)\left|\frac{w_{Q1}\Re_1 \hat{p}_2}{\hat{p}_1}\right|^2 + \left(1 - F_3^2\right)\left|\frac{w_{Q2}\Re_2 \hat{p}_3}{\hat{p}_1}\right|^2 + \\ & \left(1 - F_4^2\right)\left|\frac{w_{Q1}\Re_1 w_{Q2}\Re_2 \hat{p}_4}{\hat{p}_1}\right|^2 \end{aligned}} \quad \textbf{(215)}$$

The incoherent reflection coefficients $\Re_1$ and $\Re_2$ in Eq. (215) are determined by Eq. (216).

$$\begin{aligned}\Re_1 &= \Re\left(f, \hat{Z}_{G1}\right)\\ \Re_2 &= \Re\left(f, \hat{Z}_{G2}\right)\end{aligned} \quad \textbf{(216)}$$

If d'$_1$ > 0.95d$_{SZ,1}$ and d'$_2$ ≤ 0.95d$_{SZ,2}$ shadow zone effects will occur on the source side of the screen and $|p_G|$ has to be calculated by Eq. (217) where $|p_G|^{Eq.215}$ indicates the value calculated by Eq. (215) with modified values of Q_1, p_2 and p_4.

$$\begin{aligned}&\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,1}(f)}{20}} \left|\hat{p}_G\right|^{Eq.215}\\ &where\\ &\Delta L_{SZ,1}(f) = ShadowZoneShielding\left(f, d_1', h_{S1}', h_{R1}', \xi_S, c_{0S}, d_{SZ,1}\right)\\ &\hat{Q}_1(f) = \hat{Q}\left(f, \tau_{1S}, 0, \hat{Z}_{G1}(f)\right)\\ &\hat{p}_2 = \hat{p}_1\\ &\hat{p}_4 = \hat{p}_3\end{aligned} \quad \textbf{(217)}$$

If d'$_2$ > 0.95d$_{SZ,2}$ and d'$_1$ ≤ 0.95d$_{SZ,1}$ shadow zone effects will occur on the receiver side of the screen and $|p_G|$ has to be calculated by Eq. (218) where $|p_G|^{Eq.215}$ indicates the value calculated by Eq. (215) with modified values of Q_2, p_3 and p_4.

$$\begin{aligned}&\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,2}(f)}{20}} \left|\hat{p}_G\right|^{Eq.215}\\ &where\\ &\Delta L_{SZ,2}(f) = ShadowZoneShielding\left(f, d_2', h_{S2}', h_{R2}', \xi_R, c_{0R}, d_{SZ,2}\right)\\ &\hat{Q}_2(f) = \hat{Q}\left(f, \tau_{1R}, 0, \hat{Z}_{G2}(f)\right)\\ &\hat{p}_3 = \hat{p}_1\\ &\hat{p}_4 = \hat{p}_2\end{aligned} \quad \textbf{(218)}$$

If d'$_1$ > 0.95d$_{SZ,1}$ and d'$_2$ > 0.95d$_{SZ,2}$ shadow zone effects will occur on both sides of the screen and $|p_G|$ has to be calculated by Eq. (219) where $|p_G|^{Eq.215}$ indicates the value calculated by Eq. (215) with modified values of Q_1, Q_2 ,p_2 , p_3, and p_4.

$$
\begin{aligned}
&\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,1}(f)}{20}} 10^{\frac{\Delta L_{SZ,2}(f)}{20}} \left|\hat{p}_G\right|^{Eq.215} \\
&where \\
&\Delta L_{SZ,1}(f) = ShadowZoneShielding\left(f, d_1', h_{S1}', h_{R1}', \xi_S, c_{0S}, d_{SZ,1}\right) \\
&\Delta L_{SZ,2}(f) = ShadowZoneShielding\left(f, d_2', h_{S2}', h_{R2}', \xi_R, c_{0R}, d_{SZ,2}\right) \\
&\hat{Q}_1(f) = \hat{Q}\left(f, \tau_{1S}, 0, \hat{Z}_{G1}(f)\right) \\
&\hat{Q}_2(f) = \hat{Q}\left(f, \tau_{1R}, 0, \hat{Z}_{G2}(f)\right) \\
&\hat{p}_4 = \hat{p}_1 \\
&\hat{p}_3 = \hat{p}_1 \\
&\hat{p}_2 = \hat{p}_1
\end{aligned}
\qquad \textbf{(219)}
$$

5.14.2 General Model

If the terrain has been found to contain one screen with two significant diffracting edge, the terrain effect is calculated by Sub-model 5 described in this section. An example of such a terrain is shown in Figure 23 where the three segments denoted 4-6 form a thick screen. The remaining five segments will be considered reflecting surfaces. Segments 1–3 will form the surface on the source side of the screen while segments 7–8 form the surface on the receiver side.

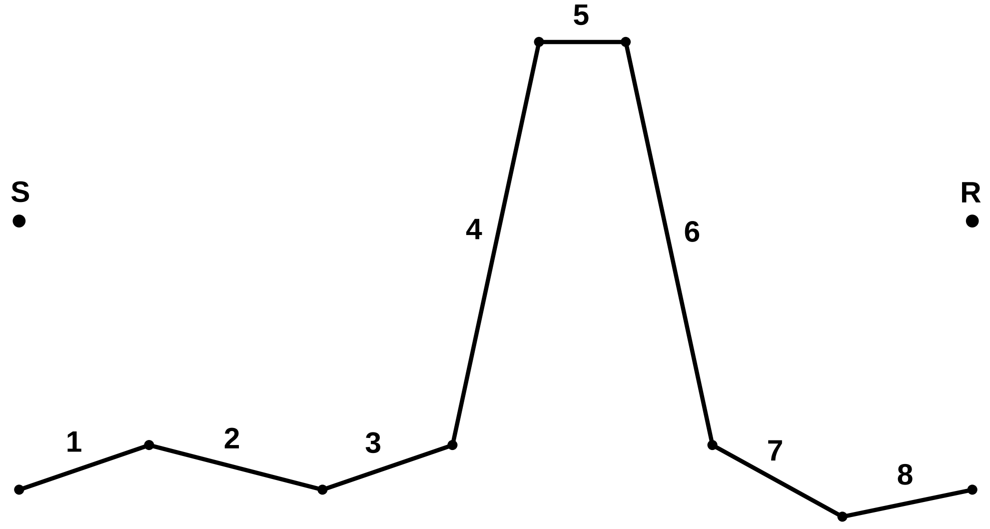

Figure 23
Example of a segmented terrain with one screen having two diffracting edges.

At this point it is assumed that the screen part of the terrain profile has already been identified and therefore that the number of segments before and after the screen which are considered reflecting segments are known. If the part of the input terrain forming the screen shape contains more than four ground points the screen shape is reduced to four points as described in Section 5.21.

The screen is defined by the following point numbers in the terrain profile (numbered 1 to N_{ts}+1 where N_{ts} is the number of segments in the terrain profile).

- iSCR,1 terrain point number closest to the source
- iSCR,2 terrain point number closest to the receiver
- iSCR,T1 terrain point number of the diffracting edge closest to source
- iSCR,T2 terrain point number of the diffracting edge closest to receiver

Therefore, the line segment representing the screen face closest to the source has the end coordinates $W_1 = (x_{iSCR,1}, z_{iSCR,1})$ and $T_1 = (x_{iSCR,T1}, z_{iSCR,T1})$ while the line segment representing the screen face closest to the receiver has the end coordinates $W_2 = (x_{iSCR,2}, z_{iSCR,2})$ and $T_2 = (x_{iSCR,T2}, z_{iSCR,T2})$. The line segment between T_1 and T_2 is the top of the screen. Possible terrain points between point no. iSCR,1 and iSCR,T1, between point no. iSCR,T1 and iSCR,T2, and between point no. iSCR,T2 and iSCR,2 are ignored. In this case the flow resistivity $\sigma_{iSCR,T1-1}$ is used as representative to the source side screen face and $\sigma_{iSCR,T2}$ is used as representative to the receiver side screen face.

The number of reflecting segments before the screen will therefore be iSCR,1-1 numbered from N_{S1} = 1 to N_{S2} = iSCR,1-1 while the number of reflecting segments after the screen will be N_{ts}+1-iSCR,2 numbered from N_{R1} = iSCR,2 to $N_{R2} = N_{ts}$.

The base model will now used for all combinations of segments of the source side (i_1 = N_{S1} to N_{S2}) and on the receiver side (i_2 = N_{R1} to N_{R2}). For each case of i1 and i2 the coordinates to use in the base model are:

- $T_1 = (x_{T1},z_{T1}) = (x_{iSCR,T1},z_{iSCR,T1})$
- $T_2 = (x_{T2},z_{T2}) = (x_{iSCR,T2},z_{iSCR,T2})$
- $W_1 = (x_1,z_1) = (x_{iSCR,1},z_{iSCR,1})$
- $W_2 = (x_2,x_2) = (x_{iSCR,2},z_{iSCR,2})$
- $Z_S = Z_{iSCR,T1-1}$
- $Z_R = Z_{iSCR,T2}$
- $P_{S1} = (x_{S1},z_{S1}) = (x_{i1},z_{i1})$

- $P_{S2} = (x_{S2},z_{S2}) = (x_{i1+1},z_{i1+1})$
- $Z_{G1} = Z_{i1}$
- $w''_1(f) = w''_{i1}(f)$
- $P_{R1} = (x_{R1},z_{R1}) = (x_{i2},z_{i2})$
- $P_{R2} = (x_{R2},z_{R2}) = (x_{i2+1},z_{i2+1})$
- $Z_{G2} = Z_{i2}$
- $w''_2(f) = w''_{i2}(f)$

The base model is used to calculate the screen effect $|p_{SCR}|$ and the ground effect $|p_G|$. The former will be identical for all combinations of terrain segment and has to be calculated only once while the latter will vary for each combination of terrain terrain segments and will be denoted $|p_{G,i1,i2}|$ for segment i1 on the source side of the screen and i2 on the receiver side.

Based on the sum of Fresnel-zone weights $w''_{i1}(f) = w''_1(f)$ and $w''_{i2}(f) = w''_2(f)$ on each side of the screen the Fresnel-zone weights are normalized as shown in Eq. (220) and the weights w_{Q1} and w_{Q2} used the base model are determined.

$$w_{1t}(f) = \sum_{i1=N_{S1}}^{N_{S2}} w''_{i1}(f)$$

$$w_{2t}(f) = \sum_{i2=N_{R1}}^{N_{R2}} w''_{i2}(f)$$

$$\Delta w_{1t}(f) = \begin{cases} w_{1t}(f) - 1 & if\ w_{1t}(f) > 1 \\ 0 & if\ w_{1t}(f) \le 1 \end{cases}$$

$$\Delta w_{2t}(f) = \begin{cases} w_{2t}(f) - 1 & if\ w_{2t}(f) > 1 \\ 0 & if\ w_{2t}(f) \le 1 \end{cases}$$

$$\Delta w_t(f) = \Delta w_{1t}(f) + \Delta w_{2t}(f)$$

$$w'_{i1}(f) = \begin{cases} \frac{w''_{i1}(f)}{w_{1t}(f)}\left(\frac{\Delta w_{1t}(f)}{\Delta w_t(f)} + 1\right) & if\ w_{1t}(f) > 1 \\ \frac{w''_{i1}(f)}{w_{1t}(f)} & if\ 0 < w_{1t}(f) \le 1 \\ 0 & if\ w_{1t}(f) = 0 \end{cases} \tag{220}$$

$$w'_{i2}(f) = \begin{cases} \frac{w''_{i2}(f)}{w_{2t}(f)}\left(\frac{\Delta w_{2t}(f)}{\Delta w_t(f)} + 1\right) & if\ w_{2t}(f) > 1 \\ \frac{w''_{i2}(f)}{w_{2t}(f)} & if\ 0 < w_{2t}(f) \le 1 \\ 0 & if\ w_{2t}(f) = 0 \end{cases}$$

$$w_{Q1}(f) = \begin{cases} 1 & if\ w_{1t}(f) \ge 1 \\ w_{1t}^2(f) & if\ w_{1t}(f) < 1 \end{cases}$$

$$w_{Q2}(f) = \begin{cases} 1 & if\ w_{2t}(f) \ge 1 \\ w_{2t}^2(f) & if\ w_{2t}(f) < 1 \end{cases}$$

Finally the sound pressure level ΔL_5 of Sub-model 5 for a terrain with one screen having two edges is calculated according to Eq. (221).

$$\Delta L_5 = 20\log\left(\left|\hat{p}_{SCR}(f)\right| \prod_{i1=N_{S1}}^{N_{R1}} \prod_{i2=N_{R1}}^{N_{R2}} \left|\hat{p}_{G,i1,i2}\right|^{w'_{i1}(f) w'_{i2}(f)} \right) \tag{221}$$

5.15 Sub-Model 6: Terrain with Two Screens

If the terrain has been found to contain two screens, each with one significant diffracting edge, the terrain effect is calculated by Sub-model 6 described in this section. The description has been divided into two parts. In Section 5.15.1 the base model is described where there is one reflecting surface in the regions before the first screen, after the second screen, and between the screens. In Section 0 the general model is described which can have any number of segments in each region.

5.15.1 Base Model

In the base model there is one reflecting surface in source region before the first wedge-shaped screen, in the receiver region after the second wedge-shaped screen, and in the middle region between the two screens as shown in Figure 24. The first wedge is defined by the points $W_{11,}$ T_1, and W_{12} and the second wedge by the points $W_{21,}$ T_2, and W_{22}. The reflecting surfaces are defined by $P_{S1}P_{S2}$ in the source region, by $P_{M1}P_{M2}$ in the middle region of the screen and by $P_{R1}P_{R2}$ in the receiver region. S_i and R_i are the image of the source S and receiver R reflected in the source and receiver segment, respectively. T_{1i} and T_{2i} are the image of T_1 and T_2 reflected in the middle segment, respectively. The rays shown in the figure are straight line rays corresponding to a non-refracting atmosphere. For refracting atmospheres the rays will be arcs of circles instead as described in Section 5.5.

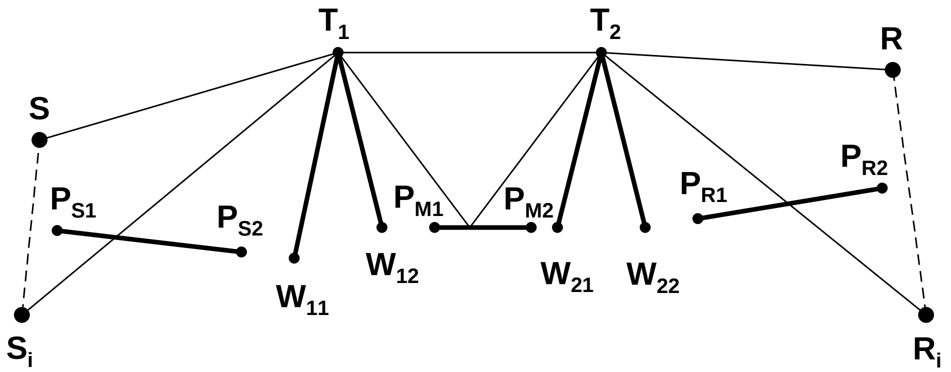

Figure 24
Definition of geometry for the base model.

In the base model the so-called the image method is used where the sound pressure at the receiver is the sum of coherent contributions from eights rays as expressed by Eq. (222). p_1 is the diffracted sound pressure at the receiver from the source over the top of the screens. p_2 is the diffracted sound pressure at the receiver from the image source, p_3 is the diffracted sound pressure at the image receiver from the source and p_4 is the diffracted sound pressure at the image receiver from the image source. p_5 to p_8 correspond to p_1 to p_4 but the rays are in this case reflected by the ground segment between the screens. The spherical wave reflection coefficient Q_1 in the source region is calculated by replacing R with T_1. Similarly, Q_3 in the receiver region is calculated by replacing S with T_2 and Q_2 in the middle region is calculated by replacing S and R with T_1 and T_2.

$$\hat{p} = \hat{p}_1 + \hat{Q}_1 \hat{p}_2 + \hat{Q}_3 \hat{p}_3 + \hat{Q}_1 \hat{Q}_3 \ \hat{p}_4 + \hat{Q}_2 \hat{p}_5 + \hat{Q}_1 \hat{Q}_2 \hat{p}_6 + \hat{Q}_2 \hat{Q}_3 \hat{p}_7 + \hat{Q}_1 \hat{Q}_2 \hat{Q}_3 \ \hat{p}_8 \qquad \textbf{(222)}$$

In order to apply the Fresnel-zone interpolation principle described in Section 5.8 the propagation effect is obtained by expressing the sound pressure relative to the free-field sound pressure p_0 and screen effect and ground effect are separated as shown in Eq. (223). Allthough not indicated all variables in the equation are a function of the frequency. In this equation $p_{1,ff}/p_0$ is the effect of the screens in free space and the term in brackets is the effect of the ground in excess of the screen effect. The reason for denoting the diffracted sound pressure from source to receiver $p_{1,ff}$ in the screen effect part of the equation and p_1 in ground effect is that different equivalent sound speed profiles are used in the two cases. The linearization used to calculate $p_{1,ff}$ is independent of the position of the reflecting ground surfaces.

$$\frac{\hat{p}}{\hat{p}_0} = \frac{\hat{p}_{1,ff}}{\hat{p}_0} \left(\begin{array}{l} 1 + \hat{Q}_1 \dfrac{\hat{p}_2}{\hat{p}_1} + \hat{Q}_3 \dfrac{\hat{p}_3}{\hat{p}_1} + \hat{Q}_1 \hat{Q}_3 \dfrac{\hat{p}_4}{\hat{p}_1} + \hat{Q}_2 \dfrac{\hat{p}_5}{\hat{p}_1} \\ + \hat{Q}_1 \hat{Q}_2 \dfrac{\hat{p}_6}{\hat{p}_1} + \hat{Q}_2 \hat{Q}_3 \dfrac{\hat{p}_7}{\hat{p}_1} + \hat{Q}_1 \hat{Q}_2 \hat{Q}_3 \dfrac{\hat{p}_8}{\hat{p}_1} \end{array} \right) \qquad \textbf{(223)}$$

If case of reduced efficiency of the ground reflection on the source or receiver side of the screen it may be necessary to modify Q_1 , Q_2 and Q_3. In Eq. (224) the modified values are denoted Q'_1, Q'_2 and Q'_3 and are obtained by multiplying the original values by a real number w_Q between 0 and 1. The value 1 indicates a fully efficient ground reflection while 0 indicates no reflection at all. The calculation of w_{Q1}, w_{Q1} and w_{Q3} will be described in the general model in Section 0. As mentioned above the term outside the brackets is the effect of the screen in free space and is denoted p_{SCR} while the term inside the brackets is the effect of the ground and is denoted p_G.

$$\frac{\hat{p}}{\hat{p}_0} = \frac{\hat{p}_{1,ff}}{\hat{p}_0}\left(\begin{matrix} 1+\hat{Q}_1'\frac{\hat{p}_2}{\hat{p}_1}+\hat{Q}_2'\frac{\hat{p}_3}{\hat{p}_1}+\hat{Q}_1'\hat{Q}_2'\frac{\hat{p}_4}{\hat{p}_1}+\hat{Q}_2'\frac{\hat{p}_5}{\hat{p}_1} \\ +\hat{Q}_1'\hat{Q}_2'\frac{\hat{p}_6}{\hat{p}_1}+\hat{Q}_2'\hat{Q}_3'\frac{\hat{p}_7}{\hat{p}_1}+\hat{Q}_1'\hat{Q}_2'\hat{Q}_3'\frac{\hat{p}_8}{\hat{p}_1}\end{matrix}\right) = \hat{p}_{SCR}\hat{p}_G$$

where **(224)**

$$\hat{Q}_1' = w_{Q1}\hat{Q}_1$$
$$\hat{Q}_2' = w_{Q2}\hat{Q}_2$$
$$\hat{Q}_3' = w_{Q3}\hat{Q}_3$$

The first step is to determine the variables that have to be used to calculate the diffracted sound pressures $p_{1,ff}$, p_1, p_2, p_3, p_4, p_5, p_6, p_7 and p_8 by the auxiliary function *p2wedge* as shown in Eq. (225). $Z_{1S}(f)$, $Z_{1R}(f)$, $Z_{2S}(f)$ and $Z_{2R}(f)$ are the impedancees of the source and receiver side wedge face of the first and second screen, respectively.

$$\hat{p}(f) = p2wedge\left(\begin{matrix} f,\beta_1,\theta_{1S},\theta_{1R},\beta_2,\theta_{2S},\theta_{2R}, \\ \tau_S,\tau_M,\tau_R,R_S,R_M,R_R,\hat{Z}_{1S}(f),\hat{Z}_{1R}(f),\hat{Z}_{2S}(f),\hat{Z}_{2R}(f)\end{matrix}\right) \quad \textbf{(225)}$$

To calculate the diffracted sound pressure the input variables in Eq. (225) which are defined in Section 5.7.3 have to be determined. The first wedge-shaped screen are defined by the diffracting edge $T_1 = (x_{T1},z_{T1})$, the start of the wedge $W_{11} = (x_{11},z_{11})$ closest to source and the end of the wedge $W_{12} = (x_{12},z_{12})$ closest to receiver. The second wedge-shaped screen are defined by the diffracting edge $T_2 = (x_{T2},z_{T2})$, the start of the wedge $W_{21} = (x_{21},z_{21})$ closest to source and the end of the wedge $W_{22} = (x_{22},z_{22})$ closest to receiver.The source region ground segment is defined by the end points $P_{S1} = (x_{S1},z_{S1})$ and $P_{S2} = (x_{S2},z_{S2})$ and the ground impedance $Z_{G1}(f)$, the middle region ground segment by the end points $P_{M1} = (x_{M1},z_{M1})$ and $P_{M2} = (x_{M2},z_{M2})$ and the ground impedance $Z_{G2}(f)$, and the receiver region ground segment by the end points $P_{R1} = (x_{R1},z_{R1})$ and $P_{R2} = (x_{R2},z_{R2})$ and the ground impedance $Z_{G3}(f)$.

The variables used to calculate $p_{1,ff}$ is determined according to Eqs. (226) to (228). h''_{SCR} is determined by Eq. **(22)**. When calculating $p_{1,ff}$ the equivalent linear sound speed profile is independent of the frequency.

$$
\begin{aligned}
&(x'_{T1}, z'_{T1}, h_{SCR1}) = NormLine(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}, x_{T1}, z_{T1}) \\
&(x'_{T2}, z'_{T2}, h_{SCR2}) = NormLine(x_{SGv}, z_{SGv}, x_{RGv}, z_{RGv}, x_{T2}, z_{T2}) \\
&d_{SCR1} = Length(x_{SGv}, z_{SGv}, x'_{T1}, z'_{T1}) \\
&d_{SCR2} = Length(x'_{T1}, z'_{T1}, x'_{T2}, z'_{T2}) \\
&d_{SCR3} = Length(x'_{T2}, z'_{T2}, x_{RGv}, z_{RGv}) \\
&(\xi_S, c_{0S}, NA) = CalcEqSSP(h_{Sv,}, h''_{SCR}, z_0, A, B, C) \\
&(\tau_S, R_S, \Delta\theta_S, NA, d_{SZ,S})) = DirectRay(d_{SCR1}, h_{S,}, h_{SCR1}, \xi_S, c_{0S}) \\
&(\xi_M, c_{0M}, NA) = CalcEqSSP(h''_{SCR}, h''_{SCR}, z_0, A, B, C) \\
&(\tau_M, R_M, \Delta\theta_M, NA, d_{SZ,M})) = DirectRay(d_{SCR2}, h_{SCR1,}, h_{SCR2}, \xi_M, c_{0M}) \\
&(\xi_R, c_{0R}, NA) = CalcEqSSP(h_{Rv,}, h''_{SCR}, z_0, A, B, C) \\
&(\tau_R, R_R, \Delta\theta_R, NA, d_{SZ,R}) = DirectRay(d_{SCR3}, h_{R,}, h_{SCR2}, \xi_R, c_{0R})
\end{aligned}
\qquad \textbf{(226)}
$$

The wedge angle β_1 and diffraction angles θ_{1S} and θ_{1R} can now be determined by Eq. (227) on basis of the wedge coordinates of the first screen.

$$
\begin{aligned}
&\beta_{11} = \arctan\left(\frac{z_{11} - z_{T1}}{x_{T1} - x_{11}}\right) + \frac{\pi}{2} \\
&\beta_{12} = \arctan\left(\frac{z_{12} - z_{T1}}{x_{12} - x_{T1}}\right) + \frac{\pi}{2} \\
&\theta_{11} = \arctan\left(\frac{z_S - z_{T1}}{x_{T1} - x_S}\right) + \frac{\pi}{2} \\
&\theta_{12} = \arctan\left(\frac{z_R - z_{T1}}{x_R - x_{T1}}\right) + \frac{\pi}{2} \\
&\beta_1 = 2\pi - \beta_{11} - \beta_{12} \\
&\theta_{1S} = 2\pi - \theta_{11} - \beta_{12} - \Delta\theta_S \\
&\theta_{1R} = \theta_{12} - \beta_{12} + \Delta\theta_M
\end{aligned}
\qquad \textbf{(227)}
$$

The wedge angle β_2 and diffraction angles θ_{2S} and θ_{2R} can now be determined by Eq. (228) on basis of the wedge coordinates of the first screen.

$$\begin{aligned}
\beta_{21} &= \arctan\left(\frac{z_{21}-z_{T2}}{x_{T2}-x_{21}}\right)+\frac{\pi}{2} \\
\beta_{22} &= \arctan\left(\frac{z_{22}-z_{T2}}{x_{22}-x_{T2}}\right)+\frac{\pi}{2} \\
\theta_{21} &= \arctan\left(\frac{z_{S}-z_{T2}}{x_{T2}-x_{S}}\right)+\frac{\pi}{2} \\
\theta_{22} &= \arctan\left(\frac{z_{R}-z_{T2}}{x_{R}-x_{T2}}\right)+\frac{\pi}{2} \\
\beta_{2} &= 2\pi-\beta_{21}-\beta_{22} \\
\theta_{2S} &= 2\pi-\theta_{21}-\beta_{22}-\Delta\theta_{M} \\
\theta_{2R} &= \theta_{22}-\beta_{22}+\Delta\theta_{R}
\end{aligned} \qquad \textbf{(228)}$$

The numerical value of the screen effect $|p_{SCR}|$ is now determined by Eq. (229) where $p_{1,ff}(f)$ is calculated by Eq. (225) using the values of the input variables given in Eqs. (226) through (228). R_{SR} is the source-receiver distance

$$\left|\hat{p}_{SCR}(f)\right| = \left|\hat{p}_{1,ff}(f)\right| R_{SR} \qquad \textbf{(229)}$$

In the calculation of p_1 to p_8 the linearization of the sound speed profile used to determine the diffraction angles will still be independent of the frequency in the same way as described for $p_{1,ff}$ but the travel times and travel distances in the ground effect calculation will depend on the frequency as described in Section 5.5.3.

To calculate the sound pressures p_1 to p_8 in the ground attenuation part of Eq. (224) the first step is to determine the height h'_{S1} of the source S and the height h'_{R1} of the screen edge T_1 above the terrain segment on the source side of the first screen and the distances d'_1 from S to T_1, d'_{11} from S to the start of the segment, and d'_{12} from S to the end of the segment measured along the terrain segment. This is done by the auxiliary function *SegmentVariables* described in Section 5.23.15 as shown in Eq. (230). In the same way the height h'_{S2} of the screen edge T_1 and the height h'_{R2} of the screen edge T_2 above the terrain segment between the screens and the distances d'_2 from T_1 to T_2, d'_{21} from T_1 to the start of the segment, and d'_{22} from T_1 to the end of the segment measured along the terrain segment. Finally, the height h'_{S3} of the screen edge T_2 and the height h'_{R3} of the receiver R above the terrain segment on the receiver side of the second screen, and the distances d'_3 from T_2 to R, d'_{31} from T_2 to the start of the segment, and d'_{32} from T_2 to the end of the segment measured along the terrain segment. This is also shown in Eq. (230).

$$\begin{aligned}
&(d'_1, h'_{S1}, h'_{R1}, d'_{11}, d'_{12}) = SegmentVariables(x_S, z_S, x_{T1}, z_{T1}, x_{S1}, z_{S1}, x_{S2}, z_{S2}) \\
&(d'_2, h'_{S2}, h'_{R2}, d'_{21}, d'_{22}) = SegmentVariables(x_{T1}, z_{T1}, x_{T2}, z_{T2}, x_{M1}, z_{M1}, x_{M2}, z_{M2}) \\
&(d'_3, h'_{S3}, h'_{R3}, d'_{31}, d'_{32}) = SegmentVariables(x_{T2}, z_{T2}, x_R, z_R, x_{R1}, z_{R1}, x_{R2}, z_{R2})
\end{aligned} \qquad \textbf{(230)}$$

When calculating the sound pressure p_1 the diffraction angles are the same as used $p_{1,\mathrm{ff}}$. When calculating the sound pressures p_2 to p_8 diffraction angles θ_{Si} and θ_{M1i} of the first screen for the image source and image screen top T'$_2$ have to be determined as shown in Eq. (231). The angles β_1, β_{11}, and β_{12} are the same as calculated in Eq. (227). Due to numerical difficulties in strong upward refraction cases the image point angles θ_1 and θ_2 in Eq. (231) may become larger than corresponding angles of the direct ray defined in Eq. (227). This may lead to erroneuos results and in such cases the image point angle shall be set equal to the direct ray angle.

$$\begin{aligned}
&(NA, NA, NA, NA, NA, \Delta\theta_{Si}, NA, NA) = ReflectedRay(d'_1, h'_{S1,}, h'_{R1}, \xi_S, c_{0S}) \\
&(NA, NA, NA, NA, \Delta\theta_{Mi}, NA, NA, NA) = ReflectedRay(d'_2, h'_{S2,}, h'_{R2}, \xi_M, c_{0M}) \\
&(x_{Si}, z_{Si}) = ImagePoint(x_{S1}, z_{S1}, x_{S2}, z_{S2}, x_S, z_S) \\
&(x_{Mi}, z_{Mi}) = ImagePoint(x_{M1}, z_{M1}, x_{M2}, z_{M2}, x_{T2}, z_{T2}) \\
&\theta_1 = \arctan\left(\frac{z_{Si} - z_{T1}}{x_{T1} - x_{Si}}\right) + \frac{\pi}{2} \\
&\theta_2 = \arctan\left(\frac{z_{Mi} - z_{T1}}{x_{Mi} - x_{T1}}\right) + \frac{\pi}{2} \\
&\theta_{Si} = 2\pi - \theta_1 - \beta_2 - \Delta\theta_{Si} \\
&\theta_{M1i} = \theta_2 - \beta_2 + \Delta\theta_{Mi}
\end{aligned} \qquad \textbf{(231)}$$

For the second screen the diffraction angles θ_{M2i} and θ_{Ri} for the image screen top T'$_1$ and the image receiver have to be determined as shown in Eq. (232). The angles β_2, β_{21}, and β_{22} are the same as calculated in Eq. (228). Due to numerical difficulties in strong upward refraction cases the image point angles θ_1 and θ_2 in Eq. (232) may become larger than corresponding angles of the direct ray defined in Eq. (228). This may lead to erroneuos results and in such cases the image point angle shall be set equal to the direct ray angle.

$$
\begin{aligned}
&(NA, NA, NA, NA, NA, \Delta\theta_{Mi}, NA, NA) = ReflectedRay\left(d_2', h_{S2,}', h_{R2}', \xi_M, c_{0M}\right)\\
&(NA, NA, NA, NA, \Delta\theta_{Ri}, NA, NA, NA) = ReflectedRay\left(d_3', h_{S3,}', h_{R3}', \xi_R, c_{0R}\right)\\
&(x_{Mi}, z_{Mi}) = ImagePoint(x_{M1}, z_{M1}, x_{M2}, z_{M2}, x_{T1}, z_{T1})\\
&(x_{Ri}, z_{Ri}) = ImagePoint(x_{R1}, z_{R1}, x_{R2}, z_{R2}, x_R, z_R)\\
&\theta_1 = \arctan\left(\frac{z_{Mi} - z_{T2}}{x_{T2} - x_{Mi}}\right) + \frac{\pi}{2}\\
&\theta_2 = \arctan\left(\frac{z_{Ri} - z_{T2}}{x_{Ri} - x_{T2}}\right) + \frac{\pi}{2}\\
&\theta_{M2i} = 2\pi - \theta_1 - \beta_2 - \Delta\theta_{Mi}\\
&\theta_{Ri} = \theta_2 - \beta_2 + \Delta\theta_{Ri}
\end{aligned}
\tag{232}
$$

The travel times and travel distances used to calculate the sound pressures p_2 to p_8 are based on a frequency dependent linear sound speed profile and will therefore be a function of the frequency.

For the variables of the source side of the first screen the modified frequency dependent equivalent linear sound speed profile is determined by the function *CalcEqSSPGround* described in Section 5.5.3 as shown in Eq. (233) for average refraction and for upper refraction (indicates by +).

$$
\begin{aligned}
&(\xi_S(f), c_{0S}(f), \bar{c}_S, \xi_S, c_{0S}) = CalcEqSSPGround\left(h_{S1,}', h_{R1}', \hat{Z}_{G1}(f), z_0, A, B, C\right)\\
&(\xi_{S+}(f), c_{0S+}(f), NA, NA, NA) =\\
&\qquad CalcEqSSPGround\left(h_{S1,}', h_{R1}', \hat{Z}_{G1}(f), z_0, A_+, B_+, C\right)
\end{aligned}
\tag{233}
$$

The ray variables on the source side of the first screen are determined for the direct ray and the reflected ray in Eq. (234) for average refraction and upper refraction using the procedures *DirectRay* and *ReflectedRay* described in Sections 5.5.4 and 5.5.5. NA indicates that a calculated variable is not used. If the calculation by *DirectRay* shows that the screen edge T_2 is in a shadow zone ($\xi_S < 0$ and $d'_1 > 0.95\, d_{SZ,1}$ where $d_{SZ,1}$ is the distance to the shadow zone as defined in Section 5.5.4) calculations by *ReflectedRay* are not carried out. The variables τ, R, ψ_G, and $\Delta\tau$ are in the following equations of this section a function of the frequency.

$$\begin{aligned}
&(\tau_{1S}, R_{1S}, NA, NA, d_{SZ,1}) = DirectRay(d_1', h_{S1,}', h_{R1}', \xi_S(f), c_{0S}(f)) \\
&(\tau_{1S+}, NA, NA, NA, NA) = DirectRay(d_1', h_{S1,}', h_{R1}', \xi_{S+}(f), c_{0S+}(f)) \\
&(\tau_{2S}, R_{2S}, NA, NA, NA, NA, \psi_{GS}, NA) = \\
&\qquad ReflectedRay(d_1', h_{S1,}', h_{R1}', \xi_S(f), c_{0S}(f)) \\
&(\tau_{2S+}, NA, NA, NA, NA, NA, NA, NA) = \\
&\qquad ReflectedRay(d_1', h_{S1,}', h_{R1}', \xi_{S+}(f), c_{0S+}(f))
\end{aligned} \tag{234}$$

The travel time differences $\Delta\tau_S$ and $\Delta\tau_{S+}$ for average and upper refraction are determined by Eq. (235).

$$\begin{aligned}
\Delta\tau_S &= TravelTimeDiff(\tau_{2S}, \tau_{1S}) \\
\Delta\tau_{S+} &= TravelTimeDiff(\tau_{2S+}, \tau_{1S+})
\end{aligned} \tag{235}$$

The spherical-wave reflection coefficent Q_1 for the terrain reflection on the source side of the screen is calculated by Eq. (236).

$$\hat{Q}_1 = \hat{Q}(f, \tau_{2S}, \psi_{GS}, \hat{Z}_{G1}) \tag{236}$$

For the variables between the two screens the modified frequency dependent equivalent linear sound speed profile is determined by the function *CalcEqSSPGround* described in Section 5.5.3 as shown in Eq. 237 for average refraction and for upper refraction (indicates by +).

$$\begin{aligned}
&(\xi_M(f), c_{0M}(f), \bar{c}_M, \xi_M, c_{0M}) = \\
&\qquad CalcEqSSPGround(h_{S2,}', h_{R2}', \hat{Z}_{G2}(f), z_0, A, B, C) \\
&(\xi_{M+}(f), c_{0M+}(f), NA, NA, NA) = \\
&\qquad CalcEqSSPGround(h_{S2,}', h_{R2}', \hat{Z}_{G2}(f), z_0, A_+, B_+, C)
\end{aligned} \tag{237}$$

The ray variables between the two screens are determined for the direct ray and the reflected ray in Eq. (238) for average and upper refraction using the procedures *DirectRay* and *ReflectedRay* described in Sections 5.5.4 and 5.5.5. NA indicates that a calculated variable is not used. If the calculation by *DirectRay* shows that the receiver is in a shadow zone ($\xi_M < 0$ and $d'_2 > 0.95\, d_{SZ,2}$ where $d_{SZ,2}$ is the distance to the shadow zone as defined in Section 5.5.4) calculations by *ReflectedRay* are not carried out. The variables τ, R, ψ_G, and $\Delta\tau$ are in the following equations of this section a function of the frequency.

$$
\begin{aligned}
&\left(\tau_{1M}, R_{1M}, NA, NA, d_{SZ,2}\right) = DirectRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_M(f), c_{0M}(f)\right) \\
&\left(\tau_{1M+}, NA, NA, NA, NA\right) = DirectRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_{M+}(f), c_{0M+}(f)\right) \\
&\left(\tau_{2M}, R_{2M}, NA, NA, NA, NA, \psi_{GM}, NA\right) = \\
&\qquad ReflectedRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_M(f), c_{0M}(f)\right) \\
&\left(\tau_{2M+}, NA, NA, NA, NA, NA, NA, NA\right) = \\
&\qquad ReflectedRay\left(d'_2, h'_{S2,}, h'_{R2}, \xi_{M+}(f), c_{0M+}(f)\right)
\end{aligned} \tag{238}
$$

The travel time differences $\Delta\tau_M$ and $\Delta\tau_{M+}$ for average and upper refraction are determined by Eq. (239).

$$
\begin{aligned}
\Delta\tau_M &= TravelTimeDiff\,(\tau_{2M}, \tau_{1M}) \\
\Delta\tau_{M+} &= TravelTimeDiff\,(\tau_{2M+}, \tau_{1M+})
\end{aligned} \tag{239}
$$

The spherical-wave reflection coefficent Q_2 for the terrain reflection on the receiver side of the screen is calculated by Eq. (240).

$$
\hat{Q}_2 = \hat{Q}\left(f, \tau_{2M}, \psi_{GM}, \hat{Z}_{G2}\right) \tag{240}
$$

For the variables of the receiver side of the second screen the modified frequency dependent equivalent linear sound speed profile is determined by Eq. (241) for average refraction and for upper refraction (indicates by +).

$$
\begin{aligned}
&\left(\xi_R(f), c_{0R}(f), \bar{c}_R, \xi_R, c_{0R}\right) = CalcEqSSPGround\left(h'_{S3,}, h'_{R3}, \hat{Z}_{G3}(f), z_0, A, B, C\right) \\
&\left(\xi_{R+}(f), c_{0R+}(f), NA, NA, NA\right) = \\
&\qquad CalcEqSSPGround\left(h'_{S3,}, h'_{R3}, \hat{Z}_{G3}(f), z_0, A_+, B_+, C\right)
\end{aligned} \tag{241}
$$

The ray variables on the receiver side are determined for the direct ray and the reflected ray in Eq. (242) for average and upper refraction using the procedures *DirectRay* and *ReflectedRay* described in Sections 5.5.4 and 5.5.5. NA indicates that a calculated variable is not used. If the calculation by *DirectRay* shows that the receiver is in a shadow zone (ξ_R < 0 and d'_3 > 0.95 $d_{SZ,3}$ where $d_{SZ,3}$ is the distance to the shadow zone as defined in Section 5.5.4) calculations by *ReflectedRay* are not carried out. The variables τ, R, ψ_G, and $\Delta\tau$ are in the following equations of this section a function of the frequency.

$$
\begin{aligned}
&(\tau_{1R}, R_{1R}, NA, NA, d_{SZ,3}) = DirectRay(d'_3, h'_{S3,}, h'_{R3}, \xi_R(f), c_{0R}(f)) \\
&(\tau_{1R+}, NA, NA, NA, NA) = DirectRay(d'_3, h'_{S3,}, h'_{R3}, \xi_{R+}(f), c_{0R+}(f)) \\
&(\tau_{2R}, R_{2R}, NA, NA, NA, NA, \psi_{GR}, NA) = \\
&\qquad ReflectedRay(d'_3, h'_{S3,}, h'_{R3}, \xi_R(f), c_{0R}(f)) \\
&(\tau_{2R+}, NA, NA, NA, NA, NA, NA, NA) = \\
&\qquad ReflectedRay(d'_3, h'_{S3,}, h'_{R3}, \xi_{R+}(f), c_{0R+}(f))
\end{aligned}
\tag{242}
$$

The travel time differences $\Delta\tau_R$ and $\Delta\tau_{R+}$ for average and upper refraction are determined by Eq. (243).

$$
\begin{aligned}
\Delta\tau_R &= TravelTimeDiff(\tau_{2R}, \tau_{1R}) \\
\Delta\tau_{R+} &= TravelTimeDiff(\tau_{2R+}, \tau_{1R+})
\end{aligned}
\tag{243}
$$

The spherical-wave reflection coefficent Q_3 for the terrain reflection on the receiver side of the screen is calculated by Eq. (244).

$$
\hat{Q}_3 = \hat{Q}(f, \tau_{2R}, \psi_{GR}, \hat{Z}_{G3})
\tag{244}
$$

If the size of terrain segment on the source and receiver side is not sufficient large the ground attenuation part $|p_G|$ of the propagation effect has to be corrected for the limited size of the segments. This is done by calculating the Fresnel-zone weights of each segment w_1, w_2 and w_3 as shown in Eq. (245). Subsequently the weights are modified when source or receiver is close to the extension of the segment. The modified weights are denoted w''_1, w''_2 and w''_3. The modifiers r_{S1}, r_{R1}, r_{S2}, r_{R2}, r_{S3}, and r_{R3} are calculated as shown in Eqs. (246) to (248). If source or receiver is below the extension of the segment the product of the modifiers becomes 0 which eliminates the problem of the Fresnel-zone weights w_1, w_2 and w_3 being undefined in this case. The Fresnel-zone weights are used in the general model described in Section 0.

$$
\begin{aligned}
&(w_1(f), na, na, na, na) = FresnelZoneW(d'_1, h'_{S1}, h'_{R1}, d_{11}, d_{12}, 1/16\,\lambda, \xi_S, c_{0S}) \\
&(w_2(f), na, na, na, na) = FresnelZoneW(d'_2, h'_{S2}, h'_{R2}, d_{21}, d_{22}, 1/16\,\lambda, \xi_M, c_{0M}) \\
&(w_3(f), na, na, na, na) = FresnelZoneW(d'_3, h'_{S3}, h'_{R3}, d_{31}, d_{32}, 1/16\,\lambda, \xi_R, c_{0R}) \\
&w''_1(f) = w_1(f) r_{S1} r_{R1} \\
&w''_2(f) = w_2(f) r_{S2} r_{R2} \\
&w''_3(f) = w_3(f) r_{S3} r_{R3}
\end{aligned}
\tag{245}
$$

$$h_{\max,1} = Min\left(0.0005\left(x_{T1} - x_S\right), 0.2\right)$$
$$h_1'' = Min\left(h_S, h_{\max,1}\right)$$
$$r_{S1} = \begin{cases} 1 & h_{S1}' \geq h_1'' \\ \dfrac{h_{S1}'}{h_1''} & 0 < h_{S1}' < h_1'' \\ 0 & h_{S1}' \leq 0 \end{cases}$$
$$r_{R1} = \begin{cases} 1 & h_{R1}' \geq h_{\max,1} \\ \dfrac{h_{R1}'}{h_{\max,1}} & 0 < h_{R1}' < h_{\max,1} \\ 0 & h_{R1}' \leq 0 \end{cases}$$

(246)

$$h_{\max,2} = Min\left(0.0005\left(x_{T2} - x_{T1}\right), 0.2\right)$$
$$r_{R2} = \begin{cases} 1 & h_{R2}' \geq h_2'' \\ \dfrac{h_{R2}'}{h_{\max,2}} & 0 < h_{R2}' < h_{\max,2} \\ 0 & h_{R2}' \leq 0 \end{cases}$$
$$r_{S2} = \begin{cases} 1 & h_{S2}' \geq h_{\max,2} \\ \dfrac{h_{S2}'}{h_{\max,2}} & 0 < h_{S2}' < h_{\max,2} \\ 0 & h_{S2}' \leq 0 \end{cases}$$

(247)

$$
\begin{aligned}
&h_{\max,3} = Min\left(0.0005\left(x_R - x_{T2}\right), 0.2\right)\\
&h_3'' = Min\left(h_R, h_{\max,3}\right)\\
&r_{R3} = \begin{cases} 1 & h_{R2}' \geq h_3'' \\ \dfrac{h_{R2}'}{h_3''} & 0 < h_{R2}' < h_3'' \\ 0 & h_{R2}' \leq 0 \end{cases}\\
&r_{S3} = \begin{cases} 1 & h_{S2}' \geq h_{\max,2} \\ \dfrac{h_{S2}'}{h_{\max,3}} & 0 < h_{S2}' < h_{\max,3} \\ 0 & h_{S2}' \leq 0 \end{cases}
\end{aligned}
\qquad \textbf{(248)}
$$

If the propagation of the eight rays in the image model was fully coherent the propagation effect could be determined by Eq. (224) but in order to take into account averaging and incoherent effects as described in Section 0, the coherence coefficient F_2, to F_8 describing the coherence between ray no. 2 to 8 respectively and the direct ray have to be determined.

The coherence coefficient F_2 of ray no. 2 is calculated by Eq. (249) where the coherence coefficients F_f, $F_{\Delta\tau}$, F_c, and F_r are calculated as described in Section 0. ρ_1 is the transversal separation calculated by Eq. **(250)**, k_0 is the wave number at the ground and r_2 is the roughness of the source side terrain segment. In case of propagation through a scattering zone F_s is the coherence coefficient calculated as described in Section 5.19. Otherwise F_s = 1.

$$
\begin{aligned}
F_2(f) = F_f\left(f, \Delta\tau_S\right)F_{\Delta\tau}\left(f, \Delta\tau_S, \Delta\tau_{S+}\right)F_c\left(f, C_v^2, C_T^2, t_{mean}, \bar{c}_S, \rho_1, d_1'\right)\\
F_r\left(k_0, \psi_{GS}, r_1\right)F_s(f)
\end{aligned}
\qquad \textbf{(249)}
$$

$$
\rho_1 = \frac{2h_{S1}'h_{R1}'}{h_{S1}' + h_{R1}'} \qquad (250)
$$

The coherence coefficient F_3 of ray no. 3 is calculated by Eq. (251). ρ_3 is the transversal separation calculated by Eq. **(252)**, k_0 is the wave number at the ground and r_3 is the roughness of the receiver side terrain segment.

$$
\begin{aligned}
F_3(f) = F_f\left(f, \Delta\tau_R\right)F_{\Delta\tau}\left(f, \Delta\tau_R, \Delta\tau_{R+}\right)F_c\left(f, C_v^2, C_T^2, t_{mean}, \bar{c}_R, \rho_3, d_3'\right)\\
F_r\left(k_0, \psi_{GR}, r_3\right)F_s(f)
\end{aligned}
\qquad \textbf{(251)}
$$

$$
\rho_3 = \frac{2h_{S3}'h_{R3}'}{h_{S3}' + h_{R3}'} \qquad (252)
$$

The coherence coefficient F_4 of ray no. 4 is calculated by Eq. (253).

$$F_4(f) = F_f(f, \Delta\tau_S + \Delta\tau_R) F_{\Delta\tau}(f, \Delta\tau_S + \Delta\tau_R, \Delta\tau_{S+} + \Delta\tau_{R+}) F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_S, \rho_1, d_1') F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_R, \rho_3, d_3') F_r(k_0, \psi_{GS}, r_1) F_r(k_0, \psi_{GR}, r_3) F_s(f) \qquad \textbf{(253)}$$

The coherence coefficient F_5 of ray no. 5 is calculated by Eq. (254). ρ_2 is the transversal separation calculated by Eq. **(255)**, k_0 is the wave number at the ground and r_2 is the roughness of the terrain segment between the screens.

$$F_5(f) = F_f(f, \Delta\tau_M) F_{\Delta\tau}(f, \Delta\tau_M, \Delta\tau_{M+}) F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_M, \rho_2, d_2') F_r(k_0, \psi_{GM}, r_{21}) F_s(f) \qquad \textbf{(254)}$$

$$\rho_2 = \frac{2h'_{S2}h'_{R2}}{h'_{S2} + h'_{R2}} \qquad (255)$$

The coherence coefficient F_6 of ray no. 6 is calculated by Eq. (256).

$$F_6(f) = F_f(f, \Delta\tau_S + \Delta\tau_M) F_{\Delta\tau}(f, \Delta\tau_S + \Delta\tau_M, \Delta\tau_{S+} + \Delta\tau_{M+}) F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_S, \rho_1, d_1') F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_M, \rho_2, d_2') F_r(k_0, \psi_{GS}, r_1) F_r(k_0, \psi_{GM}, r_2) F_s(f) \qquad \textbf{(256)}$$

The coherence coefficient F_7 of ray no. 7 is calculated by Eq. (257).

$$F_7(f) = F_f(f, \Delta\tau_M + \Delta\tau_R) F_{\Delta\tau}(f, \Delta\tau_M + \Delta\tau_R, \Delta\tau_{M+} + \Delta\tau_{R+}) F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_M, \rho_2, d_{21}') F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_R, \rho_3, d_3') F_r(k_0, \psi_{GM}, r_2) F_r(k_0, \psi_{GR}, r_3) F_s(f) \qquad \textbf{(257)}$$

The coherence coefficient F_8 of ray no. 8 is calculated by Eq. (258).

$$F_8(f) = F_f(f, \Delta\tau_S + \Delta\tau_M + \Delta\tau_R) F_{\Delta\tau}(f, \Delta\tau_S + \Delta\tau_M + \Delta\tau_R, \Delta\tau_{S+} + \Delta\tau_{M+} + \Delta\tau_{R+}) F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_S, \rho_1, d_1') F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_M, \rho_2, d_2') F_c(f, C_v^2, C_T^2, t_{mean}, \bar{c}_R, \rho_3, d_3') F_r(k_0, \psi_{GS}, r_1) F_r(k_0, \psi_{GM}, r_2) F_r(k_0, \psi_{GR}, r_3) F_s(f) \qquad \textbf{(258)}$$

Now the propagation effect can be determined by Eq. (259) if there are no shadow zone effects before, after or between the screens.

$$\left|\hat{p}_G\right| = \sqrt{\begin{array}{l} \left| \begin{array}{l} 1 + F_2 \dfrac{w_{Q1}\hat{Q}_1\hat{p}_2}{\hat{p}_1} + F_3 \dfrac{w_{Q3}\hat{Q}_3\hat{p}_3}{\hat{p}_1} + F_4 \dfrac{w_{Q1}\hat{Q}_1 w_{Q3}\hat{Q}_3\hat{p}_4}{\hat{p}_1} \\ + F_5 \dfrac{w_{Q2}\hat{Q}_2\hat{p}_5}{\hat{p}_1} + F_6 \dfrac{w_{Q1}\hat{Q}_1 w_{Q2}\hat{Q}_2\hat{p}_6}{\hat{p}_1} \\ + F_7 \dfrac{w_{Q2}\hat{Q}_2 w_{Q3}\hat{Q}_3\hat{p}_4}{\hat{p}_1} + F_8 \dfrac{w_{Q1}\hat{Q}_1 w_{Q2}\hat{Q}_2 w_{Q3}\hat{Q}_3\hat{p}_8}{\hat{p}_1} \end{array} \right|^2 + \\ \left(1 - F_2^2\right)\left|\dfrac{w_{Q1}\Re_1\hat{p}_2}{\hat{p}_1}\right|^2 + \left(1 - F_3^2\right)\left|\dfrac{w_{Q3}\Re_3\hat{p}_3}{\hat{p}_1}\right|^2 + \\ \left(1 - F_4^2\right)\left|\dfrac{w_{Q1}\Re_1 w_{Q3}\Re_3\hat{p}_4}{\hat{p}_1}\right|^2 + \left(1 - F_5^2\right)\left|\dfrac{w_{Q2}\Re_2\hat{p}_5}{\hat{p}_1}\right|^2 + \\ \left(1 - F_6^2\right)\left|\dfrac{w_{Q2}\Re_2 w_{Q3}\Re_3\hat{p}_6}{\hat{p}_1}\right|^2 + \left(1 - F_7^2\right)\left|\dfrac{w_{Q2}\Re_2 w_{Q3}\Re_3\hat{p}_7}{\hat{p}_1}\right|^2 + \\ \left(1 - F_8^2\right)\left|\dfrac{w_{Q1}\Re_1 w_{Q2}\Re_2 w_{Q3}\Re_3\hat{p}_8}{\hat{p}_1}\right|^2 \end{array}} \qquad \textbf{(259)}$$

The incoherent reflection coefficients $\Re_1$, $\Re_2$ and $\Re_3$ in Eq. (259) are determined by Eq. (260).

$$\begin{aligned} \Re_1 &= \Re\left(f, \hat{Z}_{G1}\right) \\ \Re_2 &= \Re\left(f, \hat{Z}_{G2}\right) \\ \Re_3 &= \Re\left(f, \hat{Z}_{G3}\right) \end{aligned} \qquad \textbf{(260)}$$

If $d'_1 > 0.95\, d_{SZ,1}$ and $d'_2 \leq 0.95 d_{SZ,2}$ and $d'_3 \leq 0.95 d_{SZ,3}$ shadow zone effects will occur on the source side of the screen and $|p_G|$ has to be calculated by Eq. (261) where $|p_G|^{Eq.259}$ indicates the value calculated by Eq. (259) with modified values of Q_1 and p_2, p_4, p_6, and p_8.

$$\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,1}(f)}{20}} \left|\hat{p}_G\right|^{Eq.259}$$
$$where$$
$$\Delta L_{SZ,1}(f) = ShadowZoneShielding\left(f, d_1', h_{S1}', h_{R1}', \xi_S, c_{0S}, d_{SZ,1}\right)$$
$$\hat{Q}_1(f) = \hat{Q}\left(f, \tau_{1S}, 0, \hat{Z}_{G1}(f)\right) \qquad \textbf{(261)}$$
$$\hat{p}_2 = \hat{p}_1$$
$$\hat{p}_4 = \hat{p}_3$$
$$\hat{p}_6 = \hat{p}_5$$
$$\hat{p}_8 = \hat{p}_7$$

If $d'_3 > 0.95 d_{SZ,2}$ and $d'_1 \le 0.95 d_{SZ,1}$ and $d'_2 \le 0.95 d_{SZ,2}$ shadow zone effects will occur on the receiver side of the second screen and $|p_G|$ has to be calculated by Eq. (262) where $|p_G|^{Eq.259}$ indicates the value calculated by Eq. (259) with modified values of Q_3 and p_3.

$$\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,2}(f)}{20}} \left|\hat{p}_G\right|^{Eq.259}$$
$$where$$
$$\Delta L_{SZ,2}(f) = ShadowZoneShielding\left(f, d_2', h_{S2}', h_{R2}', \xi_R, c_{0R}, d_{SZ,2}\right)$$
$$\hat{Q}_2(f) = \hat{Q}\left(f, \tau_{1R}, 0, \hat{Z}_{G2}(f)\right) \qquad \textbf{(262)}$$
$$\hat{p}_3 = \hat{p}_1$$
$$\hat{p}_4 = \hat{p}_2$$
$$\hat{p}_7 = \hat{p}_5$$
$$\hat{p}_8 = \hat{p}_6$$

If $d'_1 > 0.95 d_{SZ,1}$ and $d'_2 \le 0.95 d_{SZ,2}$ and $d'_3 > 0.95 d_{SZ,3}$ shadow zone effects will on the source side of the first screen and on the receiver side of the second screen and $|p_G|$ has to be calculated by Eq. (263) where $|p_G|^{Eq.259}$ indicates the value calculated by Eq. (259) with modified values of Q_1, Q_3 ,p_2 , p_3, p_4, p_6 , p_7, and p_8.

$$\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,1}(f)}{20}} 10^{\frac{\Delta L_{SZ,3}(f)}{20}} \left|\hat{p}_G\right|^{Eq.259}$$

$$\begin{aligned}
&where\\
&\Delta L_{SZ,1}(f) = ShadowZoneShielding\left(f, d_1', h_{S1}', h_{R1}', \xi_S, c_{0S}, d_{SZ,1}\right)\\
&\Delta L_{SZ,3}(f) = ShadowZoneShielding\left(f, d_3', h_{S3}', h_{R3}', \xi_R, c_{0R}, d_{SZ,3}\right)\\
&\hat{Q}_1(f) = \hat{Q}\left(f, \tau_{1S}, 0, \hat{Z}_{G1}(f)\right)\\
&\hat{Q}_3(f) = \hat{Q}\left(f, \tau_{1R}, 0, \hat{Z}_{G3}(f)\right)\\
&\hat{p}_2 = \hat{p}_1\\
&\hat{p}_3 = \hat{p}_1\\
&\hat{p}_4 = \hat{p}_1\\
&\hat{p}_6 = \hat{p}_5\\
&\hat{p}_7 = \hat{p}_5\\
&\hat{p}_8 = \hat{p}_5
\end{aligned} \qquad \textbf{(263)}$$

If $d'_2 > 0.95\, d_{SZ,2}$ and $d'_1 \le 0.95 d_{SZ,2}$ and $d'_3 \le 0.95 d_{SZ,3}$ shadow zone effects will occur on the between the screens and $|p_G|$ has to be calculated by Eq. (264) where $|p_G|^{Eq.259}$ indicates the value calculated by Eq. (259) with modified values of Q_2 and p_5.

$$\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,2}(f)}{20}} \left|\hat{p}_G\right|^{Eq.259}$$

$$\begin{aligned}
&where\\
&\Delta L_{SZ,2}(f) = ShadowZoneShielding\left(f, d_2', h_{S2}', h_{R2}', \xi_M, c_{0M}, d_{SZ,2}\right)\\
&\hat{Q}_2(f) = \hat{Q}\left(f, \tau_{1M}, 0, \hat{Z}_{G2}(f)\right)\\
&\hat{p}_5 = \hat{p}_1\\
&\hat{p}_6 = \hat{p}_2\\
&\hat{p}_7 = \hat{p}_3\\
&\hat{p}_8 = \hat{p}_4
\end{aligned} \qquad \textbf{(264)}$$

If $d'_1 > 0.95 d_{SZ,1}$ and $d'_2 > 0.95 d_{SZ,2}$ and $d'_3 \le 0.95 d_{SZ,3}$ shadow zone effects will occur on the source side of the first screen and between the screens and $|p_G|$ has to be calculated by Eq. (265) where $|p_G|^{Eq.259}$ indicates the value calculated by Eq. (259) with modified values of Q_1, Q_2 , ,p_2 , p_4, p_5, p_6 , p_7, and p_8.

$$
\begin{aligned}
&\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,1}(f)}{20}} 10^{\frac{\Delta L_{SZ,2}(f)}{20}} \left|\hat{p}_G\right|^{Eq.259} \\
&where \\
&\Delta L_{SZ,1}(f) = ShadowZoneShielding\left(f, d_1', h_{S1}', h_{R1}', \xi_S, c_{0S}, d_{SZ,1}\right) \\
&\Delta L_{SZ,2}(f) = ShadowZoneShielding\left(f, d_2', h_{S2}', h_{R2}', \xi_M, c_{0M}, d_{SZ,2}\right) \\
&\hat{Q}_1(f) = \hat{Q}\left(f, \tau_{1S}, 0, \hat{Z}_{G1}(f)\right) \\
&\hat{Q}_2(f) = \hat{Q}\left(f, \tau_{1M}, 0, \hat{Z}_{G2}(f)\right) \\
&\hat{p}_2 = \hat{p}_1 \\
&\hat{p}_4 = \hat{p}_3 \\
&\hat{p}_5 = \hat{p}_1 \\
&\hat{p}_6 = \hat{p}_1 \\
&\hat{p}_7 = \hat{p}_3 \\
&\hat{p}_8 = \hat{p}_3
\end{aligned}
\tag{265}
$$

If $d'_1 \leq 0.95 d_{SZ,1}$ and $d'_2 > 0.95 d_{SZ,2}$ and $d'_3 > 0.95 d_{SZ,3}$ shadow zone effects will occur on the receiver side of the second screen and between the screens and $|p_G|$ has to be calculated by Eq. (266) where $|p_G|^{Eq.259}$ indicates the value calculated by Eq. (259) with modified values of Q_1, Q_2 , ,p_3 , p_4, p_5, p_6 , p_7, and p_8.

$$
\begin{aligned}
&\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,2}(f)}{20}} 10^{\frac{\Delta L_{SZ,3}(f)}{20}} \left|\hat{p}_G\right|^{Eq.259} \\
&where \\
&\Delta L_{SZ,2}(f) = ShadowZoneShielding\left(f, d_2', h_{S2}', h_{R2}', \xi_M, c_{0M}, d_{SZ,2}\right) \\
&\Delta L_{SZ,3}(f) = ShadowZoneShielding\left(f, d_3', h_{S3}', h_{R3}', \xi_R, c_{0R}, d_{SZ,3}\right) \\
&\hat{Q}_2(f) = \hat{Q}\left(f, \tau_{1M}, 0, \hat{Z}_{G2}(f)\right) \\
&\hat{Q}_3(f) = \hat{Q}\left(f, \tau_{1R}, 0, \hat{Z}_{G3}(f)\right) \\
&\hat{p}_3 = \hat{p}_1 \\
&\hat{p}_4 = \hat{p}_2 \\
&\hat{p}_5 = \hat{p}_1 \\
&\hat{p}_6 = \hat{p}_2 \\
&\hat{p}_7 = \hat{p}_1 \\
&\hat{p}_8 = \hat{p}_2
\end{aligned}
\tag{266}
$$

If $d'_1 > 0.95 d_{SZ,1}$ and $d'_2 > 0.95 d_{SZ,2}$ and $d'_3 > 0.95 d_{SZ,3}$ shadow zone effects will occur in all three regions and $|p_G|$ has to be calculated by Eq. (267) where $|p_G|^{Eq.259}$ indicates the value calculated by Eq. (259) with modified values of Q_1, Q_2, Q_3, and p_2 to p_8.

$$
\begin{aligned}
&\left|\hat{p}_G\right| = 10^{\frac{\Delta L_{SZ,1}(f)}{20}} 10^{\frac{\Delta L_{SZ,2}(f)}{20}} 10^{\frac{\Delta L_{SZ,3}(f)}{20}} \left|\hat{p}_G\right|^{Eq.259} \\
&where \\
&\Delta L_{SZ,1}(f) = ShadowZoneShielding\left(f, d_1', h_{S1}', h_{R1}', \xi_S, c_{0S}, d_{SZ,1}\right) \\
&\Delta L_{SZ,2}(f) = ShadowZoneShielding\left(f, d_2', h_{S2}', h_{R2}', \xi_M, c_{0M}, d_{SZ,2}\right) \\
&\Delta L_{SZ,3}(f) = ShadowZoneShielding\left(f, d_3', h_{S3}', h_{R3}', \xi_R, c_{0R}, d_{SZ,3}\right) \\
&\hat{Q}_1(f) = \hat{Q}\left(f, \tau_{1S}, 0, \hat{Z}_{G1}(f)\right) \\
&\hat{Q}_2(f) = \hat{Q}\left(f, \tau_{1M}, 0, \hat{Z}_{G2}(f)\right) \\
&\hat{Q}_3(f) = \hat{Q}\left(f, \tau_{1R}, 0, \hat{Z}_{G3}(f)\right) \\
&\hat{p}_2 = \hat{p}_1 \\
&\hat{p}_3 = \hat{p}_1 \\
&\hat{p}_4 = \hat{p}_1 \\
&\hat{p}_5 = \hat{p}_1 \\
&\hat{p}_6 = \hat{p}_1 \\
&\hat{p}_7 = \hat{p}_1 \\
&\hat{p}_8 = \hat{p}_1
\end{aligned}
\tag{267}
$$

5.15.2 General Model

If the terrain has been found to contain two wedge-shaped screens, the terrain effect is calculated by Sub-model 6 described in this section. An example of such a terrain is shown in Figure 25 where the two segments denoted 4 and 5 form the first wedge-shaped screen and the two segments denoted 8 and 9 form the second wedge-shaped screen. The remaining seven segments will be considered reflecting surfaces. Segments 1–3 form the surface on the source side of the first screen, segments 6–7 will form the surface between the screens while segments 10–11 form the surface on the receiver side of the second screen.

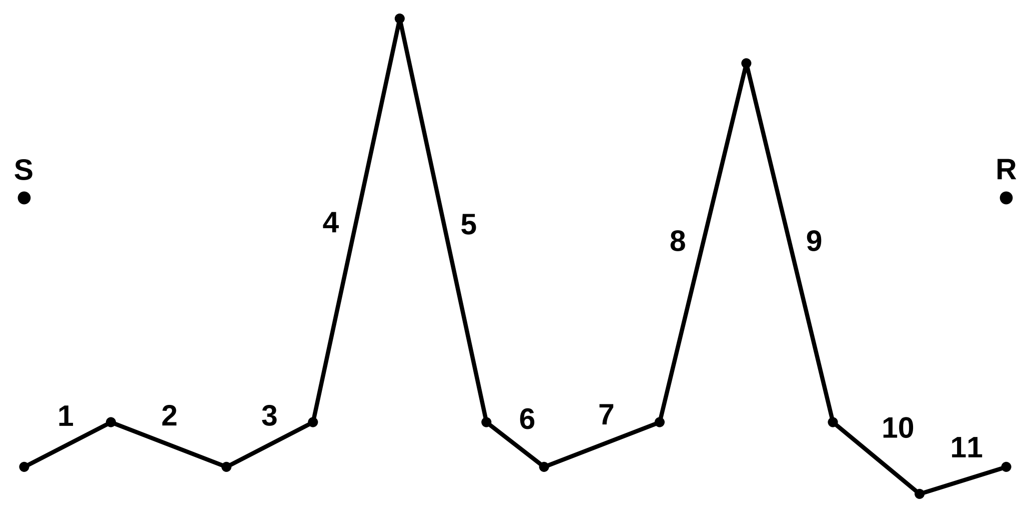

Figure 25
Example of a segmented terrain with one screen having one diffracting edge.

At this point it is assumed that the screen part of the terrain profile has already been identified and therefore that the number of segments before and after the screen which are considered reflecting segments are known. If the part of the input terrain forming the screen shape contains more than three ground points the screen shape is reduced to three points each as described in Section 5.21.

The screens are defined by the following point numbers in the terrain profile (numbered 1 to N_{ts}+1 where N_{ts} is the number of segments in the terrain profile).

- iSCR,11 first screen, terrain point number closest to the source
- iSCR,12 first screen, terrain point number closest to the receiver
- iSCR,T1 first screen, terrain point number of the diffracting edge
- iSCR,21 second screen, terrain point number closest to the source
- iSCR,22 second screen, terrain point number closest to the receiver
- iSCR,T2 second screen, terrain point number of the diffracting edge

For the first screen, the line segment representing the wedge face closest to the source has the end coordinates $W_{11} = (x_{iSCR,11}, z_{iSCR,11})$ and $T_1 = (x_{iSCR,T1}, z_{iSCR,T1})$ while the line segment representing the wedge face closest to the receiver has the end coordinates $W_{12} = (x_{iSCR,12}, z_{iSCR,12})$ and $T_1 = (x_{iSCR,T1}, z_{iSCR,T1})$. Possible terrain points between point no.

iSCR,11 and iSCR,T1 and between point no. iSCR,12 and iSCR,T1 are ignored. In this case the flow resistivity $\sigma_{iSCR,T1-1}$ and roughness $r_{iSCR,T1-1}$ are used as representatives to the source side wedge face and $\sigma_{iSCR,T1}$ and $r_{iSCR,T1}$ are used as representatives to the receiver side wedge face.

For the second screen, the line segment representing the wedge face closest to the source has the end coordinates $W_{21} = (x_{iSCR,21}, z_{iSCR,21})$ and $T_2 = (x_{iSCR,T2}, z_{iSCR,T2})$ while the line segment representing the wedge face closest to the receiver has the end coordinates $W_{22} = (x_{iSCR,22}, z_{iSCR,22})$ and $T_2 = (x_{iSCR,T2}, z_{iSCR,T2})$. Possible terrain points between point no. iSCR,21 and iSCR,T2 and between point no. iSCR,22 and iSCR,T2 are ignored. In this case the flow resistivity $\sigma_{iSCR,T2-1}$ and roughness $r_{iSCR,T2-1}$ are used as representatives to the source side wedge face and $\sigma_{iSCR,T2}$ and $r_{iSCR,T2-1}$ are used as representatives to the receiver side wedge face.

The number of reflecting segments before the first screen will therefore be iSCR,11-1 numbered from $N_{S1} = 1$ to N_{S2} = iSCR,11-1, and the number of reflecting segments between the screens will therefore be iSCR,12- iSCR,21numbered from N_{M1}= iSCR,12 to N_{M2} = iSCR,21-1 while the number of reflecting segments after the screen will be N_{ts}+1-iSCR,22 numbered from N_{R1} = iSCR,22 to $N_{R2} = N_{ts}$.

The base model will now used for all combinations of segments of the source side ($i_1 = N_{S1}$ to N_{S2}), source side ($i_2 = N_{M1}$ to N_{M2}) and on the receiver side ($i_3 = N_{R1}$ to N_{R2}). For each case of $i1$, $i2$ and $i3$ the coordinates to use in the base model are:

- $T_1 = (x_{T1},z_{T1}) = (x_{iSCR,T1},z_{iSCR,T1})$
- $W_{11} = (x_{11},z_{11}) = (x_{iSCR,11},z_{iSCR,11})$
- $W_{12} = (x_{12},x_{12}) = (x_{iSCR,12},z_{iSCR,12})$
- $T_2 = (x_{T2},z_{T2}) = (x_{iSCR,T2},z_{iSCR,T2})$
- $W_{21} = (x_{21},z_{21}) = (x_{iSCR,21},z_{iSCR,21})$
- $W_{22} = (x_{22},z_{22}) = (x_{iSCR,22},z_{iSCR,22})$
- $Z_{S1} = Z_{iSCR,T1-1}$
- $Z_{R1} = Z_{iSCR,T1}$
- $Z_{S2} = Z_{iSCR,T2-1}$
- $Z_{R2} = Z_{iSCR,T2}$
- $P_{S1} = (x_{S1},z_{S1}) = (x_{i1},z_{i1})$
- $P_{S2} = (x_{S2},z_{S2}) = (x_{i1+1},z_{i1+1})$
- $Z_{G1} = Z_{i1}$
- $w''_1(f) = w''_{i1}(f)$

- $P_{M1} = (x_{M1},z_{M1}) = (x_{i2},z_{i2})$
- $P_{M2} = (x_{M2},z_{M2}) = (x_{i2+1},z_{i2+1})$
- $Z_{G2} = Z_{i2}$
- $w''_2(f) = w''_{i2}(f)$
- $P_{R1} = (x_{R1},z_{R1}) = (x_{i3},z_{i3})$
- $P_{R2} = (x_{R2},z_{R2}) = (x_{i3+1},z_{i3+1})$
- $Z_{G3} = Z_{i3}$
- $w''_3(f) = w''_{i3}(f)$

The base model is used to calculate the screen effect $|p_{SCR}|$ and the ground effect $|p_G|$. The former will be identical for all combinations of terrain segment and has to be calculated only once while the latter will vary for each combination of terrain terrain segments and will be denoted $|p_{G,i1,i2,i3}|$ for segment i1, i2 and i3 on the source side of the screen, between the screens and on the receiver side, respectively.

Based on the sum of Fresnel-zone weights $w''_{i1}(f) = w''_1(f)$, $w''_{i2}(f) = w''_2(f)$ and $w''_{i3}(f) = w''_3(f)$ on each side of the screens the Fresnel-zone weights are normalized as shown in Eqs. (268) and (270) and the weights w_{Q1}, w_{Q2} and w_{Q3} used the base model are determined.

$$
\begin{aligned}
w_{1t}(f) &= \sum_{i1=N_{S1}}^{N_{S2}} w''_{i1}(f) \\
w_{2t}(f) &= \sum_{i2=N_{M1}}^{N_{M2}} w''_{i2}(f) \\
w_{3t}(f) &= \sum_{i3=N_{R1}}^{N_{R2}} w''_{i3}(f) \\
\Delta w_{1t}(f) &= \begin{cases} w_{1t}(f)-1 & \text{if } w_{1t}(f)>1 \\ 0 & \text{if } w_{1t}(f)\le 1 \end{cases} \\
\Delta w_{2t}(f) &= \begin{cases} w_{2t}(f)-1 & \text{if } w_{2t}(f)>1 \\ 0 & \text{if } w_{2t}(f)\le 1 \end{cases} \\
\Delta w_{3t}(f) &= \begin{cases} w_{3t}(f)-1 & \text{if } w_{3t}(f)>1 \\ 0 & \text{if } w_{3t}(f)\le 1 \end{cases} \\
\Delta w_t(f) &= \Delta w_{1t}(f)+\Delta w_{2t}(f)+\Delta w_{3t}(f)
\end{aligned}
\qquad \textbf{(268)}
$$

$$w'_{i1}(f)=\begin{cases}\dfrac{w''_{i1}(f)}{w_{1t}(f)}\left(\dfrac{\Delta w_{1t}(f)}{\Delta w_t(f)}+1\right) & \text{if } w_{1t}(f)>1\\ \dfrac{w''_{i1}(f)}{w_{1t}(f)} & \text{if } 0<w_{1t}(f)\le 1\\ 0 & \text{if } w_{1t}(f)=0\end{cases}$$

$$w'_{i2}(f)=\begin{cases}\dfrac{w''_{i2}(f)}{w_{2t}(f)}\left(\dfrac{\Delta w_{2t}(f)}{\Delta w_t(f)}+1\right) & \text{if } w_{2t}(f)>1\\ \dfrac{w''_{i2}(f)}{w_{2t}(f)} & \text{if } 0<w_{2t}(f)\le 1\\ 0 & \text{if } w_{2t}(f)=0\end{cases}$$

$$w'_{i3}(f)=\begin{cases}\dfrac{w''_{i3}(f)}{w_{3t}(f)}\left(\dfrac{\Delta w_{3t}(f)}{\Delta w_t(f)}+1\right) & \text{if } w_{3t}(f)>1\\ \dfrac{w''_{i3}(f)}{w_{3t}(f)} & \text{if } 0<w_{3t}(f)\le 1\\ 0 & \text{if } w_{3t}(f)=0\end{cases} \qquad (269)$$

$$w_{Q1}(f)=\begin{cases}1 & \text{if } w_{1t}(f)\ge 1\\ w_{1t}^3(f) & \text{if } w_{1t}(f)<1\end{cases}$$

$$w_{Q2}(f)=\begin{cases}1 & \text{if } w_{2t}(f)\ge 1\\ w_{2t}^3(f) & \text{if } w_{2t}(f)<1\end{cases}$$

$$w_{Q3}(f)=\begin{cases}1 & \text{if } w_{3t}(f)\ge 1\\ w_{3t}^3(f) & \text{if } w_{3t}(f)<1\end{cases}$$

Finally the sound pressure level ΔL_6 of Sub-model 6 for a terrain with two screens is calculated according to Eq. (270).

$$\Delta L_6 = 20\log\left(\left|\hat{p}_{SCR}(f)\right|\prod_{i1=N_{S1}}^{N_{R1}}\prod_{i2=N_{M1}}^{N_{M2}}\prod_{i3=N_{R1}}^{N_{R2}}\left|\hat{p}_{G,i1,i2,i3}\right|^{w'_{i1}(f)w'_{i2}(f)w'_{i3}(f)}\right) \qquad \textbf{(270)}$$

5.16 Sub-Model 7: Contribution from Turbulence Scattering behind Screens

The sound reduction of screens is limited by the energy scattered into the shadow zone of the screen from atmospheric turbulence. In the Nord2000 method the contribution of scattered energy in case of a non-refractive atmosphere depends on the distances R_1 and R_2 and the height h_e measured relative to the source-receiver line as defined in Figure 26. The wind and temperature turbulences are described by the turbulence strengths C_v^2 and C_T^2, respectively. If the top of screen is below the source-receiver line the contribution from turbulent scattering is ignored.

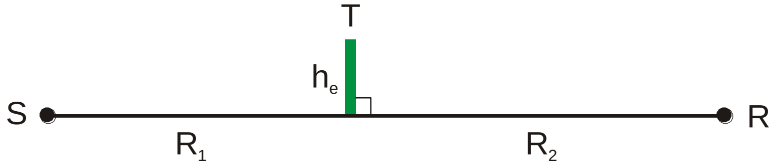

Figure 26
Definition of geometrical parameters for calculation of turbulent scattering in the shadow zone of a single edge screen.

In the Nord2000 work the original model was found to underestimate the contribution from turbulent scattering. Therefore, the effective turbulence strength parameters C_{ve}^2 and C_{Te}^2 were introduced as shown in Eq. (271).

$$C_{ve}^2 = 10C_v^2 \\ C_{Te}^2 = 10C_T^2 \qquad \textbf{(271)}$$

The sound pressure level contribution ΔL_{ws} from wind turbulence relative to the free field level is given by Eq. (272) where *f* is the frequency, *H* is the auxiliary function defined in Section 5.23.8, and *Coft* the auxiliary function defined in Section 5.23.1. L_{ws0} is the normalized scattered sound pressure level from the wind turbulence disregarding the ground. L_{ws0} is determined by linear interpolation in the two-dimensional Table 6 with input parameters $40R_2/R_1$ and $40h_e/R_1$. Due to the lack of reciprocity in Table 6 the value $L'_{wS0} = L_{ws0}(R_1,R_2,h_e) + 10\log(R_1/40)$ is also calculated the case where source and receiver are interchanged and the maximum value is used as shown in Eq. (272). When the parameters are outside the values in the table, the neareast values of the parameters are used. C_{SR} is a correction which shall account for reflections in the ground surface before and after the screen and is the ground effect part of Eq. (188) limited downwards to a value of 1.

$$L'_{ws0} = \max\left(L_{ws0}(R_1, R_2, h_e) + 10\log\left(\frac{R_1}{40}\right), L_{ws0}(R_2, R_1, h_e) + 10\log\left(\frac{R_2}{40}\right)\right)$$

$$\Delta L_{ws} = L'_{ws0} + 10\log(C_{RS}) + \frac{10}{3}\log\left(\frac{f}{2000}\right) + 10\log\left(C_{ve}^2\right)$$

$$+15H\,(f_0 - f)\log\left(\frac{f}{f_0}\right) + 15H\,(0.5f_0 - f)\log\left(\frac{f}{0.5f_0}\right)$$

where

$$\theta = \pi - \arctan\left(\frac{R_1}{h_e}\right) - \arctan\left(\frac{R_2}{h_e}\right) \tag{272}$$

$$f_0 = \frac{Coft(t_{mean})}{2\sin(\theta/2)}$$

$$C_{SR} = \begin{cases} p_G^2 & p_G > 1 \\ 1 & p_G \le 1 \end{cases}$$

$$p_G = \prod_{i1=N_{S1}}^{N_{R1}} \prod_{i2=N_{R1}}^{N_{R2}} \left|\hat{p}_{G,i1,i2}\right|^{w'_{i1}(f)w'_{i2}(f)}$$

L_{ws0}	40 R_2/R_1									
40h_e/R_1	10	20	30	40	50	60	70	80	90	100
5	-41.6	-33.9	-30.2	-27.9	-26.2	-24.9	-23.9	-23.1	-22.4	-21.8
10	-49.9	-44.0	-39.5	-36.7	-34.7	-33.1	-31.8	-30.9	-30.1	-29.3
15	-52.1	-48.9	-45.8	-42.9	-40.7	-39.1	-37.7	-36.6	-35.5	-34.7
20	-53.8	-51.0	-48.8	-46.8	-45.0	-43.5	-42.1	-40.9	-39.9	-39.1
25	-55.4	-52.4	-50.4	-48.8	-47.5	-46.2	-45.1	-44.0	-43.1	-42.2
30	-57.0	-53.8	-51.5	-50.6	-48.9	-47.8	-46.8	-45.9	-45.2	-44.4
35	-58.6	-55.1	-52.7	-51.1	-49.8	-48.8	-47.9	-47.1	-46.4	-45.7
40	-59.9	-56.5	-53.9	-52.1	-50.7	-49.6	-48.7	-48.0	-47.3	-46.6

Table 6
Normalized scattered level L_{ws0} from wind turbulence.

Similarly, the sound pressure level contribution ΔL_{ts} from temperature turbulence relative to the free field level is given by Eq. (273). L_{ts0} is the normalized scattered sound pressure level from the temperature turbulence disregarding the ground. L_{ts0} is determined by linear interpolation in Table 7.

$$L'_{ts0} = \max\left(L_{ts0}\left(R_1, R_2, h_e\right) + 10\log\left(\frac{R_1}{40}\right), L_{ts0}\left(R_2, R_1, h_e\right) + 10\log\left(\frac{R_2}{40}\right)\right)$$

$$\Delta L_{ts} = L_{ts0} + 10\log\left(C_{SR}\right) + \frac{10}{3}\log\left(\frac{f}{2000}\right) + 10\log\left(C_{Te}^2\right) \qquad \textbf{(273)}$$

$$+15H\left(f_0 - f\right)\log\left(\frac{f}{f_0}\right) + 15H\left(0.5f_0 - f\right)\log\left(\frac{f}{0.5f_0}\right)$$

L_{ts0}	**40 R_2/R_1**									
$40h_e/R_1$	10	20	30	40	50	60	70	80	90	100
5	-44.0	-39.1	-36.0	-34.0	-32.5	-31.3	-30.4	-29.6	-28.9	-28.3
10	-47.4	-44.7	-42.4	-40.5	-39.1	-37.9	-36.9	-36.0	-35.3	-34.7
15	-48.9	-46.7	-45.1	-43.6	-42.4	-41.4	-40.5	-39.7	-39.0	-38.4
20	-50.2	-48.0	-46.4	-45.2	-44.1	-43.2	-42.4	-41.7	-41.1	-40.5
25	-51.4	-49.0	-47.4	-46.2	-45.2	-44.3	-43.6	-42.9	-42.3	-41.8
30	-52.5	-50.0	-48.3	-47.0	-46.0	-45.1	-44.4	-43.7	-43.2	-42.6
35	-53.6	-51.0	-49.2	-47.8	-46.7	-45.8	-45.0	-44.4	-43.8	-43.3
40	-54.6	-52.0	-50.0	-48.5	-47.4	-46.4	-45.6	-44.9	-44.3	-43.8

Table 7
Normalized scattered level L_{ts0} from temperature turbulence.

Finally, ΔL_{ws} and ΔL_{ts} are added incoherently as shown in Eq. (274).

$$\Delta L_7 = 10\log\left(10^{\Delta L_{ws}/10} + 10^{\Delta L_{ts}/10}\right) \qquad \textbf{(274)}$$

In case of a refractive atmosphere the variables R_1, R_2 and h_e are determined by Eq. (275) where R_S and R_R are defined in Eq. (161) while θ_1, θ_2, $\Delta\theta_S$, and $\Delta\theta_R$ are defined in Eq. (162).

$$
\begin{aligned}
x'_S &= x_T - R_S \sin(\theta_1 + \Delta\theta_S) \\
z'_S &= z_T - R_S \cos(\theta_1 + \Delta\theta_S) \\
x'_R &= x_T + R_R \sin(\theta_2 + \Delta\theta_R) \\
z'_R &= z_T - R_R \cos(\theta_2 + \Delta\theta_R) \\
(x'_T, z'_T, h_e) &= NormLine(x'_S, z'_S, x'_R, z'_R, x_T, z_T) \\
R_1 &= Length(x'_S, z'_S, x'_T, z'_T) \\
R_2 &= Length(x'_R, z'_R, x'_T, z'_T)
\end{aligned}
\qquad \textbf{(275)}
$$

If two screens are included (Sub-model 5 and 6) the parameters R_1, R_2 and h_e are determined for an equivalent single screen top T as shown in Figure 27 where T_1 and T_2 are the two screen edges (may be two screens or one screen with two edges). The point T can be determined as described below. C_{SR} is in this case approximated by the ground effect part of the double edge effect screen effect p_G. (gå i detaljer med dette når sub-model 6 er beskrevet). Firstly, the parameters are calculated for T_1 and T_2 in Eq. (276)

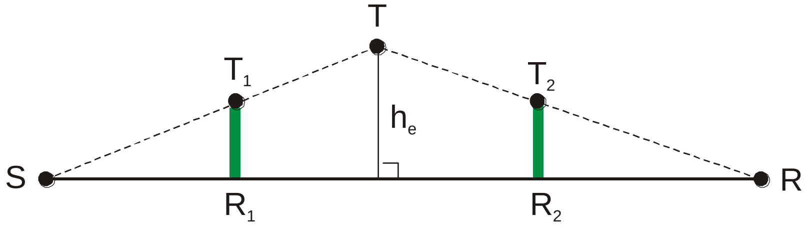

Figure 27
Definition of geometrical parameters for calculation of turbulent scattering in the shadow zone of two screens or a double edge screen.

$$
\begin{aligned}
x'_S &= x_{T1} - R_S \sin(\theta_1 + \Delta\theta_S) \\
z'_S &= z_{T1} - R_S \cos(\theta_1 + \Delta\theta_S) \\
x'_R &= x_{T2} + R_R \sin(\theta_2 + \Delta\theta_R) \\
z'_R &= z_{T2} - R_R \cos(\theta_2 + \Delta\theta_R) \\
(x'_{T1}, z'_{T1}, h_{e1}) &= NormLine(x'_S, z'_S, x'_R, z'_R, x_{T1}, z_{T1}) \\
(x'_{T2}, z'_{T2}, h_{e2}) &= NormLine(x'_S, z'_S, x'_R, z'_R, x_{T2}, z_{T2}) \\
R'_1 &= Length(x'_S, z'_S, x'_{T1}, z'_{T1}) \\
R'_2 &= Length(x'_R, z'_R, x'_{T2}, z'_{T2}) \\
R &= Length(x'_S, z'_S, x'_R, z'_R)
\end{aligned}
\qquad \textbf{(276)}
$$

The parameters corresponding to the equivalent screen top can now be determined by Eq. (393).

$$
\begin{aligned}
R_2 &= \frac{R}{1+\dfrac{h_{e2}}{h_{e1}}\dfrac{R_1'}{R_2'}} \\
R_1 &= R - R_2 \\
h_e &= h_{e1}\frac{R_1}{R_1'}
\end{aligned}
\qquad \textbf{(277)}
$$

In the combined model described in Section 5.21.6 the Sub-model 7 is referred to as Sub-model 7,1 in the one edge case and Sub-model 7,2 in the two edge case.

5.17 Sub-Model 8: Multiple Ground Reflections

In the Sub-models 1 to 6 described above the number of rays in the models are fixed even in case of strong downward refraction. In case of strong downward refraction and long propagation distances rays may be reflected by the ground more than once on the way to the receiver. This phenomenon is called multiple ground reflections. If multiple ground reflections occur the number of rays will increase beyond the number which is included in submodel 1 to 6.

The purpose of Sub-model 8 is to calculate the contribution to the sound levels from rays not included in submodel 1 to 6.

The method used in the present sub-model has been developed for a logarithmic sound speed profile as shown in Eq. (278) and for propagation over flat terrain.

$$
c(z) = A\ln\left(\frac{z}{z_0}+1\right)+C \qquad \textbf{(278)}
$$

The first step is to determine the approximate number of rays N (decimal number) by Eq. (279) where d is the horizontal propagation distance, h_{max} is the maximum value of the source height h_S and the receiver height h_R and A and C are the weather coefficients in Eq. (278).

$$
\begin{aligned}
N &= \frac{4d_{base}}{h_{\max}}\sqrt{\frac{A}{2\pi C}} \\
&\textit{where} \\
h_{\max} &= Max(h_S, h_R)
\end{aligned}
\qquad \textbf{(279)}
$$

For a value of N less than 4 the contribution from additional rays are ignored whereas the contribution will be calculated as described in the following for values of N greater than 4.

The number N is divided in an integer part N_i (N is rounded down) and a fractional part ΔN as shown in Eq. (280).

$$N = N_i + \Delta N \qquad \textbf{(280)}$$

Reflected rays are categorised by different orders, where the order n is the number of reflections of a specific ray. The order n for ray number M is determined as shown in Eq. (281) which also defines the maximum order n_{max}. The function *Int* is a function which returns the integer part of the argument.

$$\begin{aligned} n &= Int\left(\frac{M-1}{4}\right)+1 \\ n_{\max} &= Int\left(\frac{N-1}{4}\right)+1 \end{aligned} \qquad \textbf{(281)}$$

The contribution ΔL_{multi} from multiple reflections is calculated according to Eq. (282). The equation contains two solutions $\Delta L_{multi,hf}$ and $\Delta L_{multi,lf}$ which shall be used at high and low frequencies, respectively. R(n) is the reflection coefficient and $A_{ray}(n)$ is the ray tube area for a ray of order n. The high frequency solution corresponds to uncorrelated summation of the ray contributions and the low frequency solution to correlated summation. Reference [2] contains a discussion of the transition between the two solutions but a safe principle was not found within the Nord2000 project. For normal purposes where the medium and high frequency range determines the A-weighted sound pressure level it is recommended to apply the high frequency solution. However, in cases where low frequency propagation is important the low frequency solution giving higher values of ΔL_{multi} should be used instead.

$$\begin{aligned} \Delta L_{multi,hf} &= 10\log\left(\left(\Delta N\, R(n_{\max})^{n_{\max}}\, A_{ray}(n_{\max})\right)^2 + \sum_{M=5}^{N_i}\left(R(n)^n\, A_{ray}(n)\right)^2\right) \\ \Delta L_{multi,lf} &= 20\log\left(\Delta N\, R(n_{\max})^{n_{\max}}\, A_{ray}(n_{\max}) + \sum_{M=5}^{N_i}\left(R(n)^n\, A_{ray}(n)\right)\right) \end{aligned} \qquad \textbf{(282)}$$

The values R(n) and $A_{ray}(n)$ are detemined as shown in Eq. (283). $d_{segm}(i)$ is defined in Section 5.4.1, ρ_{ray} = 0.00001 and c(z) is determined by Eq. (278).

$$
\begin{aligned}
&R(n) = \sum_{i=1}^{N_{ts}} \left| \hat{R}_p\left(f, \psi_G(n), \hat{Z}_G(f)\right) \right| \frac{x_{i+1} - x_i}{x_{RGv} - x_{SGv}} \\
&A_{ray}(n) = 10^{-0.1\sqrt{\frac{\left|\psi_G(n) - \psi'_G(n)\right|}{\rho_{ray}\sin\psi_G(n)}}} \\
&\textit{where} \\
&h_{\max}(n) = \frac{d_{base}}{n}\sqrt{\frac{A}{2\pi C}} \\
&\psi_G(n) = \arccos\left(\frac{C}{c(h_{\max}(n))}\right) \\
&\psi'_G(n) = \arccos\left(\frac{C}{c((1+\rho_{ray})h_{\max}(n))}\right)
\end{aligned}
\qquad \textbf{(283)}
$$

The method described above is valid for propagation over flat terrain with a logarithmic sound speed profile defined by the weather coefficents A and C. In the general case where the vertical sound speed profile also may contain a linear part defined by the weather coefficient B as shown Eq. (2) and where the terrain may be non-flat, some interpretation is needed before the method can be applied.

In the case where the weather coefficient B is not zero, the combined refraction of the logarithmic and linear profile calculated by auxiliary function *RayCurvature* and expressed by the radius of curvature $R_{A,B}$ as shown in Eq. (284). The value A’ in a purely logarithmic sound speed profil giving the same value of $R_{A,B}$ are determined by Eq. (284) and used in Eq. (278).

$$
\begin{aligned}
&(R_{A,B}, NA) = \mathit{RayCurvature}(A, B, C, d, h_S, h_R) \\
&A' = \frac{\pi C d^2}{32 R_{A,B}^2}
\end{aligned}
\qquad \textbf{(284)}
$$

If the terrain is flat with screens, h_{max} in Eq. (279) is determined by the maximum value of the source, receiver and screen heights.

If the terrain is non-flat, the heights of source, receiver and screens are determined relative to the terrain baseline and h_{max} is defined as the maximum value of these heights. If the average deviation of the terrain from the terrain baseline is less than 0 (meaning that the terrain on average is lower than the baseline indicating a valley shaped terrain), h_{max} is modified by adding the numerical value of the deviation. This is expressed in Eq. (285). $h_{base}(i)$ and $d_{segm}(i)$ are defined in Section 5.4.1.

$$h_{\max} = Max\left(h_S, h_R, h_{base,m}, h_S - \bar{h}_{base}, h_R - \bar{h}_{base}, h_{base,m} - \bar{h}_{base}\right)$$
$$where$$
$$h_{base,m} = Max\left(h_{base}(i)\right) \quad i = 2,3,\dots,N_{ts} \tag{285}$$
$$\bar{h}_{base} = \sum_{i=1}^{N_{ts}} \frac{h_{base}(i+1) - h_{base}(i)}{2} \frac{x_{i+1} - x_i}{x_{RGv} - x_{SGv}}$$

5.18 Sub-Model 9: Air Absorption

The propagation effect of air absorption is calculated on the basis of ISO 9613-1 which predicts pure-tone attenuation in one third octave bands. The prediction according to ISO is based on the frequency f, the air temperature t_{air} (°C), the relative humidity RH (%), and the atmospheric pressure ($p_{rel} = p_a/p_r$) relative to the reference atmospheric pressure (atm). The attenuation α in dB/m at the frequency f in dB is calculated by Eq. (286).

$$T_0 = 293.15$$
$$T_{01} = 273.16$$
$$T = t_{air} + 273.15$$
$$h = \frac{RH}{p_{rel}} 10^{\left(-6.8346\left(\frac{T_{01}}{T}\right)^{1.261} + 4.6151\right)}$$
$$f_{rO} = p_{rel}\left(24 + 40400h\frac{h + 0.02}{h + 0.391}\right)$$
$$f_{rN} = p_{rel}\left(\frac{T}{T_0}\right)^{-1/2}\left(9 + 280h\exp\left(-4.170\left(\left(\frac{T}{T_0}\right)^{-1/3} - 1\right)\right)\right) \tag{286}$$
$$\alpha(f) = 8.686 f^2 \left(\frac{1.84\times10^{-11}}{p_{rel}}\left(\frac{T}{T_0}\right)^{1/2} + \left(\frac{T}{T_0}\right)^{-5/2} \times \left(\left(\frac{0.01275\exp\left(\frac{-2239.1}{T}\right)}{f_{rO} + \frac{f^2}{f_{rO}}}\right) + \left(\frac{0.1068\exp\left(\frac{-3352}{T}\right)}{f_{rN} + \frac{f^2}{f_{rN}}}\right)\right)\right)$$

The propagation effect of air absorption ΔL_a for each one-third octave band can now be determined by Eq. (287) where A_0 is the one-third octave band air attenuation for centre frequency f_0 and propagation path length R

$$A_0 = \alpha(f_0)R$$
$$\Delta L_9 = -A_0\left(1.0053255 - 0.00122622\ A_0\right)^{1.6} \qquad \textbf{(287)}$$

5.19 Sub-Model 10: Scattering Zones

A scattering zone is an area which contains so many interfering objects that almost all direct sound from source to receiver is blocked. Instead, the sound arrives at the receiver after a large number of reflections and diffractions. In such cases the complex propagation is described using statistical approaches (statistical scattering methods).

The Nordtest method ([1] and [2]) contains solutions for housing areas and forests but in the Nordtest method it has been decided only to apply the method for forests. The reason is that most computer programs is handling propagation in housing areas by directly including all ray paths reflected by buildings. The method is therefore not likely to be used in housing areas at the same time as the calculation accuracy is not well known. The Nord2000 method [1] also includes a method for combining varying types of scattering zones (mixed housing areas and forests and varying scattering zone variable. This has also been omitted from the Nordtest method.

According to Eq. (1) the propagation effect of terrain ΔL_t and scattering zones ΔL_s shall be calculated separately. However, the calculation of ΔL_t may be affected by the existence of a scattering zone giving a reduction in coherence coefficients.

In prediction of scattering zone propagation effects one of the fundamental parameters is the sound path length R_{sc} in the scattering volume as shown in Figure 28 and Figure 29. When the source-receiver is not blocked by obstacles (in excess of the scattering zones), R_{sc} is measured along the source-receiver sound path as shown in Figure 28. When the source-receiver is blocked, R_{sc} is measured along the sound path over the top of the obstacles using the "rubber band" principle shown in Figure 29. When a screen inside a scattering zone cannot be considered a natural part of the scattering zone (e. g. a house in a forest or a very large building inside a low housing area) the screen is taken into account in the calculation of ΔL_t and ignored in the calculation of ΔL_s. Therefore such a screen is taken into account when defining the sound path used to determine R_{sc}.

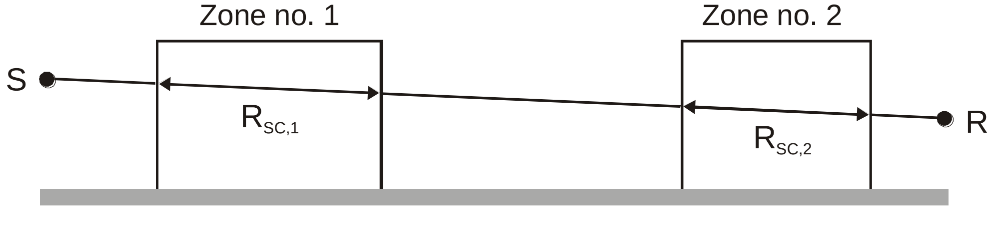

Figure 28

Propagation path used to determine the scattering zone path length R_{sc} when the line of sight is unblocked by terrain or screens.

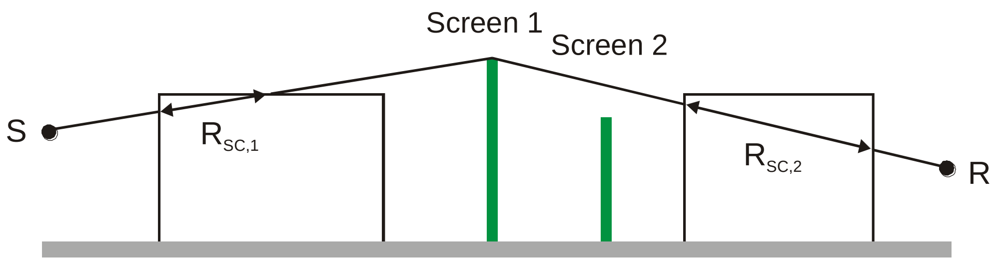

Figure 29
Propagation path used to determine the scattering zone path length R_{sc} when the line-of-sight is blocked by terrain or screens.

The coherence coefficient F_s corresponding to scattering to be used when calculating the terrain effect ΔL_t is determined by Eq. (288).

$$F_s = 1 - k_f T \tag{288}$$

The variable T in Eq. (288) is calculated by Eq. (289) where nQ is given by Eq. (290). R_{sc} is the total sound path length of the scattering zones ($R_{sc} = \Sigma R_{sc,i}$ where $R_{sc,i}$ is the sound path length of the i'th scattering zone).

$$T = Min\left(\left(\frac{R_{sc} nQ}{1.75}\right)^2, 1\right) \tag{289}$$

k_f is determined by Table 8. The parameter ka is the product of the wave number k and the mean stem radius a. Linear interpolation is used to determine k_f for other values of ka than those shown in the table.

ka	**k_f**
0	0.00
0.7	0.00
1	0.05
1.5	0.20
3	0.70
5	0.82
10	0.95
20	1.00

Table 8
Frequency weighting function k_f for forests as a function of ka where k is the wave number and a is the mean stem radius.

In case of forests (or other dense vegetation) nQ is determined by Eq. (290) where n" is the density of trees (m^{-2}) and a is the mean stem radius (m).

$$nQ = 2an'' \qquad \textbf{(290)}$$

The propagation effect of the scattering zone ΔL_s is calculated by Eq. (291) where k_f and T are as defined above. $A_e(R_{sc})$ is a level correction due to scattering. ΔL_s has been limited downwards to a value of -15 dB.

$$\Delta L_{10} = Max\left(1.25\, k_f\, T\, A_e\left(R_{sc}\right), -15\right)$$
$$\text{where} \qquad \textbf{(291)}$$
$$A_e\left(R_{sc}\right) = \Delta L(h', \alpha, R') + 20\log\left(8R'\right)$$

In Eq. (291) h' is the normalised scatter obstacle height defined by h' = nQh where h is the average scatter obstacle height. α is the absorption coefficient of the scatter obstacles (normally in the range 0.1 - 0.4). R' is the normalised effective distance through the scattering zone defined by R' = nQR_{sc}. ΔL(h',α,R') is determined from the three-dimensional Table 9 with parameters h', α, and R' using cubic interpolation.

R'	**h'=0.01**			**h'=0.1**			**h'=1**		
	α=0	α=0.2	α=0.4	α=0	α=0.2	α=0.4	α=0	α=0.2	α=0.4
0.0625	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
0.125	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.25	-7.5	-7.5	-7.5	-6.0	-7.0	-7.5	-6.0	-7.0	-7.5
0.5	-14.0	-14.25	-14.5	-12.5	-13.5	-14.5	-12.5	-13.0	-14.0
0.75	-18.0	-18.8	-19.5	-17.3	-18.0	-19.0	-16.0	-16.8	-17.7
1	-21.5	-22.5	-23.5	-20.5	-21.6	-22.8	-19.3	-20.5	-21.3
1.5	-26.3	-27.5	-29.5	-25.5	-27.2	-29.0	-24.0	-25.5	-26.3
2	-31.0	-32.5	-34.5	-30.0	-32.0	-33.3	-27.5	-29.5	-30.8
3	-40.0	-42.5	-45.5	-37.5	-40.5	-42.9	-34.2	-36.0	-37.8
4	-49.5	-52.5	-56.3	-45.5	-49.5	-52.5	-40.4	-42.8	-45.5
6	-67.0	-72.5	-78.0	-62.0	-67.0	-72.0	-52.5	-56.2	-60.0
10	-102.5	-113.0	-122.5	-94.7	-103.7	-112.0	-78.8	-84.0	-89.7

Table 9
Table for determining ΔL(h', α, R') for a scattering zone.

In the scattering zone method described above it is assumed that the height of the scattering zone is sufficiently large. In cases with a limited height of the scattering zone this may not be fulfilled. If the scattering zone is below the sound ray any effect is automatically ignored as R_{sc} will be zero. However, if the upper end of the scattering zone is just above the sound ray it is possible to have a sudden considerable change in R_{sc} and therefore a large discontinuity. To avoid this, a transition principle has been developed which will be described in the following. In the transition principle a smooth transition is obtained from the case where no effect is assumed when the scattering zone is below the sound ray to the case where the full effect is obtained when the scattering zone is sufficiently high.

In the transition principle the volume of the scattering zone within the half of the Fresnel ellipsoid above the sound ray relative to the entire volume of this half Fresnel ellipsoid is used to modify the R_{sc} as shown in Figure 30. In case of refraction the ray path from S to R is an arc of a circle and the Fresnel ellipsoid is bended along the ray path. However, as the approach is very approximate the calculation of the volumes is simplified.

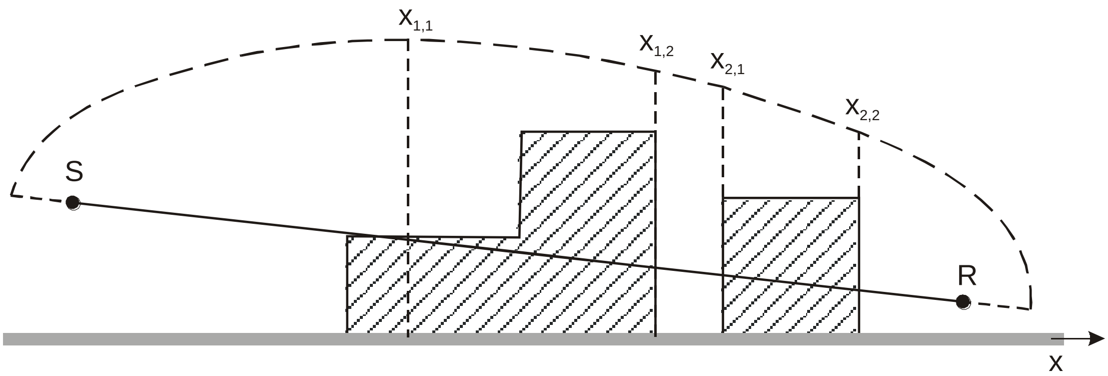

Figure 30
Limited height of the scattering zone within half of the Fresnel ellipsoid above the sound ray in case of a non-refractive atmosphere.

The height of the sound ray $z_{ray}(x)$ and the ray path lengths R1(x) and R2(x) to the source and receiver, respectively, are determined by Eq. (292).

$$\begin{aligned}&(NA,\xi_{ray}) = RayCurvature(A,B,C,x_R - x_S,h_S,h_R)\\&(z_{ray}(x),R_1(x),R_2(x)) = HeightOfCircularRay(x_R - x_S,h_S,h_R,\xi_{ray},x - x_S)\end{aligned} \quad \textbf{(292)}$$

The intersection between the y-plane and the Fresnel ellipsoid which is an ellipse is replaced by the circumscribed rectangle with height and width to each side of the sound ray of $r_{Fz}(x)$ as shown in Figure 31. $r_{Fz}(x)$ is half the width of Fresnel ellipsoid at x calculated according to Eq. (293) using the auxiliary function *CalcFZd*. λ is the wavelength and the calculation is based on a fraction F_λ = 1/8.

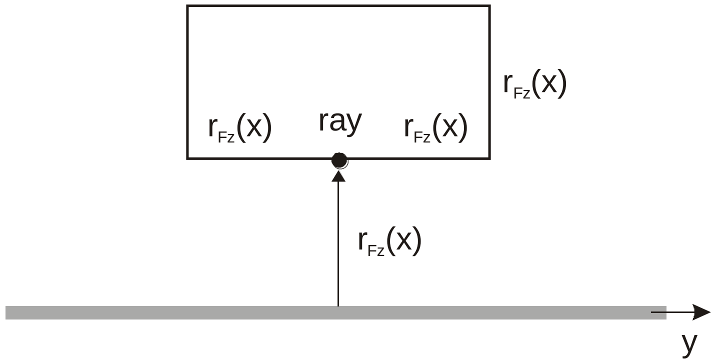

Figure 31
Simplified Fresnel shape in the y-plane.

$$r_{FZ}(f,x) = CalcFZd\left(R_1(x), R_2(x), \frac{\pi}{2}, \lambda/8\right) \tag{293}$$

Now the modified value R'_{sc} can be determined by Eq. (294) based on the volume of the simplified Fresnel-shape V_{Fz} and the scattering volume V_{sc} inside the shape. x_1 and x_2 is the start and end coordinate of the intersection between the sound ray and the scattering belt. If there is more than one scattering zone along the propagation path only values of x inside the scattering zones are included in the integration in Eq. (294). The modified value R'_{sc} is used instead of R_{sc} in the method described above. The integrals are solved approximately using the trapezoidal rule after having divided the volume in vertical strips in the x- as well as the y-direction. The maximum width of the strips depends on the shape of volume but a simple approach is to use 100 strips placed equidistanly in the two directions which is assumed to be sufficiently accurate for all practical cases.

$$
\begin{aligned}
&R'_{sc} = R_{sc}\frac{V_{sc}}{V_{Fz}} \\
&where \\
&V_{Fz} = \int_{x=x_1}^{x_2} 2\,r_{Fz}^2(x)\,dx \\
&V_{sc} = \int_{x=x_1}^{x_2}\left(\int_{y=-r_{Fz}(x)}^{r_{Fz}(x)} \Delta z_{sc}(x,y)\,dy\right)dx \\
&\Delta z_{sc}(x,y) = \begin{cases} 0 & z_{sc}(x,y) \le z_{ray}(x) \\ z_{sc}(x,y) - z_{ray}(x) & z_{ray}(x) < z_{sc}(x,y) < z_{ray}(x) + r_{Fz}(x) \\ r_{Fz}(x) & z_{sc}(x,y) \ge z_{ray}(x) + r_{Fz}(x) \end{cases}
\end{aligned}
\tag{294}
$$

5.20 Sub-Model 11: Reflection Effect

Sound reflected from an obstacle such as a building facade or a noise screen is dealt with by introducing a reflection path from the source S via the reflection point O to the receiver R as shown in Figure 1 in Section 5.3.4 where the input variables used in Sub-model 11 are defined. The reflection point is at the intersection between the straight line from the image source S’ to the receiver R and the plane which contains the reflecting surface. Therefore, the reflection point may be outside the real surface.

The propagation effect of the reflection path is predicted by the same propagation model used for the direct path on basis of the propagation parameters determined along the reflection path. However, the propagation effects in Eq. (1) also include a propagation effect ΔL_r which is a correction for the efficiency of the reflection.

As the direction of propagation is changing at the reflection point O, the weather coefficients *A* and *B* in Eq. (2) may also change at the reflection point due to the wind effects. Based on the input variables defined in Section 5.3.4 *A* and *B* are determined by Eq. (295). This principle can easily be extented to more than one reflection in which case the varying values of *A* and *B* for each part of the reflection path are weighted by its length *d*.

$$
\begin{aligned}
A &= \frac{d_1 A_1 + d_2 A_2}{d_1 + d_2} \\
B &= \frac{d_1 B_1 + d_2 B_2}{d_1 + d_2}
\end{aligned}
\tag{295}
$$

The correction ΔL_r depends on the size of the reflector and reflection coefficient of the reflecting surface as shown in Eq. (296). The first term in the equation is a correction for the effective energy reflection coefficient ρ_E and the second term is a correction for the “effective" size of the reflecting surface. If the reflector placed over a terrain surface the "effective" size is the combination of the reflector itself and the image of the reflector in the terrain surface. S_{refl} is the area of the "effective" surface within the Fresnel-zone in the plane of reflection and S_{Fz} is the total area of the Fresnel-zone. S_{refl} is determined on basis of the input varables $z_{r,upp}$, $z_{r,low}$, $d_{r,l}$, and $d_{r,r}$ defined in Section 5.3.4. In order to avoid unnecessary calculation of S_{refl} and S_{Fz} a reflecting surface is ignored if the point of reflection is more than 2 m outside one of the surface edges.

$$\Delta L_{11} = 10 \log\left(\rho_E(f)\right) + 20 \log\left(\frac{S_{refl}(f)}{S_{Fz}(f)}\right) \tag{296}$$

For a reflecting surface with a frequency dependent absorption coefficient α the energy reflection coefficient ρ_E is calculated by Eq. (297).

$$\rho_E(f) = 1 - \alpha(f) \tag{297}$$

In order to calculate S_{Fz} and S_{refl} the position of the Fresnel-zone around the reflection point O = (x_O,z_O) has to be determined ($x_O = d_1$). If the reflector is vertical (the method is applicable also for non-vertical reflectors but a description has not been included in the present Nordtest standard due to the substantial complexity of the geometrical calculations) The coordinate x_O is easily determined by the intersection between the line S'R and the reflector as shown in Figure 1. The coordinate z_O is more difficult to calculate as the ray path is circular but can be determined on basis of Eq. (298) giving the height $h_{O,base}$ of O above the terrain baseline. R_1 and R_2 are lengths of the ray path from O to S and R, respecively, as defined in Figure 32.

$$\begin{aligned} (NA, \xi_{ray}) &= RayCurvature(A, B, C, d, h_S, h_R) \\ (h_{O,base}, R_1, R_2) &= HeightOfCircularRay(d, h_S, h_R, \xi_{ray}, d_1) \end{aligned} \tag{298}$$

The dimension $d_{FZ}(f)$ of the Fresnel-zone above, below, left or right of O can be determined by Eq. (299) where θ_r is the angle between the ray path at O and the direction to the Fresnel-zone border under consideration, F_λ = 1/8, and λ is the wavelength.

$$d_{FZ}(f) = CalcFZd(R_1, R_2, \theta_r, F_\lambda \lambda) \tag{299}$$

As mentioned in Section 5.8 the Fresnel zone is in the Nord2000 method geometrically simplified by using the circumscribed rectangle symmetrically placed around the major axis of the Fresnel ellipse. If $d >> h_S+h_R$ which most often is fulfilled at the same time as the reflector is assumed to be vertical, the two axes of the ellipse can be assumed to be horisontal and vertical which simplifies the geometrical calculations.

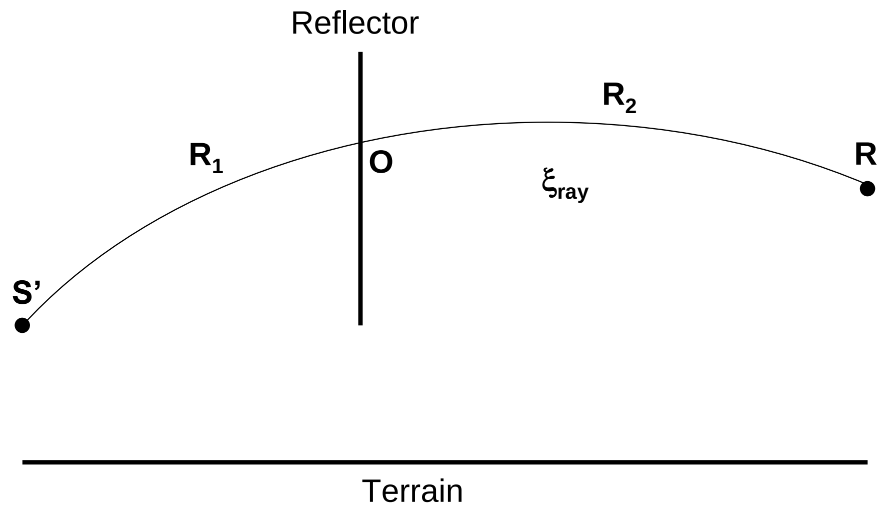

Figure 32
Geometrical definition of a reflection ray path.

A difference in directivity between the direct and reflected sound path is assumed to be incorporated in L_W in Eq. (1).

The reflected sound is added incoherently to the direct sound.

Irregularly shaped obstacles may be divided into a number of sub-surfaces which each fulfils the requirement of being a plane surface, and the overall effect is obtained by a simple incoherent summation of the contributions from all surfaces.

5.21 Interpretation of Terrain

Before the sound pressure level can be determined by the combined model described in Section 5.21.6 the terrain must be characterized as one of the following sub-models:

1. Flat terrain with one type of surface

2. Flat terrain with more than one type of surface

3. Non-flat terrain without screens

4. Terrain with one screen having one edge

5. Terrain with one screen having two edges

6. Terrain with two screens

The result may also be a combination of the six sub-models where the calculation is carried by two or more sub-models and where the final results is obtained by interpolation between the sub-model results.

In the following models will be mentioned which are a combination of the sub-models shown above. These are:

- The "Flat" model with the propagation effect ΔL_{flat} is either the model for flat terrain with one type of surface or with more than one type of surface (Sub-models 1 or 2)
- The "NoScreen" model with the propagation effect ΔL_{noscr} is a combination of the "Non-flat terrain without screens" model (Sub-model 3) and the "Flat terrain" model.
- The "OneScreen" model with the propagation effect ΔL_{scr1} may be a combination of the two one screen models (Sub-models 4 and 5).
- The "Screen" model with the propagation effect ΔL_{scr} may be a combination of the three screen models (Sub-models 4, 5, and 6).

The first step will therefore be to make an interpretation of the terrain to determine if a part of the terrain is a screen. If so, the most efficient screen is found (is denoted the primary screen in the method). If the terrain contains more than one screen, the second most efficient screen is then found (is denoted the secondary screen in the method). Screens other than the two most efficient screens are ignored and the terrain segments forming these screens are considered simple ground reflection segments. If the screen shape of the primary and secondary screen has more than one edge it is determined which edge is the most efficient edge. If only one screen has been found it is investigated if the screen shape has more than one efficient edge. Such an edge will be denoted the secondary edge. Finally the primary screen shape and a possible secondary screen will be simplified to include only the primary edge and a possible secondary edge in the primary screen.

5.21.1 Determination of a Primary Edge of a Primary Screen

The presence of a screen in the terrain profile is only possible if the number of terrain segment N_{ts} (=nxz-1) exceeds one. If this is the case, the procedure described in the following is used for determining the most efficient edge of the primary screen.

Each point in the terrain except the first and last point and points at or below the terrain baseline ($h_{base}(i) \leq 0$ where i is the number of the point) are considered a potential diffraction point. To determine the most efficient diffraction point the path length difference $\Delta\ell_0$ for a non-reacting atmosphere is calculated by Eq. (300) where the terrain point considered is $P_i = (x_i,z_i)$ and z_m is the height of the line of sight SR at x_i. The use of the auxiliary function *H(x)* will cause $\Delta\ell$ to be greater than zero if P_i is above the line SR (z_i-z_m > 0) and less than zero if P_i is below the line.

$$\Delta\ell_0 = H(z_i - z_m)(|SP_i| + |RP_i| - |SR|)$$
where
$$z_m = (z_R - z_S)\frac{x_i - x_S}{x_R - x_S} + z_S \qquad \textbf{(300)}$$

The point no. i with the largest value of $\Delta\ell_0$ will be defined as the most efficient edge of the primary screen. Later in the procedure this edge may turn out to be inefficient in which case the screen is ignored. The point is denoted $T_1 = (x_{T1},z_{T1})$.

When T_1 has been determined, the next step will be to determine the efficiency of the diffraction point. This is done by calculating a transition parameter denoted r_{scr1}. This parameter will be determined on basis of the path length difference $\Delta\ell$ including the effect of refraction and on the distance $h_{base,T1}$ of T_1 to the terrain baseline.

$\Delta\ell$ is calculated by Eq. (301) where R_S and R_R are the source and receiver ray path length calculated by Eq. (161) and θ_S and θ_R are the diffraction angles calculated by Eq. (162).

$$\Delta\ell = Sign(\theta_S - \theta_R - \pi)\sqrt{R_S^2 + R_R^2 - 2R_S R_R \cos(\theta_S - \theta_R)} - R_S - R_R \qquad \textbf{(301)}$$

The efficiency of the diffraction point T_1 is determined based on three criterions:

1) $\Delta\ell'$ shall be sufficiently large where $\Delta\ell' = max(\Delta\ell,\Delta\ell_0)$

2) The height of the screen above the ground surface shall be sufficiently large compared to the wavelength

3) The height of the screen above the ground surface shall be sufficiently large compared to the effective width of the sound field at the screen

The first criterion is based on an interpolation parameter $r_{\Delta\ell}(\lambda)$ determined according to Eq. (302). A value of $r_{\Delta\ell}$ equal to 1 indicates full screening effect and 0 indicates insignificant screening effect. $r_{\Delta\ell}$ is a function of the wavelength λ.

$$r_{\Delta\ell}(\lambda)=\begin{cases}1 & \dfrac{\Delta\ell'}{\lambda}\geq 0\\ 1-\sqrt{7.5\left|\dfrac{\Delta\ell'}{\lambda}\right|} & -0.133<\dfrac{\Delta\ell'}{\lambda}<0\\ 0 & \dfrac{\Delta\ell'}{\lambda}\leq -0.133\end{cases} \qquad \textbf{(302)}$$

The second criterion is based on an interpolation parameter $r_\lambda(\lambda)$ determined according to Eq. (303). A value of r_λ equal to 0 and 1 indicates no screening and full screening, respectively. $h_{SCR} = h_{base}(i_{T1})$ is the perpendicular distance from P_{T1} to the terrain baseline.

$$r_\lambda(\lambda)=\begin{cases}1 & \dfrac{h_{SCR}}{\lambda}\geq 0.3\\ \dfrac{h_{SCR}/\lambda-0.1}{0.2} & 0.1<\dfrac{h_{SCR}}{\lambda}<0.3\\ 0 & \dfrac{h_{SCR}}{\lambda}\leq 0.1\end{cases} \qquad \textbf{(303)}$$

The third criterion is based on an interpolation parameter $r_{Fz}(\lambda)$ determined according to Eq. (304). A value of r_λ equal to 0 and 1 indicates no screening and full screening, respectively. h_{SCR} is defined in the same way as in Eq. (337) and the effective width of the sound field is quantified by half the width of the Fresnel-zone $h_{Fz}(f)$ determined by the auxiliary function *CalcFZd* using af fraction of the wavelength $F_\lambda = 0.5$.

$$r_{Fz}(\lambda)=\begin{cases}1 & \dfrac{h_{SCR}}{h_{Fz}}\geq 0.082\\ \dfrac{h_{SCR}/h_{Fz}(\lambda)-0.026}{0.056} & 0.026<\dfrac{h_{SCR}}{h_{Fz}}<0.082\\ 0 & \dfrac{h_{SCR}}{h_{Fz}}\leq 0.026\end{cases} \qquad \textbf{(304)}$$

where

$$h_{Fz}(\lambda)=CalcFZd\left(d_{base}(i_{T1}),d_{base}-d_{base}(i_{T1}),\pi/2,0.5\lambda\right)$$

The three transition parameters are finally combined into the screen transition parameter $r_{scr1}(f)$ calculated by Eq. (339).

$$r_{scr1}(f)=r_{\Delta\ell}(f)\,r_\lambda(f)\,r_{Fz}(f) \qquad \textbf{(305)}$$

For screens below the line-of-sight the parameter $r_{\Delta\ell}$ will reduce the efficiency of a screen at high frequencies whereas r_{λ} and r_{Fz} will reduce the efficiency at low frequencies.

The purpose of transition parameter r_{scr} is used to combine the "NoScreen" model and the "Screen" model as shown in Eq. (340).

$$\Delta L(f) = r_{scr1}(f)\Delta L_{scr}(f) + (1 - r_{scr1}(f))\Delta L_{noscr}(f) \qquad \textbf{(306)}$$

If r_{scr1}(f) is greater than zero at at least one frequency it will be necessary to make calculations by the "Screen" model. In this case it will be necessary to define which part of the terrain shall be interpreted as the "screen shape". The start of the screen is defined as the non-convex point closest to T_1 on the source side of T_1 and the end of the screen is defined as the non-convex point closest to T_1 on the receiver side of T_1. Whether a point is convex or non-convex is determined by the auxiliary function *Convex(i)*. The start point of the screen is denoted W_1 and the end point W_2.

5.21.2 Determination of a Primary Edge of a Secondary Screen

If a primary screen was found in Section 5.21.1 and r_{scr1}(f) is greater than zero at at least one frequency the next step will be to search for a secondary screen.

Each point in the terrain except the first and last point, the points being a part of the primary screen shape, and points at or below the terrain baseline ($h_{base}(i) \leq 0$ where i is the number of the point) the point is considered a potential diffraction point in the secondary screen. To determine the most efficient diffraction point the path length difference $\Delta\ell$ has to be determined by a procedure slighly modified compared to the procedure used for the primary screen.

If $\Delta\ell$ calculated in Section 5.21.1 for the primary edge of the primary screen is less than zero T_1 is below the line SR. In this case the first step will be to determine the point $T_1' = (x_{T1}, z_{T1'})$ on the line SR vertically above T_1 as shown in Fig. 24.

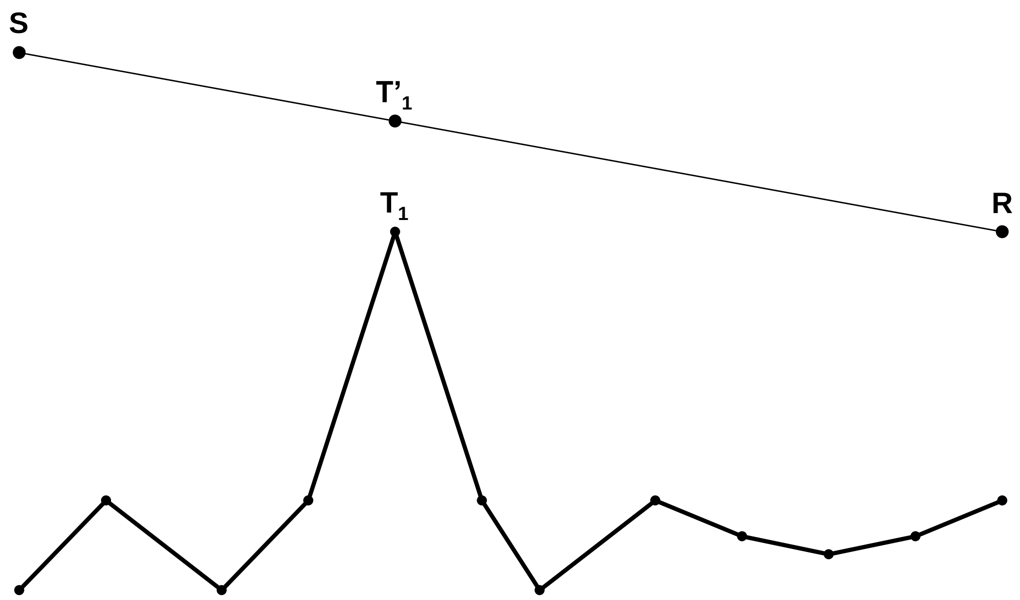

Figure 33
Definition of T_1' in cases where T_1 is below the line SR

The procedure is now to determine the path length difference $\Delta\ell_0$ on the source and on receiver side of the screen. This is done using a procedure similar to the one described in Section 5.21.1 where $\Delta\ell_0$ is calculated according Eq. (300). However, when calculating the maximum value of $\Delta\ell_0$ on the source side the point R is replaced by T_1 or T_1' if T_1 is below the line SR. In the same way, when calculating the maximum value of $\Delta\ell_0$ on the receiver side of the screen the point S is replaced by T_1 or T_1' if T_1 is below the line SR. The point giving the maximum value of $\Delta\ell_0$ is defined as the primary diffracting edge of the secondary screen and is denoted $T_2 = (x_{T2},z_{T2})$.

When T_2 has been determined, the next step is to determine the efficiency of the diffraction point. This is done by calculating a transition parameter denoted r_{SCR2}. This parameter will be determined on basis of the path length difference $\Delta\ell$ including the effect of refraction and on the distance $h_{base}(i_{T2})$ of T_2 to the terrain baseline.

$\Delta\ell$ is calculated by Eq. (307) where R'_S and R'_R are ray path length determined on basis of R_S, R_M, R_R in Eq. (226) and θ'_S and θ'_R are the diffraction angles determined on basis of θ_{1S} and θ_{1R} in Eq. (227) and θ_{2S} and θ_{2R} in Eq. (228). If the secondary screen is the screen closest to the receiver $R'_S = R_M$, $R_R' = R_R$, $\theta'_S = \theta_{2S}$ og $\theta'_R = \theta_{2R}$. If the secondary screen is the screen closest to the source $R'_S = R_S$, $R_R' = R_M$, $\theta'_S = \theta_{1S}$ og $\theta'_R = \theta_{1R}$.

$$\Delta\ell = Sign\left(\theta'_S - \theta'_R - \pi\right)\sqrt{R'^2_S + R'^2_R - 2R'_S R'_R \cos\left(\theta'_S - \theta'_R\right)} - R'_S - R'_R \qquad \textbf{(307)}$$

The efficiency of the diffraction point T_2 is based on the three criterions described in Section 5.21.1 and a fourth criterion saying that the distance between T_1 and T_2 shall be sufficiently large compared to the wavelength. The interpolation parameters $r_{\Delta\ell}(\lambda)$, $r_\lambda(\lambda)$, and $r_{Fz}(\lambda)$ corresponding to the three criterions are calculated by Eqs. (302) through (304) in the same way as for the primary edge of the primary screen but for T_2 instead of T_1. The interpolation parameters are in this case denoted $r_{\Delta\ell 2}(\lambda)$, $r_{\lambda 2}(\lambda)$, and $r_{Fz2}(\lambda)$, respectively The interpolation parameter $r_w(\lambda)$ corresponding to the fourth criterion is determined by Eq. (308).

$$r_w(\lambda) = \begin{cases} 1 & d_{12} \geq \lambda \\ \dfrac{d_{12}/\lambda - 0.3}{0.7} & 0.3\lambda < d_{12} < \lambda \\ 0 & d_{12} \leq 0.3\lambda \end{cases} \tag{308}$$

where

$$d_{12} = Length(x_{T1}, z_{T1}, x_{T2}, z_{T2})$$

The four interpolation parameters are finally combined into the transition parameter of the secondary screen $r_{scr2}(f)$ calculated by Eq. (309).

$$r_{scr2}(f) = r_{\Delta\ell 2}(f)\, r_{\lambda 2}(f)\, r_{Fz2}(f)\, r_w(f) \tag{309}$$

The purpose of transition parameter r_{scr2} is to combine the result of Sub-model 6 (terrain with screens) and the result by the “OneScreen” model (Sub-model 4 or a combination of Sub-model 4 and 5) as shown in Eq. (310).

$$\Delta L_{scr}(f) = r_{scr2}(f)\Delta L_6(f) + (1 - r_{scr2}(f))\Delta L_{scr1}(f) \tag{310}$$

If $r_{scr2}(f)$ is greater than zero at at least one frequency it will be necessary to make calculations by Sub-model 6. In this case it will be necessary to define which part of the terrain shall be interpreted as the “secondary screen shape”. The start of the screen is defined as the non-convex point closest to T_2 on the source side of T_2 and the end of the screen is defined as the non-convex point closest to T_2 on the receiver side of T_2. Whether a point is convex or non-convex is determined by the auxiliary function *Convex(i)*.

5.21.3 Determination of a Secondary Edge of the Primary Screen

If a secondary screen was found as described in Section 5.21.2 and $r_{scr2}(f)$ is equal to one at all frequencies, the “Screen” model is covered by Sub-model 6 (terrain with two screens). Otherwise, the next step will be to search for a secondary edge of the primary screen.

The selection of a secondary edge and the determination of the efficiency of the edge follow by and large the same principles used for the primary edge of the secondary screen. The main difference is that only points in the primary screen shape are considered with the exclusion of W_1, W_2 and T_1. Therefore, if the primary screen shape consists of 3 points there is no secondary edge. If the primary screen shape consists of more than 3 points, the point with largest path length difference $\Delta\ell_0$ has to be selected in the same way as for the primary edge of the secondary screen (if the screen shape consists of four points the selection becomes simple as only one possible point exists). This point point is denoted $T_{12} = (x_{T12}, z_{T12})$.

The interpolation parameters $r_{\Delta\ell}(\lambda)$, $r_\lambda(\lambda)$, $r_{Fz}(\lambda)$, and $r_w(\lambda)$ are calculated in the same way as for the secondary screen as described in Section 5.21.2 but T_2 is replaced by T_{12}. The interpolation parameters are in this case denoted $r_{\Delta\ell 12}(\lambda)$, $r_{\lambda 12}(\lambda)$, $r_{Fz12}(\lambda)$, and $r_{w12}(\lambda)$, respectively. The determination of the transition parameter r_{scr12} of the secondary edge contains two more modifiers $r'_{\lambda 12}(\lambda)$ and $r'_{Fz12}(\lambda)$. The purpose of the extra modifiers is to quantify that the shape T_1, T_{12}, W (=W_1 or W_2) deviates significantly from the straight line T_1 to W from a propagation point of view.

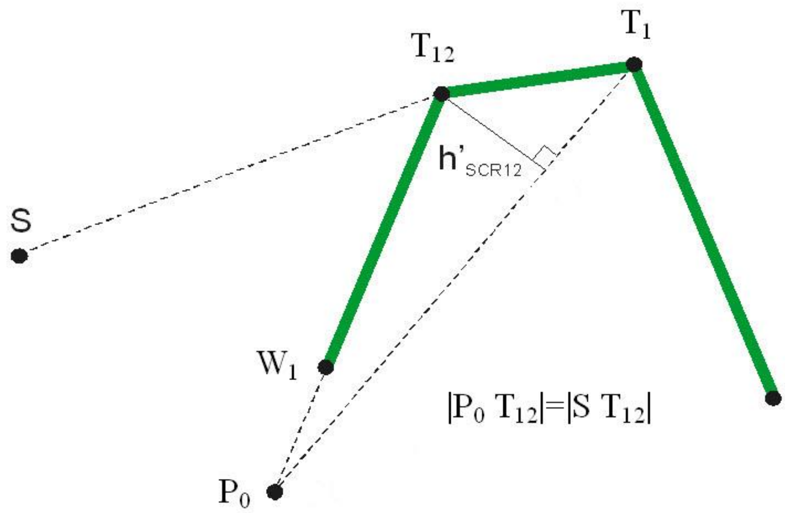

Figure 34
Definition of h'_{SCR12} used for determination of $r'_{\lambda 12}$ and r'_{Fz12}.

In order to determine the height h'_{SCR12} defined in Figure 34, the point P_0 is determined by Eq. (311) if T_{12} is on the source side of T_1. If T_{12} is on the receiver side of T_1 S has to be replaced by R and W_1 by W_2.

$$\overrightarrow{T_{12}P_0} = \frac{|T_{12}S|}{|T_{12}W_1|}\overrightarrow{T_{12}W_1} \qquad \textbf{(311)}$$

If $P_0 = (x_0, z_0)$ h'_{SCR12} can be calculated by Eq. (312).

$$\left(x'_{T12}, z'_{T12}, h'_{SCR12}\right) = NormLine\left(x_0, z_0, x_{T1}, z_{T1}, x_{T12}, z_{T12}\right) \qquad \textbf{(312)}$$

Finally $r'_{\lambda 12}(\lambda)$ and $r'_{Fz12}(\lambda)$ are calculated according to Eq. (303) and (304). In the equations $h_{SCR} = h'_{SCR12}$ and $h_{Fz}(\lambda)$ is determined by Eq. (313).

$$\begin{aligned} & h_{Fz}(\lambda) = CalcFZd\left(d_1, d_2, \pi/2, 0.5\lambda\right) \\ & where \\ & d_1 = Length\left(x_0, z_0, x'_{T12}, z'_{T12}\right) \\ & d_2 = Length\left(x_{T1}, z_{T1}, x'_{T12}, z'_{T12}\right) \end{aligned} \qquad \textbf{(313)}$$

The six interpolation parameters are finally combined into the transition parameter of the secondary edge $r_{scr12}(f)$ calculated by Eq. (314).

$$r_{scr12}(f) = r_{\Delta\ell 12}(f)\, r_{\lambda 12}(f)\, r_{Fz12}(f) r_{w12}(f) r'_{\lambda 12}(f)\, r'_{Fz12}(f) \qquad \textbf{(314)}$$

The purpose of transition parameter r_{scr12} is to combine the results by Sub-model 4 and 5 into a result by the "OneScreen" model and as shown in Eq. (315).

$$\Delta L_{scr1}(f) = r_{scr12}(f)\Delta L_5(f) + \left(1 - r_{scr12}(f)\right)\Delta L_4(f) \qquad \textbf{(315)}$$

5.21.4 Determination of Terrain Flatness

In the Section Determination of a Primary Edge of a Primary Screen the transition between the "NoScreen" and "Screen" model is described. The "NoScreen" model itself is a combination of the "Flat" model (Sub-model 1 or 2) and the "Non-flat terrain without screens" model (Sub-model 3). The transition between the "NoScreen" and "Screen" model is quantified by the transition parameter r_{flat}.

Before determining r_{flat} the equivalent flat terrain has to be determined as described in Section 5.21.5. Then the source height h_{Se}, receiver height h_{Re} and distance along the terrain d_e measured relative to the equivalent flat terrain can be determined as shown in Eq. (316).

$$\begin{aligned} & \left(x'_{SGe}, z'_{SGe}, h'_{Se}\right) = NormLine\left(x_{SGe}, z_{SGe}, x_{RGe}, z_{RGe}, x_S, z_S\right) \\ & \left(x'_{RGe}, z'_{RGe}, h'_{Re}\right) = NormLine\left(x_{SGe}, z_{SGe}, x_{RGe}, z_{RGe}, x_R, z_R\right) \\ & d_e = Length\left(x'_{SGe}, z'_{SGe}, x'_{RGe}, z'_{RGe}\right) \\ & h_{Se} = Max\left(h'_{Se}, 0.01\right) \\ & h_{Re} = Max\left(h'_{Re}, 0.01\right) \end{aligned} \qquad \textbf{(316)}$$

The interpolation parameter $r_f(f)$ defining the "flatness" of the terrain can now be calculated by Eq. (317) where ΔR_2 is the increase in path length if the flat terrain is displaced by downwards by Δh. Δh is the average height of the terrain above the equivalent flat terrain calculated in Section 5.21.5. Eq. (317) is only used in the frequency range 25 Hz to 2000

Hz. At higher frequencies the value at 2000 Hz is used to avoid that the terrain always will be interpreted as being non-flat at very high frequencies. $r_f = 1$ indicates a flat terrain while $r_f = 0$ indicates a non-flat terrain.

$$r_f(f) = \begin{cases} 1 & \frac{\Delta R_2}{\lambda} \le 0.01 \\ \frac{0.03 - \Delta R_2/\lambda}{0.02} & 0.01 < \frac{\Delta R_2}{\lambda} < 0.03 \\ 0 & \frac{\Delta R_2}{\lambda} \ge 0.03 \end{cases} \qquad \textbf{(317)}$$

where

$$\Delta R_2 = \sqrt{(h_{Se} + h_{Re} + 2\Delta h)^2 + d_e^2} - \sqrt{(h_{Se} + h_{Re})^2 + d_e^2}$$

Due to the fact that r_f according to Eq. (317) in most cases will be 1 at very low frequencies even in cases of a highly concavely shaped terrain where submodel 3 for non-flat is known to produce better result, the transition parameter is modified as shown in Eq. (393) based on a the sum of Fresnel-zone weights for concave segments and the concave part of the transition segments in Sub-model 3.

$$r_{flat}(f) = \begin{cases} r_f & w_{con} \le 1.05 \\ \frac{1.4 - \sum_{i=1}^{N_{ts}} w_{con,i}(f)}{0.35} r_f & 1.05 < w_{con} < 1.4 \\ 0 & w_{con} \ge 1.4 \end{cases} \qquad \textbf{(318)}$$

where

$$w_{con,i}(f) = \begin{cases} w_i(f) & \textit{for concave segments, from Eq.}(131) \\ w_{i,concave}(f)r(f) & \textit{for transition segments, from Eq.}(152) \\ 0 & \textit{for convex segments} \end{cases}$$

The purpose of transition parameter r_{flat} is to combine the results by the "Flat" model (Sub-model 1 or 2) and Sub-model 3 for non-flat terrain without screens as shown in Eq. (319).

$$\Delta L_{noscr}(f) = r_{flat}(f)\Delta L_{flat}(f) + (1 - r_{flat}(f))\Delta L_3(f) \qquad \textbf{(319)}$$

5.21.5 Equivalent Flat Terrain

The equivalent flat terrain is defined as the flat terrain giving the best fit to a non-flat terrain using the least squares method.

The equivalent flat terrain is defined by the coefficients α and β as shown in Eq. (320).

$$z = \alpha + \beta x \qquad \textbf{(320)}$$

The first step when determining the parameters α and β is to calculate the mean value of x and z as shown in Eq. (321).

$$\begin{aligned}
\bar{x} &= \frac{x_{nxz} + x_1}{2} \\
\bar{z} &= \frac{1}{x_{nxz} - x_1} \sum_{i=1}^{nxz-1} \frac{\gamma_i}{2}\left(x_{i+1}^2 - x_i^2\right) + \left(z_i - \gamma_i x_i\right)\left(x_{i+1} - x_i\right) \\
&\textit{where} \\
\gamma_i &= \frac{z_{i+1} - z_i}{x_{i+1} - x_i}
\end{aligned} \qquad \textbf{(321)}$$

Then α and β can be determined as shown in Eq. (322).

$$\begin{aligned}
t_2 &= \frac{x_{nxz}^2 - x_1^2}{3} - \bar{x}\left(x_{nxz}^2 - x_1^2\right) + \bar{x}^2\left(x_{nxz} - x_1\right) \\
t_1 &= \sum_{i=1}^{nxz-1} \frac{\gamma_i}{3}\left(x_{i+1}^2 - x_i^2\right) + \frac{z_i - \bar{z} - \gamma_i\left(x_i + \bar{x}\right)}{2}\left(x_{i+1}^2 - x_i^2\right) + \\
&\qquad \bar{x}\left(\gamma_i x_i - z_i + \bar{z}\right)\left(x_{i+1} - x_i\right) \\
\beta &= \frac{t_1}{t_2} \\
\alpha &= \bar{z} - \bar{x}\beta
\end{aligned} \qquad \textbf{(322)}$$

The average height of the terrain Δh above the equivalent flat terrain can subsequently be calculated based on the area of each segment A_i above the equivalent flat terrain (Δh will be the same if A_i is the area of the terrain below the equivalent flat terrain) as shown in Eq. (323). A_i is calculated as shown in the following.

$$\Delta h = \frac{1}{x_{nxz} - x_1} \sum_{i=1}^{nxz-1} A_i \qquad \textbf{(323)}$$

For each segment the vertical height of the terrain relative to the equivalent flat terrain h_i at the start of the segment and h_{i+1} at the end of the segment are determined by Eq. (324).

$$\begin{aligned}
h_i &= z_i - \alpha - \beta x_i \\
h_{i+1} &= z_{i+1} - \alpha - \beta x_{i+1}
\end{aligned} \qquad \textbf{(324)}$$

If h_i and h_{i+1} have the same sign ($h_i h_{i+1} \geq 0$) indicating that the segment and the equivalent flat terrain do not intersect, A_i is calculated by Eq. (325). If $A_i<0$, A_i is set to 0 when applied in Eq. (323).

$$A_i = \frac{h_{i+1} + h_i}{2}\left(x_{i+1} - x_i\right) \tag{325}$$

If h_i and h_{i+1} have opposite signs ($h_i h_{i+1} < 0$) indicating that the segment and the equivalent flat terrain intersects, A_i is calculated by Eq. (326). If $A_i<0$, A_i is set to 0 when applied in Eq. (323).

$$A_i = \begin{cases} \frac{h_i}{2}\left(x_x - x_i\right) & h_i > 0 \\ \frac{h_{i+1}}{2}\left(x_{i+1} - x_x\right) & h_i < 0 \end{cases} \tag{326}$$

where

$$x_x = \frac{|h_i|}{|h_{i+1}| + |h_i|}\left(x_{i+1} - x_i\right) + x_i$$

Instead of characterizing the equivalent flat terrain by the coefficients α and β, the terrain can also be characterized by start and end coordinates as defined as shown in Eq. (327).

$$\begin{aligned} x_{SGe} &= x_S \\ z_{SGe} &= \alpha + \beta x_S \\ x_{RGe} &= x_R \\ z_{SGe} &= \alpha + \beta x_R \end{aligned} \tag{327}$$

5.21.6 Finite Screens

As already stated in Section 2 screens are in the Nordtest standard method assumed to have infinite horizontal length perpendicular to the direction of propagation. However, if a screen has a finite horizontal size a significant contribution of sound may propagate laterally from source to receiver around the vertical edges of the screen. This can be taken into account as described in the informative Annex E. It is in general recommended to ignore lateral diffraction in case of moving sources due to the averaging caused by the movement.

In some cases the height of the screen may vary laterally. For such screens the calculation is performed for a screen height determined by the average height within the significant part of the screen. The significant part of the screen is defined by the part of the screen which is inside the horizontal limits of the Fresnel-zone around the propagation path as shown in Figure 35.

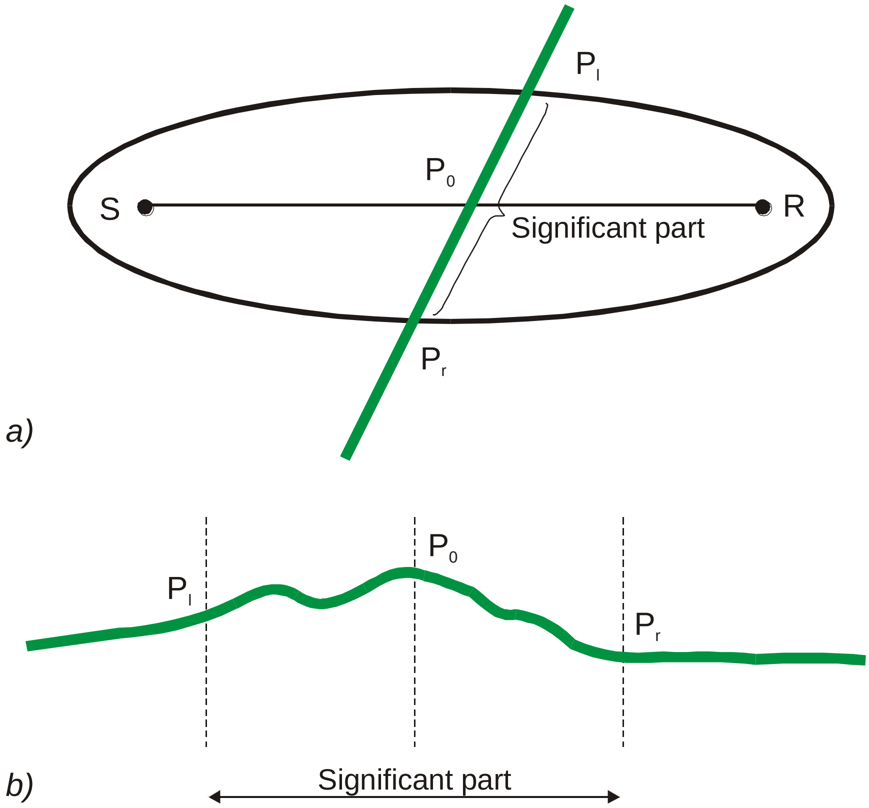

Figure 35
Significant part of screen used to calculate the average height. a) top view, b) front view.

The width of the Fresnel-zone defined by the distance $d(\theta)$ from P_0 to P_l or P_r is determined by Eq. (328) where θ is the angle between the line SR and P_0P_l or P_0P_r. The constant 0.4 corresponds approximately to a frequency of 250 Hz and a fraction F_λ of the wavelength equal to ½.

$$d(\theta) = CalcFZd\left(|SP_0|,|RP_0|,\theta,0.4\right) \qquad \textbf{(328)}$$

5.22 Compound Model

The sound pressure level L_R at the receiver is for each frequency band predicted according to Eq. (329).

$$L_R(f) = L_W(f) + \Delta L_d + \Delta L_a(f) + \Delta L_t(f) + \Delta L_s(f) + \Delta L_r(f) \qquad \textbf{(329)}$$

ΔL_d is the effect of free field attenuation in a homogeneous atmosphere due to spherical spreading of the sound energy and is calculated by Eq. (330).

$$\Delta L_d = -10 \log\left(4\pi R^2\right) \tag{330}$$

$\Delta L_a(f)$ is the effect of air absorption calculated by Sub-model 9 as shown in Eq. (331).

$$\Delta L_a(f) = \Delta L_9(f) \tag{331}$$

$\Delta L_t(f)$ is the propagation effect of ground and screens. $\Delta L_t(f)$ is combined of several sub-models as shown in Eq. (332).

$$\begin{aligned}
&\Delta L_t(f) = \left(r_{scr1}(f)\Delta L_{scr}(f) + \left(1 - r_{scr1}(f)\right)\Delta L_{noscr}(f)\right) \oplus \Delta L_8(f)\\
&\Delta L_{scr}(f) = r_{scr2}(f)\left(\Delta L_6(f) \oplus \Delta L_{7,2}(f)\right) + \left(1 - r_{scr2}(f)\right)\Delta L_{scr1}(f)\\
&\Delta L_{scr1}(f) = r_{scr12}(f)\left(\Delta L_5(f) \oplus \Delta L_{7,2}(f)\right) + \left(1 - r_{scr12}(f)\right)\left(\Delta L_4(f) \oplus \Delta L_{7,1}(f)\right)\\
&\Delta L_{noscr}(f) = r_{flat}(f)\Delta L_{flat}(f) + \left(1 - r_{flat}(f)\right)\Delta L_3(f)\\
&\Delta L_{flat}(f) = \begin{cases} \Delta L_1 & \textit{one impedance and one roughness} \\ \Delta L_2 & \textit{otherwise} \end{cases}
\end{aligned} \tag{332}$$

$\Delta L_s(f)$ is the propagation effect of a scattering zone (mainly forest and other vegetation) calculated by Sub-model 10 as shown in Eq. (333). Another propagation effect of a scattering zone is that the coherence between rays are reduced in the ground and screen model used to predict $\Delta L_t(f)$. This is quantified by the coherence coefficient $F_s(f)$.

$$\Delta L_s(f) = \begin{cases} \Delta L_{10}(f) & \textit{scattering zone along propagation path} \\ 0 & \textit{otherwise} \end{cases} \tag{333}$$

$\Delta L_r(f)$ is the propagation effect of a reflector calculated by Sub-model 11 as shown in Eq. (334).

$$\Delta L_r(f) = \begin{cases} \Delta L_{11}(f) & \textit{propagation path is a reflection path} \\ 0 & \textit{otherwise} \end{cases} \tag{334}$$

5.23 Auxiliary Functions

This section contains a number of auxiliary functions used to solve a number of calculation problems in the method.

5.23.1 Coft

The function *Coft* calculates the adiabatic sound speed c (m/s) in dry air at the temperature t (°C).

The sound speed c is calculated by Eq. (335).

$$c = Coft(t) = 20.05\sqrt{t + 273.15} \qquad \textbf{(335)}$$

5.23.2 Convex

The function *Convex* determines whether two terrain segments intersecting at $P_i = (x_i,z_i)$ in the terrain profile form a convex shape (angle between segments above π) as shown i Eq. (336) where i is the terrain point number and b_{cvx} is a logical variable (1 means convex intersection, 0 if concave or straight).

$$b_{cvx}(i) = Convex(i) = H(VertDist(x_{i-1}, z_{i-1}, x_{i+1}, z_{i+1}, x_i, z_i) - 0.0001) \qquad \textbf{(336)}$$

The value 0.0001 has been introduced to avoid numerical problems in the calculations.

5.23.3 Exp'

The function Exp' is a practically modified exponential function. The function is modified to be zero below the argument -2. The function is defined in Eq. (337).

$$y = \exp'(x) = \begin{cases} \exp(x) & x \geq -1 \\ (2 + x)\exp(1) & -2 < x < -1 \\ 0 & x \leq -2 \end{cases} \qquad \textbf{(337)}$$

5.23.4 CalcFZd

The function *CalcFZd* is used to calculate the distance from the reflection point O within the Fresnel-zone to a point on the elliptic Fresnel-zone in direction θ as shown in Figure 36. S and R are the foci of the ellipse and $r_S = |SO|$ and $r_R = |RO|$.

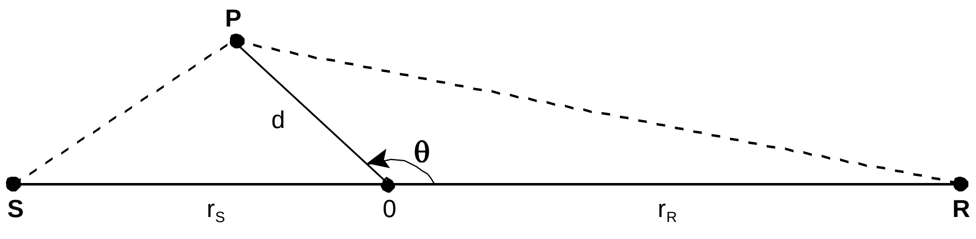

Figure 36
Definition of calculation parameters.

The function *CalcFZd* is defined by Eq. (338) where $F_\lambda\lambda$ is the product of a fraction F_λ and the wavelength λ.

$$d = CalcFZd\left(r_S, r_R, \theta, F_\lambda \lambda\right) \quad \textbf{(338)}$$

The distance d = $|OP|$ is calculated as shown in Eq. (339).

$$\begin{aligned}
r &= r_S + r_R \\
\ell &= r + F_\lambda \lambda \\
A &= 4\left(\ell^2 - (r\cos\theta)^2\right) \\
B &= 4\,r\cos\theta\left(r_R^2 - r_S^2\right) + 4\left(r_S - r_R\right)\ell^2\cos\theta \\
C &= -\ell^4 + 2\left(r_S^2 + r_R^2\right)\ell^2 - \left(r_S^2 - r_R^2\right) \\
d &= \frac{-B + \sqrt{B^2 - 4AC}}{2A}
\end{aligned} \quad \textbf{(339)}$$

5.23.5 FresnelZoneSize

The function *FresnelZoneSize* calculates the size of a Fresnel-zone of a reflecting plane assuming a non-refracting atmosphere. The function is defined by Eq. (340).

$$\left(a_1, a_2, b\right) = FresnelZoneSize\left(d, h_S, h_R, F_\lambda \lambda\right) \quad \textbf{(340)}$$

where

d is the distance from image source S’ to receiver R measured along the reflection plane

h_S is the height of the source above the plane

h_R is the height of the receiver above the plane

$F_\lambda\lambda$ is the product of a fraction F_λ and the wavelength λ

a_1 is the distance from the reflection point O to the source side Fresnel-zone borderline in the direction of propagation

a_2 is the distance from the reflection point O to the receiver side Fresnel-zone borderline in the direction of propagation

b is half the width of the Fresnel-zone perpendicular to the direction of propagation

The variables are defined in Figure 37.

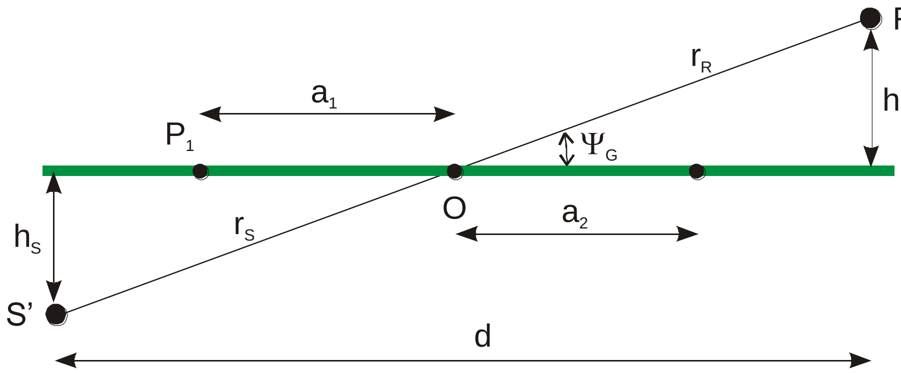

Figure 37
Definition of variables used when calculating the size of the Fresnel-zone in case of reflection by a plane surface.

The variables a_1, a_2, and b are calculated by Eqs. (341) to **(343)**.

$$a_1 = |P_1O| = CalcFZd\left(r_S, r_R, \pi - \psi_G, F_\lambda \lambda\right) \tag{341}$$

$$a_2 = |P_2O| = CalcFZd\left(r_S, r_R, \psi_G, F_\lambda \lambda\right) \tag{342}$$

$$b = \sqrt{\frac{CalcFZd\left(r_S, r_R, \frac{\pi}{2}, F_\lambda \lambda\right)^2}{1 - \left(\frac{a_2 - a_1}{a_2 + a_1}\right)^2}} \tag{343}$$

In Eqs. (341) to **(343)** r_S, r_R and ψ_G are determined as shown in Eq. (344).

$$\begin{aligned}
\psi_G &= \arctan\left(\frac{h_S + h_R}{d}\right) \\
r &= \sqrt{(h_S + h_R)^2 + d^2} \\
r_S &= \frac{h_S}{h_S + h_R} r \\
r_R &= \frac{h_R}{h_S + h_R} r
\end{aligned} \tag{344}$$

5.23.6 FresnelZoneW

The function *FresnelZoneW* calculates the frequency dependent Fresnel-zone weight of a ground segment assuming a refracting atmosphere. The function is defined by Eq. (345).

$$\left(w(f), \breve{d}, \breve{h}_S, \breve{h}_R, \breve{d}_{refl}\right) = FresnelZoneW\left(d, h_S, h_R, d_1, d_2, F_\lambda \lambda, \xi, c_0\right) \quad \textbf{(345)}$$

where

d is the horizontal distance measured along the extended ground segment from source S to receiver R

h_S is the height of S above the extended ground segment (if $h_S < 0.01$, $h_S = 0.01$ is used instead)

h_R is the height of R above the extended ground segment (if $h_R < 0.01$, $h_R = 0.01$ is used instead)

d_1 is the horizontal distance measured along the extended ground segment from source S to end point of the ground segment closest to S

d_2 is the horizontal distance measured along the extended ground segment from source S to end point of the ground segment closest to R

$F_\lambda \lambda$ is the product of a fraction F_λ and the wavelength λ

ξ is the relative sound speed gradient in the equivalent linear sound speed profile

c_0 is the sound speed at the ground in the equivalent linear sound speed profile

$\breve{d}, \breve{h}_S, \breve{h}_R, \breve{d}_{refl}$ are the modified propagation variables corresponding to the modified source S' and receiver position R' when the curved ray case is transformed into the straight ray case as described in the following.

The first step is to determine the position of the reflection point defined by the horizontal distance d_{refl} measured along the extended ground segment from source S, the grazing reflection angle ψ_G, and the ray path distances from source to reflection point R_S and from receiver to reflection point R_R taking into account the effect of refraction. This is done according to Eq. (346) if the receiver is not in the shadow zone (is determined by Eq. (43) in Section 5.5.4).

$$\left(NA, NA, R_S, R_R, NA, NA, \psi_G, d_{drefl}\right) = ReflectedRay\left(d, h_{S,}, h_R, \xi, c_0\right) \quad \textbf{(346)}$$

The variables are shown in Figure 38.

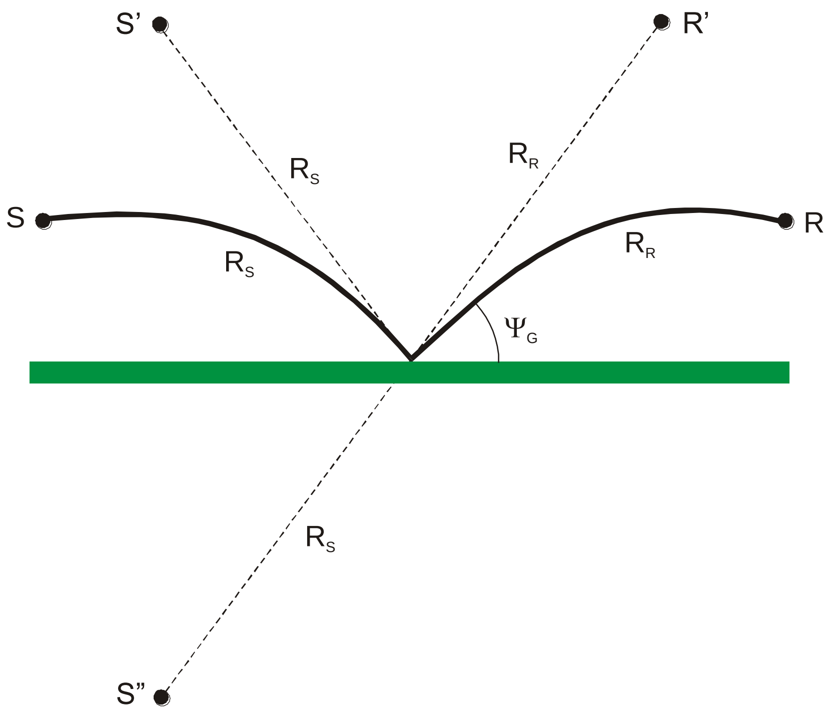

Figure 38
Definition of variables when determining of the Fresnel-zone weight in case of refraction (circular rays).

If the receiver is in the shadow zone the variables are instead determined by Eq. (347).

$$\begin{aligned}
&\psi_G = 0 \\
&d_{refl} = d\frac{\sqrt{h_S}}{\sqrt{h_S}+\sqrt{h_R}} \\
&R_S = R_0 \arccos\left(1-\frac{h_S}{R_0}\right) \\
&R_R = R_0 \arccos\left(1-\frac{h_R}{R_0}\right) \\
&\textit{where} \\
&R_0 = \left(\frac{d}{2\left(\sqrt{h_S}+\sqrt{h_R}\right)}\right)
\end{aligned} \qquad \textbf{(347)}$$

In order to calculate the size of the Fresnel-zone by the auxiliary function *FresnelZoneSize* valid for a non-refracting atmosphere the curved ray case is transformed into the straight ray case by determining modified source and receiver positions S' and R' as indicated in Figure 38. The modified variables d', h'_S, h'_R and d'_{refl} are calculated by Eq. (348). d'_{refl} is horizontal distance from the modified source S' to the reflection point measured along the extended ground segment.

$$\begin{aligned}\breve{d} &= (R_S + R_R)\cos\psi_G \\ \breve{h}_S &= R_S \sin\psi_G \\ \breve{h}_R &= R_R \sin\psi_G \\ \breve{d}_{refl} &= R_S \cos\psi_G\end{aligned} \qquad \textbf{(348)}$$

Now the position of the Fresnel-zone borders in the direction of propagation relative to the reflection point can be determined by Eq. (349) and **(350)**. $d_{1,Fz}$ and $d_{2,Fz}$ are the horizontal frequency dependent distance measured along the extended ground segment from source S to end point of the ground segment closest to S and R, respectively.

$$(a_1(f), a_2(f), NA) = FresnelZoneSize(d, h_S, h_R, F_\lambda \lambda) \qquad \textbf{(349)}$$

$$\begin{aligned}d_{1,Fz}(f) &= d_{refl} - a_1(f) \\ d_{2,Fz}(f) &= d_{refl} + a_2(f)\end{aligned} \qquad (350)$$

The frequency dependent Fresnel-zone weight w(f) can now be determined by Eq. (351).

$$w(f) = \begin{cases} 0 & d_1 \geq d_{2,Fz} \vee d_2 \leq d_{1,Fz} \\ 1 & d_1 \leq d_{1,Fz} \wedge d_2 \geq d_{2,Fz} \\ (d_2 - d_1)/(d_{2,Fz} - d_{1,Fz}) & d_1 > d_{1,Fz} \wedge d_2 < d_{2,Fz} \\ (d_2 - d_{1,Fz})/(d_{2,Fz} - d_{1,Fz}) & d_1 \leq d_{1,Fz} \wedge d_2 < d_{2,Fz} \\ (d_{2,Fz} - d_1)/(d_{2,Fz} - d_{1,Fz}) & d_1 > d_{1,Fz} \wedge d_2 \geq d_{2,Fz} \end{cases} \qquad \textbf{(351)}$$

5.23.7 FresnelZoneWm

The function *FresnelZoneWm* calculates a modified Fresnel-zone weight w'(f) of a ground segment assuming a refracting atmosphere. The function is defined by Eq. (352).

$$w'(f) = FresnelZoneWm(d, h_S, h_R, d_1, d_2, F_\lambda \lambda, \xi, c_0) \qquad \textbf{(352)}$$

The input variables are the same as for the function *FresnelZoneW* described in Section 5.23.6. The procedure for calculating the weight is the same as described in Section 5.23.6 except that the Eq. (351) has been replaced by Eq. (353). According to the principle in Eq. (353) the contribution to the Fresnel-zone weight on each side of the reflection point is the same size.

$$w(f) = 0.5(w_S(f) + w_R(f))$$
where

$$w_S(f) = \begin{cases} 0 & d_1 \geq d_{refl} \vee d_2 \leq d_{1,Fz} \\ 1 & d_1 \leq d_{1,Fz} \wedge d_2 \geq d_{refl} \\ (d_2 - d_1)/(d_{refl} - d_{1,Fz}) & d_1 > d_{1,Fz} \wedge d_2 < d_{refl} \\ (d_2 - d_{1,Fz})/(d_{refl} - d_{1,Fz}) & d_1 \leq d_{1,Fz} \wedge d_2 < d_{refl} \\ (d_{2,Fz} - d_1)/(d_{refl} - d_{1,Fz}) & d_1 > d_{1,Fz} \wedge d_2 \geq d_{refl} \end{cases}$$

$$w_R(f) = \begin{cases} 0 & d_1 \geq d_{2,Fz} \vee d_2 \leq d_{refl} \\ 1 & d_1 \leq d_{refl} \wedge d_2 \geq d_{2,Fz} \\ (d_2 - d_1)/(d_{2,Fz} - d_{refl}) & d_1 > d_{refl} \wedge d_2 < d_{2,Fz} \\ (d_2 - d_{refl})/(d_{2,Fz} - d_{refl}) & d_1 \leq d_{refl} \wedge d_2 < d_{2,Fz} \\ (d_{2,Fz} - d_1)/(d_{2,Fz} - d_{refl}) & d_1 > d_{refl} \wedge d_2 \geq d_{2,Fz} \end{cases}$$ **(353)**

5.23.8 H

The function *H(x)* is Heavisides step function calculated as shown in Eq. (354).

$$H(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases}$$ **(354)**

5.23.9 HeightOfCircularRay

The function *HeightOfCircularRay* calculates the height of a circular ray. As shown in Figure 39 the ray starts at the point (0,h_1) and ends at the point (d,h_2). The curvature of the ray corresponds to a relative sound speed gradient ξ. The function calculates the height of the ray h_0 at point P_0 in the horizontal distance d_0 from the start of the ray as defined in Eq. (355). The function also calculates the lengths of the ray R_1 and R_2 from P_0 to the starting and end points, respectively.

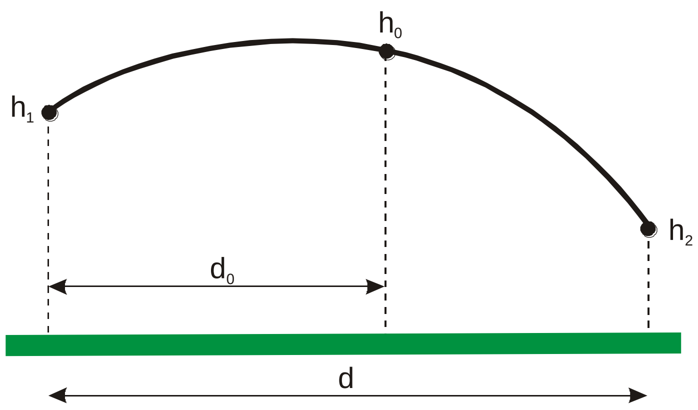

Figure 39
Definition of geometrical parameters in the function HeightOfCircularRay.

$$(h_0, R_1, R_2) = HeightOfCircularRay(d, h_1, h_2, \xi, d_0) \qquad \textbf{(355)}$$

In order to normalise the problem to the solution given in Section 5.5.4, the parameters ξ', d_0', h_1' and Δh are defined as shown in Eqs. (356) to **(361)**.

$$\xi' = |\xi| \qquad \textbf{(356)}$$

$$\Delta h = |h_1 - h_2| \qquad (357)$$

$$\xi > 0 \wedge h_1 > h_2 : \quad h_1' = h_2, \quad d_0' = d - d_0 \qquad (358)$$

$$\xi > 0 \wedge h_1 \le h_2 : \quad h_1' = h_1, \quad d_0' = d_0 \qquad (359)$$

$$\xi < 0 \wedge h_1 \ge h_2 : \quad h_1' = -h_1, \quad d_0' = d_0 \qquad (360)$$

$$\xi < 0 \wedge h_1 < h_2 : \quad h_1' = -h_2, \quad d_0' = d - d_0 \qquad (361)$$

Now the height h_0 can be determined by Eqs. (362) to **(367)** where Sign(x) is the signum function. (x_0,z_0) is the centre of circular ray with radius of curvature R_c.

$$\tan\psi_L = \frac{\xi' d}{2} + \frac{\Delta h\,(2 + \xi' \Delta h)}{2d} \qquad \textbf{(362)}$$

$$x_0 = \frac{\tan\psi_L}{\xi'} \qquad (363)$$

$$z_0 = h_1' - \frac{1}{\xi'} \tag{364}$$

$$R_c = \frac{1}{\xi' \cos(\psi_L)} \tag{365}$$

$$\theta = \arccos\left(\frac{d_0' - x_0}{R_c}\right) \tag{366}$$

$$h_0 = Sign(\xi)\left(R_c \sin(\theta) + z_0\right) \tag{367}$$

Finally, R_1 and R_2 can be calculated by Eq. (368).

$$\begin{aligned} R_1 &= 2R_c \arcsin\left(\frac{r_1}{2R_c}\right) \\ R_2 &= 2R_c \arcsin\left(\frac{r_2}{2R_c}\right) \\ &\textit{where} \\ r_1 &= Length(0, h_1, d_0, h_0) \\ r_2 &= Length(d_0, h_0, d, h_2) \end{aligned} \tag{368}$$

5.23.10 ImagePoint

The function *ImagePoint* calculates the coordinates of the image P_{image} of a point P reflected in a line P_1P_2 as shown in Eq. (369).

$$(x_i, y_i) = Length(x_1, y_1, x_2, y_2, x, y) \tag{369}$$

where

P = (x,y)

$P_1 = (x_1,y_1)$

$P_2 = (x_2,y_2)$

$P_{image} = (x_i,y_i)$

The coordinates of P_{image} is calculated by Eq. (370).

$$\begin{aligned}(x_0, y_0, NA) &= NormLine(x_1, y_1, x_2, y_2, x, y)\\ x_i &= 2x_0 - x\\ z_i &= 2z_0 - z\end{aligned} \quad \textbf{(370)}$$

5.23.11 Length

The function *Length* calculates the length of a line P_1P_2 as shown in Eq. (371).

$$d = Length(x_1, y_1, x_2, y_2) \quad \textbf{(371)}$$

where

$P_1 = (x_1,y_1)$

$P_2 = (x_2,y_2)$

d is the distance between P_1 and P_2

The distance d is calculated by Eq. (372)

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad \textbf{(372)}$$

5.23.12 MinConcaveHeight

The function *MinConcaveHeight* calculates the smallest source or receiver height where the end point of the ground segment closest to the source or receiver point under consideration is at the border of the Fresnel-zone. This height which depends on the frequency is used in Sub-model 3 (non-flat terrain without screening effects) to determine whether a segment is concave or not. The principle is illustrated in Figure 40 for the source case.

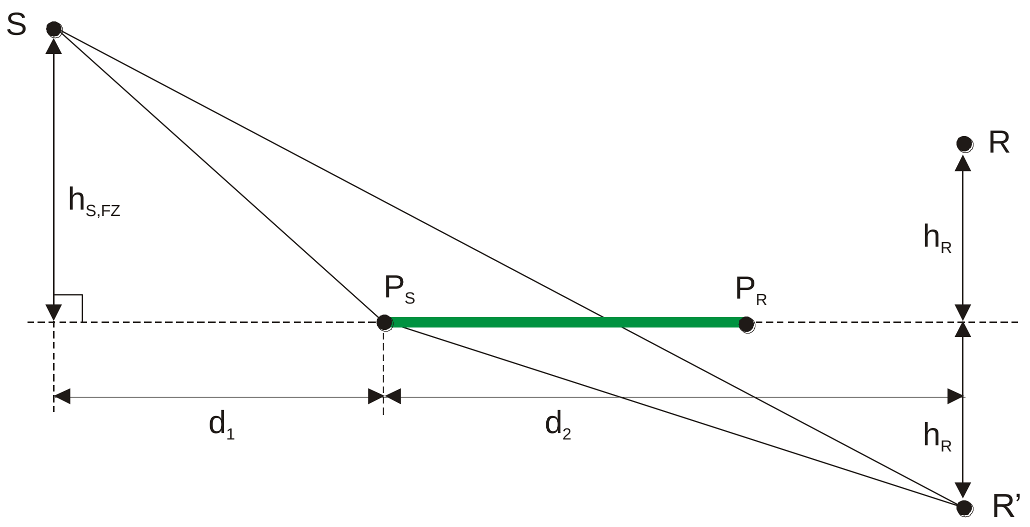

Figure 40
Definition of the principle for calculating the minimum source height $h_{S,Fz}$ of a concave segment and definition of variables used in the calculation.

The function is defined by Eq. (373) where the variables h_R, d_1 and $d = d_1 + d_2$ are defined in Figure 40 and where λ is the wavelength. The same function is used to calculate $h_{R,Fz}$ by interchanging S and R.

$$h_{S,Fz}(f) = MinConcaveHeight(h_R, d_1, d, \lambda) \quad \textbf{(373)}$$

If Eq. (374) is fulfilled $h_{S,Fz}(f)$ is set equal to ∞. Otherwise $h_{S,Fz}$ is calculated by Eq. **(375)** where F_λ = 1/16. The variables A, B, C, x_1 and x_2 in Eq. **(375)** are a function of the frequency although not indicated.

$$\sqrt{d_2^2 + h_R^2} - h_R \le F_\lambda \lambda \quad \textbf{(374)}$$

$$h_{S,Fz}(f) = \frac{-B - \sqrt{B^2 - 4AC}}{2A}$$

where

$$A = 4h_R^2 - 4x_1$$
$$B = 4h_R x_2$$
$$C = x_2^2 - 4d_1^2 x_1 \quad (375)$$

and

$$x_1 = \left(\sqrt{\left(h_R^2 + d_2^2\right)} - F_\lambda \lambda\right)^2$$
$$x_2 = h_R^2 + (d_1 + d_2)^2 - d_1^2 - x_1$$

5.23.13 NormLine

The function *NormLine* determines the projection of a point P onto a line P_1P_2 and the signed distance to the directed line as shown in Eq. (376).

$$(x_0, y_0, d) = NormLine(x_1, y_1, x_2, y_2, x, y) \quad \textbf{(376)}$$

where

P = (x,y)

$P_1 = (x_1,y_1)$

$P_2 = (x_2,y_2)$

$P_0 = (x_0,y_0)$ is the projection point

d is the signed distance to the line. Positive and negative values indicate that the point P is left or right of the line, respectively.

The projection point P_0 and the distance d is calculated by Eq. (377).

$$\begin{aligned}
x_{21} &= x_2 - x_1 \\
y_{21} &= y_2 - y_1 \\
x_{01} &= x - x_1 \\
y_{01} &= y - y_1 \\
c &= (x_{21}x_{01} + y_{21}y_{01}) / (x_{21}^2 + y_{21}^2) \\
x_0 &= cx_{21} + x_1 \\
y_0 &= cy_{21} + y_1 \\
d &= (x_{21}y_{01} - y_{21}x_{01}) / \sqrt{x_{21}^2 + y_{21}^2}
\end{aligned} \quad \textbf{(377)}$$

5.23.14 PhaseDiffFreq

The function *PhaseDiffFreq* calculates a frequency $f_{\Delta\alpha}$ corresponding to a phase difference $\Delta\alpha$ between direct sound and sound reflected by flat ground in case of straight line propagation (homogeneous atmosphere) as shown in Eq. (378) where d is the horizontal propagation distance, h_S is the source height, h_R is the receiver height, $Z_G(f)$ is the terrain impedance as a function of the one-third octave band frequency from 25 Hz to 10 kHz, and the c_0 is the sound speed at the ground.

$$f_{\Delta\alpha} = PhaseDiffFreq(d, h_S, h_R, \hat{Z}_G(f), c_0, \Delta\alpha) \quad \textbf{(378)}$$

The phase shift $\Delta\alpha(f)$ is calculated at the frequency f by Eq. (379) where arg is the argument of the plane-wave reflection coefficient R_p (complex number). $\Delta\alpha$ given by Eq. (379) is increasing with the frequency.

$$\Delta\alpha(f) = \frac{2\pi f}{c_0}\Delta R + \arg\left(\hat{R}_p(f,\psi_G)\right)$$

where

$$\Delta R = \sqrt{d^2 + (h_S + h_R)^2} - \sqrt{d^2 + (h_S - h_R)^2} \qquad \textbf{(379)}$$

$$\psi_G = \arcsin\left(\frac{h_S + h_R}{\sqrt{d^2 + (h_S + h_R)^2}}\right)$$

The problem of determining the frequency f corresponding to the phase shift $\Delta\alpha$ using Eq. (379) can only be solved by iteration. In order to reduce the calculation time the recommended procedure is to calculate $\Delta\alpha$ at the one-third octave band frequencies until $\Delta\alpha$ is within the range of two neighbouring frequencies (denoted f_1 and f_2). Interpolation with the logarithmic frequency is used to obtain the value $f_{\Delta\alpha}$ corresponding $\Delta\alpha$ as shown in Eq. (380).

$$\log(f_{\Delta\alpha}) = \frac{\Delta\alpha - \Delta\alpha(f_1)}{\Delta\alpha(f_2) - \Delta\alpha(f_1)}\left(\log(f_2) - \log(f_1)\right) + \log(f_1) \qquad \textbf{(380)}$$

If $\Delta\alpha$ is greater than $\Delta\alpha$(10 kHz), linear extrapolation based on the values at 8 and 10 kHz is used up to 100 kHz. Above 100 kHz the value at 100 kHz is used. If $\Delta\alpha$ is less than $\Delta\alpha$(25 Hz), logarithmic extrapolation is used as shown by Eq. (381).

$$f_{\Delta\alpha} = 25^{\frac{\Delta\alpha}{\Delta\alpha(25Hz)}} \qquad \textbf{(381)}$$

5.23.15 SegmentVariables

The function *SegmentVariables* determines the geometrical variables needed for a terrain segment as defined in Eq. (382) where (x_S,z_S) are the source coordinates, (x_R,z_R) are the receiver coordinates, and (x_1,z_1) and (x_2,z_2) are the segment end coordinates ($x_2 > x_1$).

$$(d', h'_S, h'_R, d'_1, d'_2) = SegmentVariables(x_S, z_S, x_R, z_R, x_1, z_1, x_2, z_2) \qquad \textbf{(382)}$$

The calculated variables are:

d' is the horizontal distance measured along the extended ground segment from source S to receiver R

h'_S is the perpendicular distance from S to the extended ground segment

h'_R is the perpendicular distance from R to the extended ground segment

d'_1 is the signed distance measured along the extended ground segment from source S to end point (x_1,z_1). $d'_1 = 0$ means (x_1,z_1) is below the source while $d'_1 = d'$ means below the receiver

d'_2 is the signed distance measured along the extended ground segment from source S to end point (x_2,z_2)

The variables are calculated as shown in Eq. (383).

$$\begin{aligned}
&(x'_S, z'_S, h'_S) = NormLine(x_1, z_1, x_2, z_2, x_S, z_S) \\
&(x'_R, z'_R, h'_R) = NormLine(x_1, z_1, x_2, z_2, x_R, z_R) \\
&d' = Length(x'_S, z'_S, x'_R, z'_R) \\
&|d'_1| = Length(x'_S, z'_S, x_1, z_1) \\
&|d''_1| = Length(x'_R, z'_R, x_1, z_1) \\
&|d'_2| = Length(x'_S, z'_S, x_2, z_2) \\
&|d''_2| = Length(x'_R, z'_R, x_2, z_2) \\
&d'_1 = \begin{cases} -|d'_1| & if\ |d'_1| < |d''_1| \wedge |d''_1| > d' \\ |d'_1| & otherwise \end{cases} \\
&d'_2 = \begin{cases} -|d'_2| & if\ |d'_2| < |d''_2| \wedge |d''_2| > d' \\ |d'_2| & otherwise \end{cases}
\end{aligned} \tag{383}$$

5.23.16 ShadowZoneShielding

The function *ShadowZoneShielding* determines the part of the attenuation in a meteorological shadow zone that is called the shadow zone shielding in the Nord2000 method as defined in Eq. (384).

$$\Delta L_{SZ}(f) = ShadowZoneShielding(f, d, h_S, h_R, \xi, c_0 d_{SZ}) \tag{384}$$

where

f is the frequency

d is the horizontal source-receiver distance

h_S is the source height

h_R is the receiver height

ξ is the relative sound speed gradient in the equivalent linear sound speed profile

c_0 is the sound speed at the ground in the equivalent linear sound speed profile

d_{SZ} is shadow zone distance defined in Section 5.5.4.

The shadow zone shielding contribution is based on the attenuation of an equivalent wedge. The geometry of the wedge is defined in Figure 41. The height of the wedge h_{SZ} is determined as illustrated in Figure 42 and depends on the curvature of a source-receiver ray.

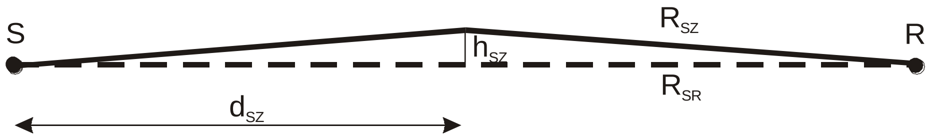

Figure 41
Equivalent wedge used to calculate the shadow zone shielding contribution.

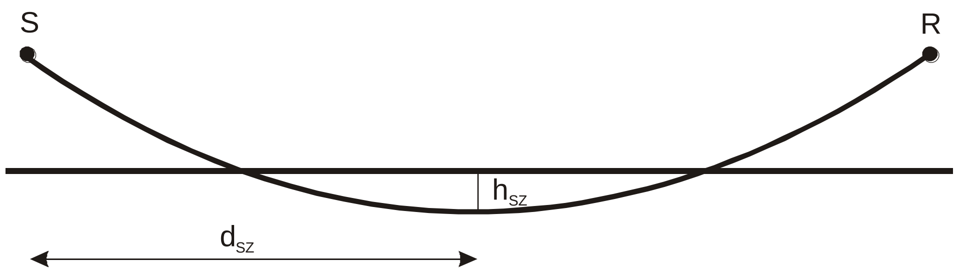

Figure 42
Ray defining the equivalent wedge used to calculated the shadow zone shielding contribution.

To determine h_{SZ} a frequency dependent relative sound speed profile ξ_{SZ} is determined by Eq. (385).

$$\xi_{SZ}(f) = \begin{cases} \xi \dfrac{\log(f) - \log(20)}{\log(2000) - \log(20)} & f < 2000 \\ \xi & f \geq 2000 \end{cases} \qquad \textbf{(385)}$$

The next step is to determine the height of the ray h_{SZ} at the horizontal distance d_{SZ} using the auxiliary function *HeightOf CircularRay*. h_{SZ} depends on the frequency as shown in Eq. (386).

$$h_{SZ}(f) = HeightOfCircularRay(d, h_1, h_2, \xi_{SZ}(f), d_{SZ}) \quad \textbf{(386)}$$

Finally the attenuation is calculated by Eq. (387).

$$\begin{aligned}
&\Delta L_{SZ}(f) = 10\log\left(2R_{SR}\left|pwedge(f, \beta, \theta_S, \theta_R, \tau, \tau_S, \tau_R, \ell, R_S, R_R)\right|\right) \\
&where \\
&\theta_S = \pi + \arctan\left(\frac{h_{SZ}(f)}{d_{SZ}}\right) + \arctan\left(\frac{h_{SZ}(f)}{d - d_{SZ}}\right) \\
&\theta_R = 0 \\
&\beta = \theta_S \\
&R_S = \sqrt{h_{SZ}^2(f) + d_{SZ}^2} \\
&R_R = \sqrt{h_{SZ}^2(f) + (d - d_{SZ})^2} \\
&\ell = R_S + R_R \\
&\tau_S = \frac{R_S}{c_0} \\
&\tau_R = \frac{R_R}{c_0} \\
&\tau = \frac{\ell}{c_0}
\end{aligned} \quad \textbf{(387)}$$

5.23.17 Sign

The function *Sign(x)* is the signum calculated as shown in Eq. (388).

$$Sign(x) = \begin{cases} 1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases} \quad \textbf{(388)}$$

5.23.18 VertDist

The function *VertDist* determines the vertical signed height Δz from a point P to a directed line P_1P_2 as shown in Eq. (389).

$$\Delta z = VertDist(x_1, z_1, x_2, z_2, x, z) \quad \textbf{(389)}$$

where

P = (x,z)

$P_1 = (x_1,y_1)$

$P_2 = (x_2,y_2)$

Δz is the signed vertical height above the line. Positive and negative values indicate that the point P is above or below the directed line ($x_2 > x_1$), respectively.

The height Δz d is calculated by Eq. (390).

$$\Delta z = z - z_1 - (z_2 - z_1)\frac{x - x_1}{x_2 - x_1} \quad \textbf{(390)}$$

5.23.19 WedgeCross

The function *WedgeCross* determines the top point of the equivalent wedge defined by two non-adjacent ground segments as shown in Eq. (391). It is required that $x_1<x_2<x_3<x_4$. The geometrical variables are defined in Figure 43 and the coordinates (x_0,z_0) are calculated as shown in Eq. (392).

$$(x_0, z_0) = WedgeCross(x_1, z_1, x_2, z_2, x_3, z_3, x_4, z_4) \quad \textbf{(391)}$$

where

(x_1,z_1) is the start point of the source side segment

(x_2,z_2) is the end point of the source side segment

(x_3,z_3) is the start point of the receiver side segment

(x_3,z_3) is the end point of the receiver side segment

(x_0,z_0) is the top point of the equivalent wedge

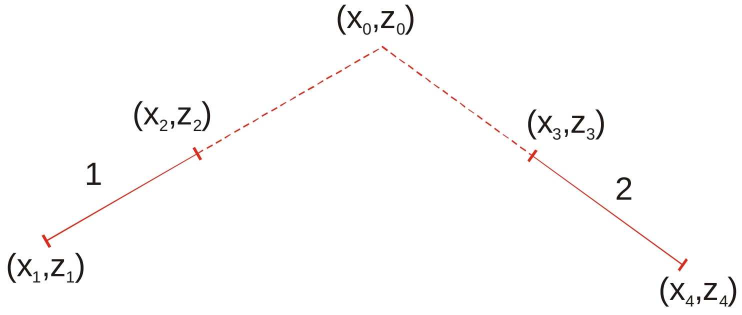

Figure 43
Definition of equivalent wedge detemined by two non-adjacent ground segments.

$$
\begin{aligned}
&D = (x_2 - x_1)(z_4 - z_3) - (x_4 - x_3)(x_4, z_4) \\
&s = \frac{(x_4 - x_1)(z_4 - z_3) - (x_4 - x_3)(z_4 - z_1)}{D} \\
&t = \frac{(x_2 - x_1)(z_4 - z_1) - (x_4 - x_1)(z_2 - z_1)}{D} \\
&s \geq 1 \wedge t \geq 1: \begin{cases} x_0 = x_1 + (x_2 - x_1)s \\ z_0 = z_1 + (z_2 - z_1)s \end{cases} \\
&t < 1: \quad \begin{cases} x_0 = x_3 \\ z_0 = z_3 \end{cases} \\
&s < 1: \quad \begin{cases} x_0 = x_2 \\ z_0 = z_2 \end{cases}
\end{aligned}
\qquad \textbf{(392)}
$$

5.23.20 Other Auxiliary Functions

Some auxiliary functions have been defined throughout the sections of Nordtest method and is therefore not mentioned in Section 5.23. These functions are mentioned in Table 10 below with a reference to the section where they have been described.

Name of the function	**Section**
CalcEqSSP	5.5.2
CalcEqSSPGround	5.5.3
Dwedge	5.7.2
Dwedge0	5.7.5
DirectRay	5.5.4
p2edge	5.7.4
p2wedge	5.7.3
pwedge	5.7.1
pwedge0	5.7.5
RayCurvature	5.5.7
ReflectedRay	5.5.5
TravelTimeDiff	5.5.6
$F_f(....)$	5.9.1
$F_{\Delta\tau}(....)$	5.9.2
$F_c(....)$	5.9.3
$F_r(....)$	5.9.4
$F_s(....)$	5.19
$\hat{Z}_G(....)$	5.6.2
$\hat{Q}(....)$	5.6.3
$\hat{R}_i(....)$	5.6.4
$\hat{R}_p(....)$	5.6.5

Table 10
Sections where auxiliary functions are described which are in Section 5.23.

5.24 References

[1] B. Plovsing and J. Kragh: Nord2000. Comprehensive Outdoor Sound Propagation Model. Part 1: Propagation in an Atmosphere without Significant Refraction, DELTA Acoustics & Vibration Revised Report AV 1849/00, Hørsholm 2006

[2] B. Plovsing and J. Kragh: Nord2000. Comprehensive Outdoor Sound Propagation Model. Part 2: Propagation in an Atmosphere with Refraction, DELTA Acoustics & Vibration Report AV 1851/00, 2006

[3] B. Plovsing: *Nord2000. Validation of the Propagation Model*, DELTA Noise & Vibration Report AV 1117/06, 2006

[4] European Commision: Position paper on EU noise indicators, 2000

[5] Numerical Recipes in FORTRAN 77: The Art of Scientific Computing, Cambridge University Press, ISBN 0-521-43064-X

[6] Nordtest NT ACOU 104: Ground surfaces: Determination of the acoustic impedance, 1999.

Annex A (Informative)

Composite Noise Sources

Most often “real” noise sources cannot be approximated by a single point source. In this case the real source which is denoted the extended source in the Nord2000 methodology has to be approximated by a number of incoherent point sources. Subsequently a calculation is performed for each sub-source and the sound pressure levels of the sub-sources are added incoherently.

Another case where the use of a single point source is insufficient is moving sources (e. g. road or railway traffic). A moving source sometimes called an incoherent line source can be approximated by a number of source points along the source track. A suitable incremental distance, angle or time spacing between points must be chosen to ensure that the point is representative to the propagation condition of any point on the small track segment where the source point is placed in the middle. A discussion of the topic can be found in [1].

Annex B (Informative)

Determination of the Simplified Terrain from the Actual Terrain

A method has been outlined in ref. [1] for approximating any real terrain shapes possibly defined on basis of digital elevation data by a segmented terrain. When using the method, artificial screens should be preferably be ignored.

The method is based on "the maximum deviation principle" in which the ground point P having the maximum perpendicular distance r_{max} to the line between the first and the last ground point P_1 and P_2 will become a new ground point in the segmented terrain. The principle is illustrated in Figure 47.

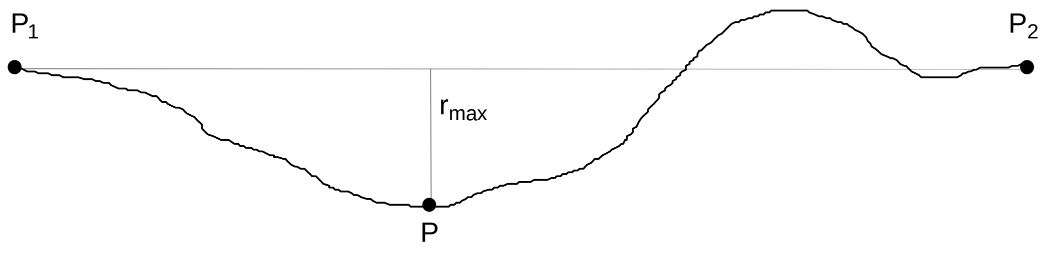

Figure 44
"Maximum deviation principle" used to determine a new ground point

In the first step the ground point P between P_1 (equal to the source ground point S_G) and P_2 (equal to the receiver ground point R_G) is determined according to the maximum deviation principle. If r_{max} is below a specified limit the terrain is defined as being flat but if not, P will become a new ground point in the simplified terrain shape which now consists of two straight segments P_1P and PP_2.

In the next step the process is repeated for the two ground shapes P_1 to P and P to P_2. r_{max} is determined for each of these two shapes and the point corresponding to the largest value of r_{max} will become the next ground point in the simplified shape which now consists of three segments.

This process may be repeated to any degree of perfection but each time a new point is added, an existing segment is replaced by two new segments. As the calculation time of the Nord2000 propagation model will increase strongly with the number of segments this should only be repeated until deviations between the real and the segmented terrain are within acceptable limits.

It is recommended that additional extra ground points are added to the segmented terrain until the following requirements are fulfilled:

- The maximum deviation r_{max} fulfils a distance dependent requirement as e. g. shown in Eq. (393)
- The length of the segments d_{segm} fulfils a distance dependent requirement as e. g. shown in Eq. (393)
- The maximum number of segments is $N_{ts,max}$. For most purposes $N_{ts,max}$ = 10 seems to be a reasonable choice.

$$r_{\max} \le \begin{cases} 0.1 & d \le 50 \\ 0.002\,d & 50 < d < 500 \\ 1 & d \ge 500 \end{cases}$$
$$d_{segm} \le \begin{cases} 1 & d \le 20 \\ 0.05\,d & 20 < d < 200 \\ 10 & d \ge 200 \end{cases} \qquad \textbf{(393)}$$

The outlined procedure shall only be considered a proposal and the requirement in Eq. (393) depends on the purpose of the calculations. If a more efficient procedure can be developed, such a method should be used instead.

The “maximum deviation principle” described above is applicable if no part of the terrain is causing significant shielding effects. If one or more parts of the terrain produce screening effects the screen or screens has to be identified and the “screen shape” has to be determined and simplified as described in Section 5.21. The rest of the terrain between source and screen, between screen and receiver and between the two screens in the double screen case is simplified using the “maximum deviation principle”. When simplifying the terrain between source and the screen closest to source the receiver is replaced by the top of the screen. When simplifying the terrain between the receiver and the screen closest to receiver the source is replaced by the top of the screen. When simplifying the terrain between two screens source and receiver are replaced by the screen tops. Where the maximum number of segments $N_{ts,max}$ for terrain with no significant shielding effects is recommended to be in the order of 10, an order of 5 is recommended for terrain before, after or between screens.

Annex C (Informative)

Other Impedance Models

Only the Delany and Bazley impedance model described in Section 5.6.2 is used in the Nord2000 mehod and the frequency dependent sound speed profile linearization principle described in Section 5.5.3 is closely related to this impedance model. The use of the Nord2000 method has shown that other impedance models can be applied with a reasonable accuracy. However, a preliminary investigation shows that a frequency independent linearization similar to hard surfaces should be preferred in the whole frequency range until this topic has been investigated more closely.

Annex D (Informative)

Change in Vertical Source Emission Angle due to Refraction

If the noise source has a vertical directivity it has been assumed so far when applying the Nord2000 method that the vertical source emission angle is defined by the direction from the source to the receiver. In case of refraction this is a reasonable assumption when the vertical directivity is not too strong or when the refraction is moderate. However, in cases of strong vertical directivity and strong refraction this may not necessarily be true. In such cases it can be necessary to correct the vertical source emission angle for the effect of refraction. A simplified method for estimating the effect of atmospheric refraction on the source emission angle can be found in the DELTA report AV 1025/06: "Change in Source Emission Angle due to Refraction, Simplified Method". The method determines the vertical change in source emission angle in relation to the source emission angle of a non-refracting atmosphere.

Annex E (Informative)

Lateral Diffraction of Finite Screens

In Sub-models 4-6 described in Section 5.13 through 5.15 which include screen effects it is assumed that the screens have an infinite length. In practice, screens will have a finite length and it is therefore possible that the screen effect will be reduced significantly when sound is diffracted laterally around the vertical edges of the screen. In Nord2000 this phenomena is called lateral diffraction. Figure 45 shows the basic case where a finite screen blocks the direct propagation but where sound is diffracted around the vertical edges reducing the efficiency of the screen compared to an infinite screen. Figure 46 shows another importent case where the direct line from source to receiver is unblocked but where a part of the sound field is affected by the finite screen which will increase the attenuation at the receiver compared to a situation where the screen is ignored. Both cases are included in the Nord2000 method.

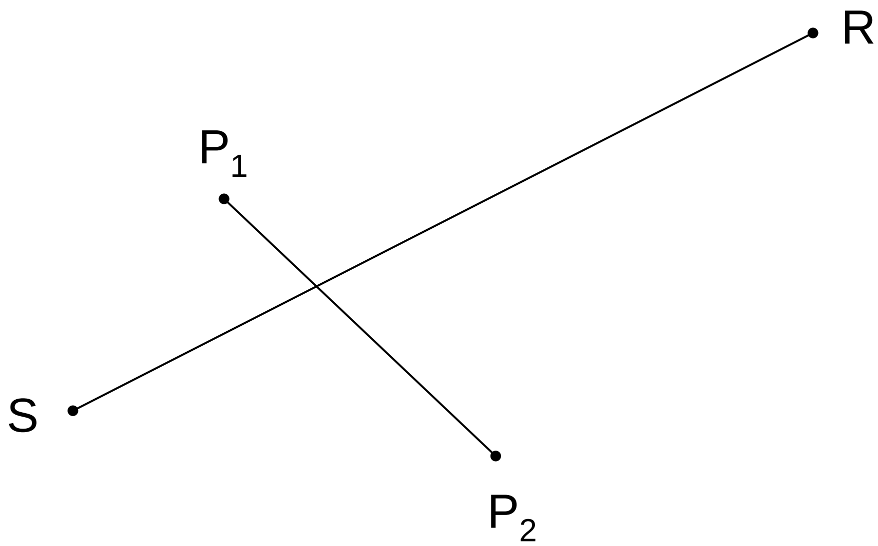

Figure 45
Finite screen with vertical edges at P_1 to P_2 blocking the propagation plane from the source S to the receiver R (top view).

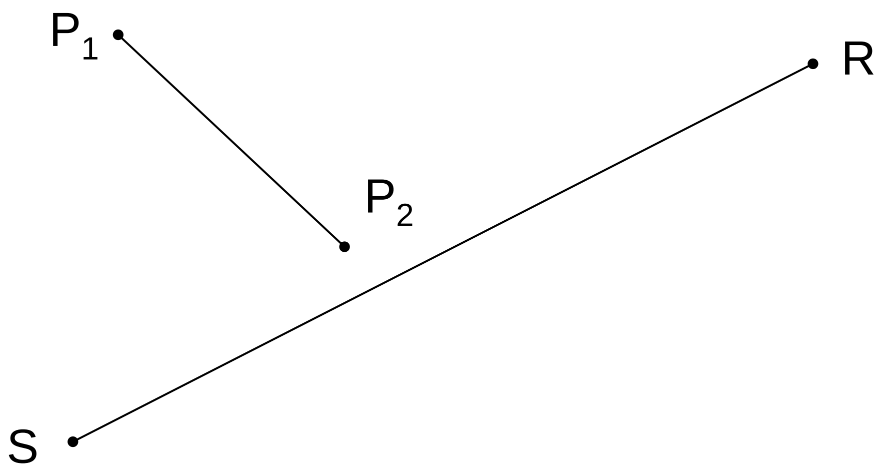

Figure 46
Finite screen with vertical edges at P_1 to P_2 outside the propagation plane from the source S to the receiver R (top view).

The contribution from lateral diffraction is taken into account by adding additional propagation paths as shown in Figure 47. Such a propagation path is in the method called a lateral diffraction path. Normally two lateral diffraction paths are added for each end of the finite screen as shown in the figure (Plane 1 and 2). The path is going from S to R via P_1 or P_2.

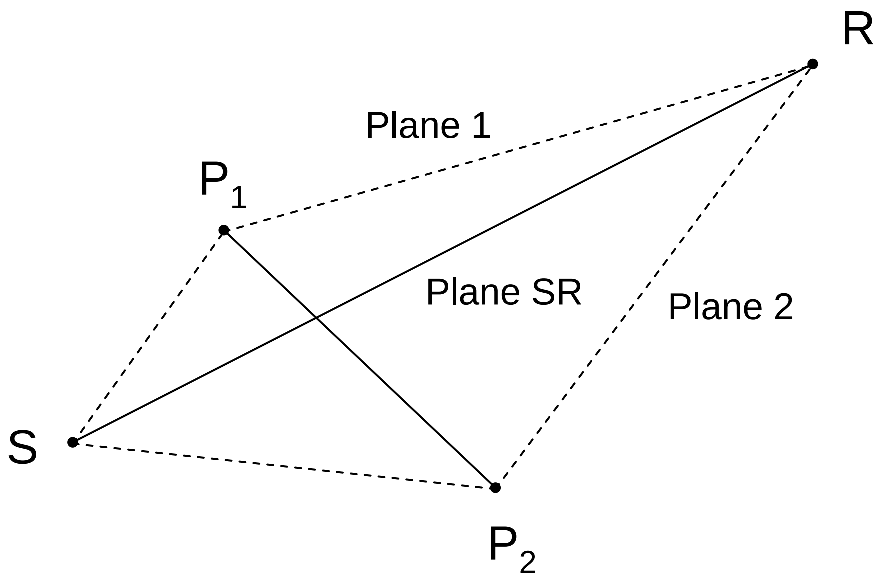

Figure 47
Lateral dispersion paths for the case where the direct source receiver path is blocked by the finite screen.

The sound pressure is calculated for each lateral diffraction path using the comprehensive propagation model with propagation parameters measured along the vertical propagation planes and added after a correction for the screening effect of the vertical edges.

The sound pressure level from a lateral diffraction path is predicted by the same propagation model used for the direct path on basis of the propagation parameters determined along the lateral diffraction path but ignoring the finite screen. However, the propagation effects in Eq. (1) will in this case also include the propagation effect ΔL_v which is a correction for diffraction around the vertical edge. The sound pressures corresponding to lateral diffraction path 1 and 2 (plane 1 and 2) and the direct propagation path (Plane SR) are denoted p_1, p_2, and p_{SR}, respectively.

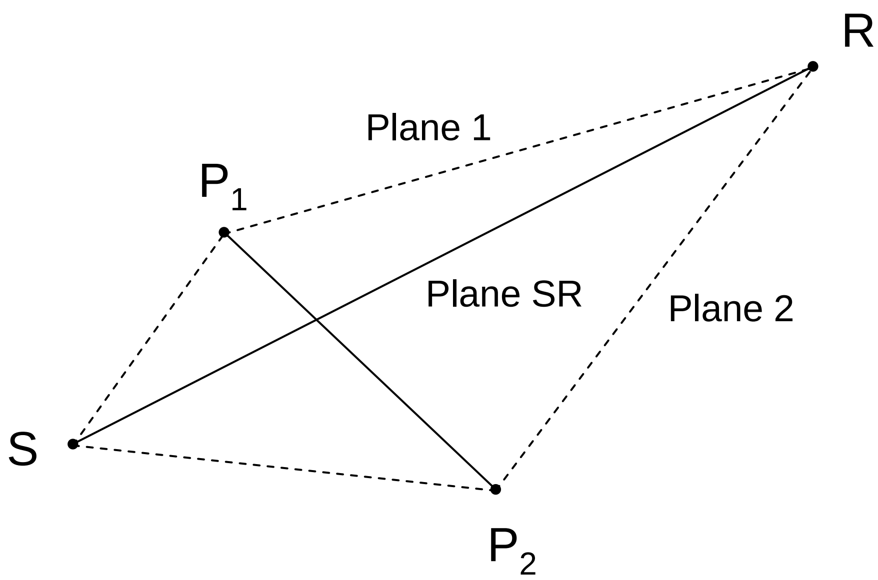

Figure 48
Definition of vertical propagation planes in case of a blocked direct propagation plane (top view).

If the lateral diffraction paths are far away from the direct propagation path the sound level from the three propagation paths shall be added incoherently but if the paths are very close to each other the contributions shall be added coherently. This is done according to Eq. (394). The weights w_1, w_2, and w_{SR} depend on the correction for lateral diffractions (ΔL_l in Eq. (1) is equal to 20 log(w)) and F_1 and F_2 are coherence coefficients which accounts for the coherence between the lateral diffraction paths and the direct path.

$$|p|^2 = |w_{SR} p_{SR} + F_1 w_1 p_1 + F_2 w_2 p_2|^2 + (1 - F_1^2)|w_1 p_1|^2 + (1 - F_2^2)|w_2 p_2|^2 \qquad \textbf{(394)}$$

Before determining the weights w_{SR}, w_1 and w_2 and the coherence coefficients F_1 and F_2 a number of variables used in the calculations have to be defined. Figure 49 defines the geometry used to calculate the variables for sound diffracted around the left vertical edge of the screen. P_S, P_R, and P_1 are the horizontal projections of the source, receiver and left edge. The variables r_S, r_R, θ_S, θ_R, β, ρ in Figure 49 and other variables necessary for the calculation are determined by Eq. (395).

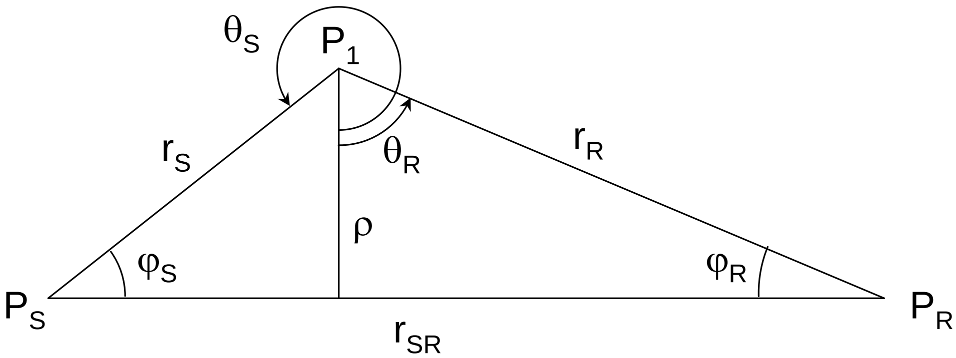

Figure 49
Definition of parameters θ_S, θ_R, β, r_S and r_R to be used in the diffraction calculation and the transversal separation ρ to be used in calculation of F_c.

$$
\begin{aligned}
\cos\varphi_S &= \frac{\overrightarrow{P_S P_R}\cdot\overrightarrow{P_S P_1}}{|P_S P_R||P_S P_1|}\\
\cos\varphi_R &= \frac{\overrightarrow{P_R P_S}\cdot\overrightarrow{P_R P_1}}{|P_R P_S||P_R P_1|}\\
\theta_S &= \frac{3\pi}{2}+\varphi_S\\
\theta_R &= \frac{\pi}{2}-\varphi_R\\
\beta &= 2\pi\\
r_S &= |P_S P_1|\\
r_R &= |P_R P_1|\\
r_{SR} &= r_S + r_R\\
\rho &= r_S\cos(\varphi_S)\\
\tau_S &= \frac{r_S}{c_{mean}}\\
\tau_R &= \frac{r_R}{c_{mean}}\\
\tau_{SR} &= \tau_S + \tau_R\\
c_{mean} &= Coft(t_{mean})
\end{aligned}
\tag{395}
$$

The weight w_1 can now be determined by Eq. (396) as the diffracted sound pressure relative to the free-field pressure ($p_0 = 1/r_{SR}$). The diffracted sound pressure is calculated by the auxiliary function *pwedge0* for a non-reflecting wedge.

$$
w_1 = \left|\frac{pwedge0(f,\beta,\theta_S,\theta_R,\tau_{SR},\tau_S,\tau_R,r_{SR},r_S,r_R)}{p_0}\right|
\tag{396}
$$

The coherence coefficients F_1 is calculated by Eq. (397) where F_f is the coherence coefficient due to frequency band averaging (see Section 5.9.1) and F_c is the coherence coefficient due to turbulence (see Section 5.9.3).

$$
F_1(f) = F_f(f,\tau_S+\tau_R-\tau_{SR})F_c(f,C_v^2,C_T^2,t_{mean},c_{mean},\rho,r_{SR})
\tag{397}
$$

The weight w_2 and the coherence coefficient F_2 corresponding to the contribution of sound diffracted around the right vertical edge of the screen can be calculated in a similar manner with the only alteration that P_1 has to be replaced by P_2.

Now w_{SR} has to be determined by Eq. (398).

$$w_{SR} = -F_1 w_1 - F_2 w_2 + \sqrt{1 - w_1^2 - w_2^2 + (F_1 w_1)^2 + (F_2 w_2)^2} \quad \textbf{(398)}$$

When the screen length becomes 0 the method described above will produce a result identical to the result obtained when ignoring the screen.

In the subsidiary case of unblocked direct propagation and the screen left of the source-receiver line, the sound pressure is calculated for the three vertical propagation planes defined in Figure 50. P_1 is the more remote of the two edges in the sense that it is the edge giving the largest sound pressure reduction. Plane SR is the direct propagation plane from the source to the receiver and Plane 1 and Plane 2 are defined as the lateral propagation paths around the left and the right edge of the screen. Plane 1 is passing just outside the screen so that the screen is not included in the lateral propagation parameters while plane 2 includes the screen. The corresponding sound pressures are denoted p_{SR}, p_1 and p_2.

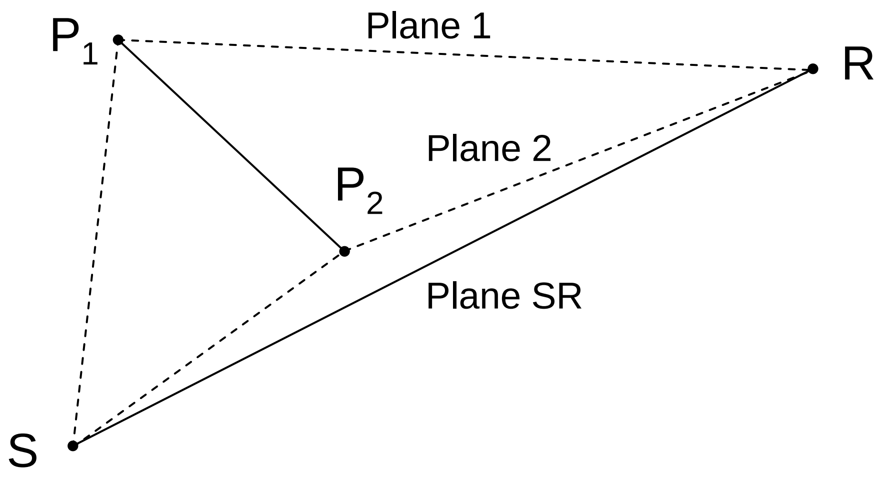

Figure 50
Definition of vertical propagation planes in case of an unblocked direct propagation plane (top view).

The sound pressure level for the unblocked case is also calculated by Eq. (394) but in this case the weights w_1 are in the same way calculated by Eq. (396) whereas w_{SR} are calculated by Eq.(399). The input variables of the function *pwedge0* correspond to edge P_2.

$$w_{SR} = 1 - \left| \frac{pwedge0(f, \beta, \theta_S, \theta_R, \tau_{SR}, \tau_S, \tau_R, r_{SR}, r_S, r_R)}{p_0} \right| \quad \textbf{(399)}$$

Finally, w_2 is calculated by Eq. (400)

$$w_2 = -F_1 w_1 - F_2 w_{SR} + \sqrt{1 - w_1^2 - w_{SR}^2 + (F_1 w_1)^2 + (F_2 w_{SR})^2} \quad \mathbf{(400)}$$

The same principle is used if the screen is right of the source-receiver line and P_1 is again defined as the more remote of the two edges in the sense that it is the edge giving the largest sound pressure reduction.

If the uncertainties introduced by using the incoherent summation ($F_1 = F_2 = 0$) can be accepted in cases where one of the vertical screen edges are close to the direct propagation plane it may be considered to apply this simplification.

Lateral diffraction can normally be ignored in case of moving sources due to the averaging caused by the movement.

Annex F

Solution of Integral in Eq. (19)

The average sound speed $\bar{c}$ between the heights h_S and h_R is determined by Eq. (19). The equation contains an integral which is solved as shown below in this Annex. In the solution it is assumed that the vertical sound speed profile is defined by Eq. (2).

$$\bar{c} = \frac{1}{h_R - h_S} \int_{h_S}^{h_R} \left(A \ln\left(\frac{z}{z_0} + 1 \right) + Bz + C \right) dz \qquad \textbf{(401)}$$

Eq. (401) can divided into three integral terms as shown in Eq. (402).

$$\bar{c} = \frac{1}{h_R - h_S} \int_{h_S}^{h_R} A \ln\left(\frac{z}{z_0} + 1 \right) dz + \frac{1}{h_R - h_S} \int_{h_S}^{h_R} Bz\ dz + \frac{1}{h_R - h_S} \int_{h_S}^{h_R} C\ dz \qquad \textbf{(402)}$$

Each term is then solved as shown in Eq. (403).

$$\bar{c} = A \frac{z_0}{h_R - h_S} \left(\left(\frac{h_R}{z_0} + 1 \right) \left(\ln\left(\frac{h_R}{z_0} + 1 \right) - 1 \right) - \left(\frac{h_S}{z_0} + 1 \right) \left(\ln\left(\frac{h_S}{z_0} + 1 \right) - 1 \right) \right) + \frac{B}{2}(h_R - h_S) + C \qquad \textbf{(403)}$$