inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 2.4

NORD 2000. COMPREHENSIVE MODEL FOR PREDICTING THE EFFECT OF TERRAIN AND SCREENS IN THE NEW NORDIC PREDICTION METHODS FOR ENVIRONMENTAL NOISE

B. Plovsing

DELTA, Akademivej, Building 356, DK-2800, Lyngby, Denmark

Tel.: +45 45 93 12 11 / Fax: +45 45 93 19 90 / Email: bp@delta.dk

Keywords:
SOUND PROPAGATION, SCREEN ATTENUATION, GROUND ATTENUATION, WEATHER EFFECTS

ABSTRACT
A Nordic project is in progress to elaborate prediction methods for various types of environmental noise sources. A sound propagation model based on geometrical ray theory and theory of diffraction has been elaborated for calculating one-third octave band attenuation in a homogeneous atmosphere. The model has been extended to calculation of attenuation in a refractive atmosphere by geometrical modifications of rays according to the "heuristic model" concept. The comprehensive model is applicable for any terrain profile assuming that the terrain is approximated by a number of straight segments. Each segment is characterized by its surface impedance and roughness (unevenness). The model combines solutions for base models (flat terrain, one or two screens with a flat surface before, after or between the screens) by means of Fresnel-zone interpolation. The use of the Fresnel-zone method has previously been described in conference papers. The base models assume coherent summation of ray contributions. However, the models have been extended to include partial coherence and averaging effects to obtain better agreement with outdoor sound propagation measurement results. A frequency dependent coherence coefficient defines the transition from coherent to incoherent propagation. The coherence coefficient includes effects of frequency band averaging, fluctuating refraction, reduction in source and propagation coherence (turbulence) and surface roughness. The effect of turbulence in the shadow zone behind screens is also included. The method appears to be sufficiently accurate for engineering purposes and agrees well with measurements and with predictions by accurate prediction methods.

1 - INTRODUCTION
In the new Nordic noise prediction model the sound pressure level at the receiver is calculated in one-third octave bands from 25 Hz to 10 kHz. The propagation model is based on available theory for sound propagation in a homogeneous atmosphere without refraction effects. The theory has in an approximate manner been extended to complex terrain shapes and to include propagation in moderately refracting atmosphere. The latter has been done using the so-called heuristic model approach [1] in which straight propagation rays are replaced by curved rays. An overview of the Nordic prediction model is given in [2].

2 - BASIC MODELS
The effect of terrain and screens is mainly based on geometrical ray theory and theory of diffraction. In geometrical ray theory models, propagation from a point source is predicted on the basis of the free space Green's function shown in Eq. (1), where p is the sound pressure at the receiver, R is the distance from source to receiver, k is the wave number, and j is the imaginary unit.

$$p = \frac{e^{jkR}}{R} \tag{1}$$

When a spherical sound field is reflected by a flat finite impedance surface, the pressure of the reflected sound at the receiver is also predicted by Eq. (1) but in this case R is the distance along the reflected path, and p shall be multiplied by the spherical reflection coefficient Q to account for effects on amplitude and phase at the reflection from the impedance surface. The ground effect is the result of the interference between the direct and the reflected sound [3]. However, it is required in such a model that each reflecting surface is flat and sufficiently large to be considered infinite.
When screens are present between source and receiver, the propagation effect can be predicted using theory of diffraction. If an impedance surface exists before and after the screen or between screens, reflected ray paths can be introduced according to the so-called 'image method'. The sound pressure for a reflected path predicted by the diffraction theory shall be multiplied by the spherical reflection coefficient Q for each reflection. The basic models for screens with a flat impedance surface before and after the screen or between screens are described in [4]. Again, it is required that each reflecting surface is flat and sufficiently large to be considered infinite. The screen model [4] may in principle be applied for multiple screens and screens with multiple edges. However, in the comprehensive model it has been decided to include only the two most efficient screens and the two most efficient edges of each screen. An extension of the number of screens and edges beyond two would increase the complexity of the model considerably, possibly without significant gain in accuracy.

3 - COMPLEX TERRAIN

In the new Nordic prediction model a complex terrain profile is represented by a number of straight segments. An impedance type and a roughness parameter are assigned to each segment. The solution for complex terrain is divided into three propagation models:

- A flat terrain model including all cases with insignificant deviation from flat terrain.
- A valley model including all non-flat cases with insignificant screening effect.
- A hill model including all cases with significant screening effect.

Examples of the three types of terrain profile are shown in Fig. 1.

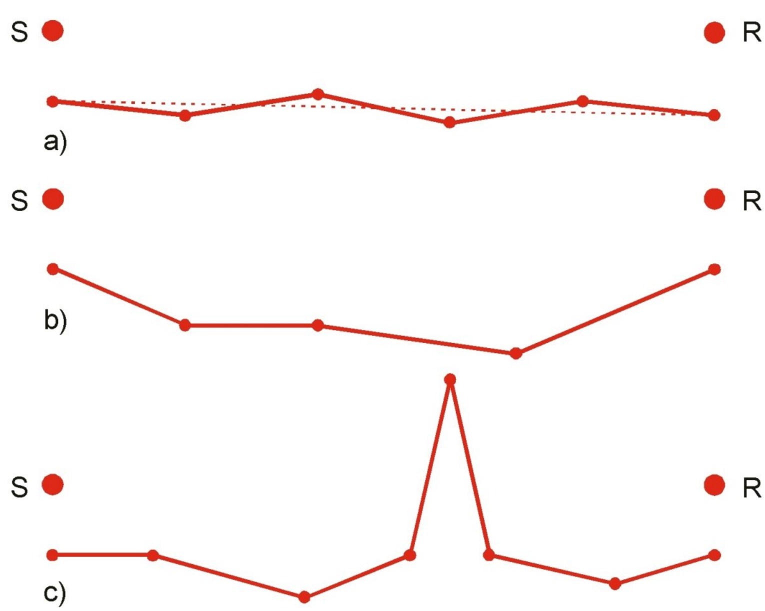

Figure 1: Segmented terrain in the propagation model: a) flat terrain b) valley-shaped terrain c) hill-shaped terrain.

In the flat terrain model the complex terrain is approximated by an equivalent, flat terrain as shown in Fig. 1a), and the ground effect is calculated using the basic geometrical ray theory model for a flat ground surface. However, in the two other models the terrain segments will only in rare cases fulfil the requirement of being large enough to be considered infinite.
To cover cases where segments do not fulfil this requirement, a principle has been developed in the project, denoted 'Fresnel-zone interpolation'. The idea originates from an approximate model for propagation

above a flat multi-impedance terrain [5]. In this model predictions for each impedance are combined by means of Fresnel-zone weighting. The Fresnel-zone interpolation principle has been presented in [6], and the method is described in detail in [7].
Instructions for how to choose between the models and how to obtain smooth transition from one model to another at borderline cases have been elaborated in [7]. The transition depends on frequency, and it is therefore possible that a certain complex terrain is interpreted as being flat at low frequencies, valley-shaped at high frequencies, and hill-shaped in the mid-frequency range.

4 - INCOHERENT EFFECTS

In the theoretical propagation models, which form the basis of the complex terrain model, the ray contributions are added coherently. However, at high frequencies a coherent prediction procedure produces stronger phase effects than is observed in outdoor measurements. In order to introduce more realism in the predictions at high frequencies, the prediction procedure has been modified to account for incoherent and averaging effects.
Incoherent effects concern reduction in coherence between different rays. This can be the result of turbulent scattering occurring along the propagation path or reduced coherence of sound emitted in different directions from the source. The averaging effects comprise averaging within the frequency band and averaging due to fluctuations in refraction and therefore to fluctuations in path length difference. Also random height variations within a terrain segment can cause averaging effects.
The general principle that has been chosen to account for incoherent effects when predicting the ground effect —p/p_0— is shown in Eq. 2, where p_i is the sound pressure at the receiver from the i'th of N rays and p_0 is the free field sound pressure. F_i is a coefficient of coherence between the i'th ray and the primary ray (i=1). For flat terrain the primary ray is the direct ray. In case of screens the primary ray is the diffracted ray from source to receiver via the screen edge(s). F will be a real value between 0 and 1, with 0 and 1 indicating full incoherence and full coherence, respectively. The principle defined in Eq. 2 is not a rigorous mathematical solution when the number of rays exceeds two because only the reduction in coherence compared to the primary ray is considered. However, the principle has been found adequate in an engineering model taking into account the large uncertainty involved in describing incoherent effects.

$$\left|\frac{p}{p_0}\right|^2 = \left|\frac{p_1}{p_0}\right|^2 \left(\left|1+\sum_{i=2}^{N} F_i \frac{p_i}{p_1}\right|^2 + \sum_{i=2}^{N}(1-F_i)\left|\frac{p_i}{p_1}\right|^2\right) \tag{2}$$

In the two-ray case for flat terrain Eq. 2 will change to Eq. 3. R_1 and R_2 are the propagation distances of the direct and reflected ray, respectively.

$$\left|\frac{p}{p_0}\right|^2 = \left|1+F\frac{p_2}{p_1}\right|^2 + \left(1-F^2\right)\left|\frac{p_2}{p_1}\right|^2 = \left|1+FQ\frac{R_1}{R_2}e^{jk(R_2-R_1)}\right|^2 + \left(1-F^2\right)\left|Q\frac{R_1}{R_2}\right|^2 \tag{3}$$

The first term in Eq. 3 is the coherent part and the second term the incoherent part. The incoherent part is determined by —Q— and R_1/R_2 and is therefore independent of the phase. Q is not a true reflection coefficient, but has been derived from a mathematical solution for a spherical field reflected by an impedance surface. When propagation becomes very incoherent, it is not likely that Q keeps its physical relevance. It has therefore been decided in the incoherent part of Eq. 2 and 3 to replace —Q— by a reflection coefficient R based on the random incidence absorption coefficient. This approach saves a lot of significant calculation time. The calculation of Q is very time-consuming and determines to a very high extent the overall calculation time in the model. Q is a function of the reflection angle, propagation distance, and ground impedance whereas R only depends on the impedance. It is therefore possible to precalculate R for each impedance type in the prediction model and insert it in a table. At high frequencies where the ray contributions become fully incoherent in most cases ($F = 0$), the calculation time will decrease considerably as the calculation of Q can be replaced by a table look-up.
The overall coherence coefficient F determining the coherence between two rays is the product of a number of coherence coefficients as shown in Eq. 4. F_f, $F_{\Delta\tau}$, F_c, F_r, F_{sc} are coherence coefficients corresponding to frequency band averaging, averaging due to fluctuating refraction, partial incoherence (e.g. turbulence), surface roughness, and scattering zones.

$$F = F_f F_{\Delta\tau} F_c F_r F_{sc} \tag{4}$$

A solution to F_f is given in [3] which can be expressed for one-third octave bands as shown in Eq. 5. However, in the present model the solution has been practically modified to obtain $F_f = 0$ for arguments of sine above π. R_1 is the length of the primary ray and R_2 of the secondary ray.

$$F_f = \frac{\sin\left(0.115k\left(R_2 - R_1\right)\right)}{0.115k\left(R_2 - R_1\right)} \tag{5}$$

A similar solution can be obtained for fluctuating refraction at a fixed wave number k if it is assumed that the travel time difference $\tau_2 - \tau_1$ is varying within the range $\Delta\tau_2 - \Delta\tau_1$ and is uniformly distributed within this range. τ_1 is the travel time corresponding to the primary ray and τ_2 to the secondary ray. The solution is shown in Eq. 6. Again, the solution has been practically modified to obtain $F_{\Delta\tau} = 0$ for arguments of sine above π. In practice, the variations of $\tau_2 - \tau_1$ will be more Gaussian-like as the variations are determined by fluctuations in wind speed and temperature. However, $\Delta\tau_2 - \Delta\tau_1$ can approximately be determined from the standard deviations of the wind speed and temperature variations as described in [7].

$$F_{\Delta\tau} = \frac{\sin\left(\pi\left(\Delta\tau_2 - \Delta\tau_1\right)f\right)}{\pi\left(\Delta\tau_2 - \Delta\tau_1\right)f} \tag{6}$$

A somewhat complex method for estimating the effect of atmospheric turbulence is proposed in [1]. However, the accuracy of this method is not known, and on this background a more simple empirical proposal [8] is under consideration as shown in Eq. 7. This proposal is assumed in an approximate way to estimate the combined effect of a propagation- and source-related reduction in coherence by a dimensionless constant 0.

$$F_c = \exp\left(-\left(\eta k\left(R_2 - R_1\right)\right)^2\right) \tag{7}$$

A method to account for terrain roughness has been described in [9]. In this method it is proposed that Q used to calculate the coherent part of the sound field is modified by multiplying the plane wave reflection coefficient used in the calculation of Q by a function of the Rayleigh roughness parameter $X = k\sigma_r \cos(\theta)$. σ_r is the rms-value of surface height variations, and θ is the ground reflection angle. The coherence coefficient F_r is determined by Eq. 8 where Q' is the modified value of Q. As X is approaching 0 at low grazing angles it has been found sufficiently accurate to determine F_r by the ratio between the plane wave reflection coefficients (equal to the function of X given in [9]).

$$F_r = \left|\frac{Q'}{Q}\right| \approx \left|\frac{R'_p}{R_p}\right| \tag{8}$$

Finally, F_{sc} is a coherence coefficient that accounts for the reduction in coherence after the sound has propagated through a scattering zone (forest or dwelling area) [10].

An example of the effect of incoherence and averaging on the ground effect spectrum for propagation over flat terrain is shown in Fig. 2. The solid line shows the coherent ground effect within frequency bands, and the line with circles shows the case with reduced coherence from fluctuating refraction and partial incoherence. In the present case the reduced coherence effect is dominated by fluctuating refraction.

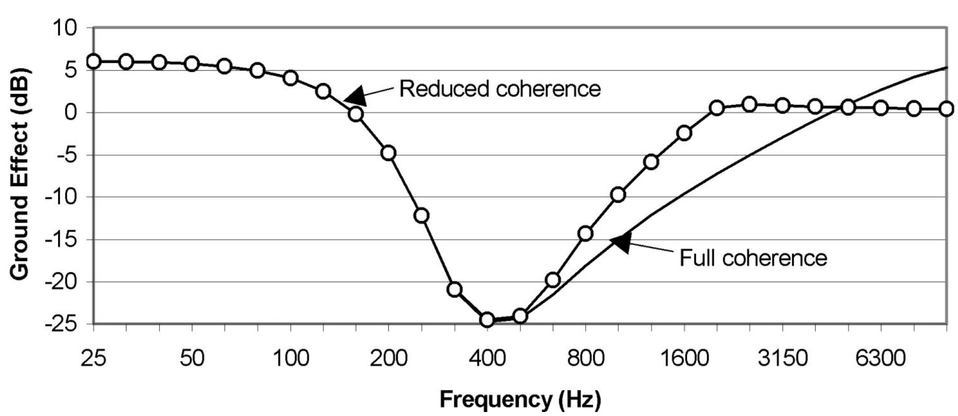

Figure 2: Effect of reduced coherence for propagation over flat terrain; d = 300 m, h_s = 1 m, h_R = 2 m, st. dev. of wind speed at 10 m = 0.5 m/s, η = 0.1.

5 - ADDITIONAL FEATURES

The comprehensive model includes a method for taking into account the energy scattered from atmospheric turbulence into the shadow zone of a screen. In the method the contribution of scattered energy is added incoherently to the prediction by the model for complex terrain outlined above. The prediction is based on geometrical parameters determined for the top of the screen in relation to the line-of-sight from source receiver.

Finite screens are taken into account by applying the solution for an infinite screen but adding the contributions from sound diffracted around the vertical edges of the screen. This is done practically by adding extra propagation paths from the source via the vertical edges of the screen to the receiver. The predicted sound pressure for each path is multiplied by the diffraction coefficient of the vertical edge and added incoherently to the sound diffracted over the top of the screen.

In the case of screens with irregularly shaped edges the equivalent straight top edge is determined as by the average within the Fresnel-zone at the position of the screen.

6 - MODIFICATION FOR REFRACTION EFFECTS

The comprehensive model for terrain and screen effects for propagation without refraction (straight-line propagation) can be modified to include curved rays according to the heuristic model principle as long as the number of rays in the base models does not have to be changed. This is fulfilled when the weather conditions are not causing multiple ground reflections (strong downwind) or shadow zones (strong upwind). In these cases the refraction problem can no longer be solved by simple geometrical modification of rays, but calls for a real extension of the model.

Prediction for any complex terrain is always the result of predictions by the base models combined according to the Fresnel-zone interpolation principle and the model transition principles. When the problem of using curved rays has been solved for each of the base models, and the Fresnel-zone interpolation and model transition principles have been modified to deal with curved rays, the problem has been solved for the entire complex terrain model. In the case of strong downward refraction, additional rays will occur in the model. A method has been developed for including the effect of multiple rays in excess of the number of rays already included in the base models. The contribution from the multiple reflection model is added incoherently to the contribution of the refraction-modified ray models. In the case of strong upward refraction no ray reaches the receiver in the model for flat terrain, resulting in an acoustical shadow zone. The problem of an acoustical shadow zone has been solved analogously to the problem of predicting sound levels behind a diffracting wedge. The refraction-modified model is described in [11].

A crucial point in the heuristic model concept is the procedure for approximating a non-linear sound speed profile by an equivalent linear profile. Such a procedure has been developed [12] by comparison with more accurate methods such as the Parabolic Equation method (PE), but the topic is still subject to considerations. Fig. 3 shows an example of ground effect predictions by the proposed model and by PE for a moderately downward refracting atmosphere. The ground effect for a non-refracting atmosphere is shown for comparison.

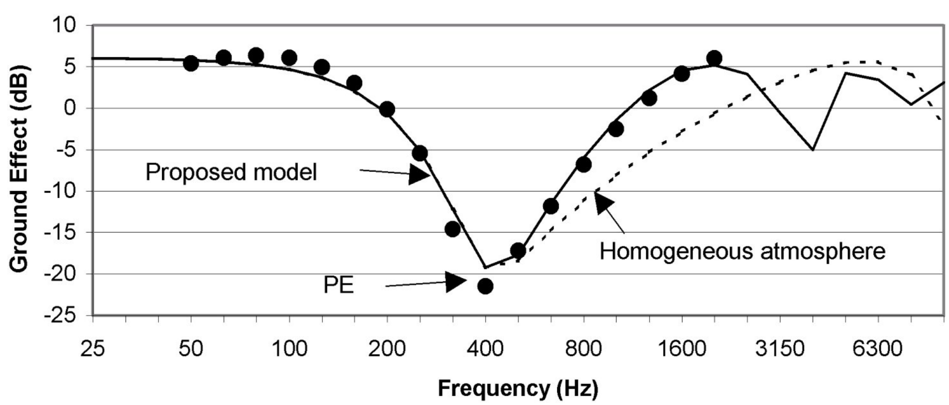

Figure 3: Ground effect over flat grass-covered terrain predicted by the proposed model and by PE in a downward refracting atmosphere; $d = 200$ m, $h_S = 2$ m, $h_R = 1.5$ m, wind speed at 10 m = 1 m/s.

REFERENCES

1. **A. L'Espérance et al.**, Heuristic model for outdoor sound propagation based on an extension of the geometrical ray theory in the case of a linear sound speed profile, *Appl. Acoust.*, Vol. 37, pp. 111-139, 1992

2. **J. Kragh**, Nord 2000. State-of-the art overview of the new Nordic prediction methods for environmental noise, In *Proceedings InterNoise 2000*

3. **C.I. Chessell**, Propagation of noise along a finite impedance boundary, *J. Acoust. Soc. Am.*, Vol. 62, pp. 825-834, 1977

4. **M. Ögren**, Nord 2000. Effects of diffraction in the new Nordic prediction methods for environmental noise, In *Proceedings InterNoise 2000*

5. **D.C. Hothersall and J.B.N. Harriott**, Approximate models for sound propagation above multi-impedance plane boundaries, *Acoust. Soc. Am.*, Vol. 97, pp. 918-926, 1995

6. **B. Plovsing**, Outdoor sound propagation over complex ground. Approximate prediction based on geometrical ray theory, diffraction theory, and Fresnel-zone considerations, In *Proceedings 6th International Congress on Sound & Vibration*, 1999

7. **B. Plovsing and J. Kragh**, *Prediction of sound propagation in an atmosphere without significant refraction. Outline of a comprehensive model*, DELTA Acoustics & Vibration, Report AV 1818/98, 1998

8. **W.L. Willshire**, Assessment of ground effects on the propagation on aircraft noise: The T-38A flight experiment, *NASA Technical Paper 1747*, 1980

9. **S.Å. Storeheier**, *Scattering effects in sound propagation outdoor. Scattering at terrain surfaces. N2000 Sub-project 1997-10*, SINTEF Report 40-N0 970225

10. **S.Å. Storeheier**, Nord 2000. Effects of scattering in the new Nordic prediction methods for environmental noise, In *Proceedings InterNoise 2000*

11. **B. Plovsing and J. Kragh**, *Comprehensive model for sound propagation - Including atmospheric refraction*, DELTA Acoustics & Vibration, Report AV 2004/99, 1999

12. **B. Plovsing and J. Kragh**, *Approximation of a non-linear sound speed profile by an equivalent linear profile*, DELTA Acoustics & Vibration, Report AV 2005/99, 1999