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ESDU 94035

Issued November 1994
With Amendment C
November 2017
Supersedes ESDU 80038

The correction of measured noise spectra for the effects of ground reflection

Associated software: ESDUpac A9435
ESDUpac B9435
VIEWpac M9435

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THE PREPARATION OF THIS DATA ITEM

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THE CORRECTION OF MEASURED NOISE SPECTRA FOR THE EFFECTS OF GROUND REFLECTION

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THE CORRECTION OF MEASURED NOISE SPECTRA FOR THE EFFECTS OF GROUND REFLECTION

1. NOTATION

		SI Units
c	speed of sound	m/s
D	horizontal separation of source and microphone	m
f	frequency	Hz
f^*	frequency of the first minimum in the ground-reflection spectrum (see Sketch 2.2)	Hz
f_g	geometric mean frequency	Hz
H_r	receiver height	m
H_s	source height	m
L	turbulence scale parameter	m
M_a	Mach number of moving source	
P	parameter in Equation (3.4)	$m^{3/2}$
r_1	pathlength of direct ray between source and receiver	m
r_2	pathlength of reflected ray between source and receiver	m
T	temperature	K
Z	normalised acoustic impedance	
α	inverse effective depth of porous surface layer	m^{-1}
β	parameter in Equation (3.3)	
Γ	mutual coherence function	
γ	ratio of specific heat capacities of air	
θ_i	angle between flight direction and source-receiver direction (*e.g.* for a jet engine, the angle measured from the inlet axis to the source-receiver direction)	deg
$<\mu^2>$	fluctuating index of refraction	

Issued November 1994
With Amendment C, November 2017 – 36 pages

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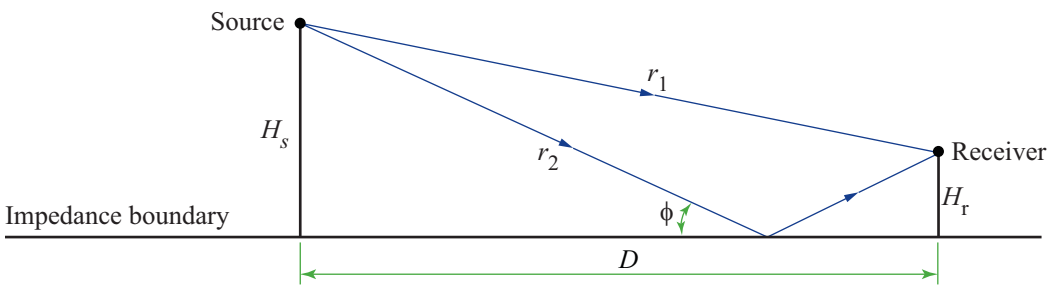
ρ	density of air	kg/m^3
σ_e	effective flow resistivity	N s/m^{4*}
σ_V	rms value of wind velocity fluctuation	m/s
σ_T	rms value of temperature fluctuation	K
ϕ	ground-reflection angle (*i.e.* angle made by incident or reflected ray with ground. See Sketch 2.1)	rad†
ω	angular frequency	rad/s

* In Equation (3.1), σ_e is given in N s/m^4. Elsewhere in the text and for input to the computer program, σ_e is kN s/m^4.

† In the equations given in Appendix A, ϕ is in radians. For convenience, elsewhere in the text ϕ is quoted in degrees.

2. INTRODUCTION

This Item provides a means of estimating the effect on noise measurements, made at a position above the ground, due to reflection of the sound wave by the ground. The ground-reflection correction is estimated in the form of a difference spectrum, which may be subtracted from a measured spectrum to give a free-field spectrum, or added to a free-field spectrum to give a measured spectrum. The geometric representation of the source and receiver is shown in Sketch 2.1.



Sketch 2.1 Diagrammatic representation of source-receiver geometry

The direct wave between the source and receiver propagates over a pathlength r_1, while the pathlength of the reflected wave is r_2. The ground-reflection corrections are due to the interference between the direct and reflected waves. The phase relationship between the two waves is determined by the pathlength difference, $r_2 - r_1$, and the impedance of the ground material, Z. Unless waves are in phase, when combined they will partially cancel. A typical one-third octave band ground-reflection spectrum for spherical waves showing the ground-reflection cancellation and reinforcement due to the interference of the direct and reflected waves is shown in Sketch 2.2. The lowest frequency at which cancellation is most marked is defined as the frequency f^* and the dip in the spectrum around this frequency is referred to as the primary hollow. The location of the frequency, f^* and the depth of the dip in the spectrum are dependent on a combination of factors. These factors are the source-receiver geometry, the ground impedance and the level of air turbulence. For example, the pattern of variation of the depth of dip with ground impedance observed during air-to-ground sound propagation is different from that observed during ground-to-ground sound propagation. In this Item, ground-to-ground sound propagation is considered to be at grazing angles of less than 5° to surface.

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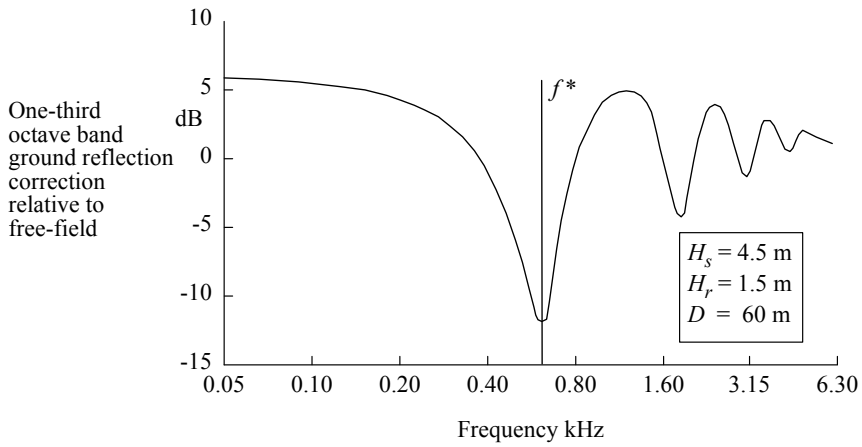

Sketch 2.2 One-third octave band ground-reflection correction over a hard surface

The general theoretical approach used in this Item is based on the reflection of a spherically diverging wave, propagating through a homogeneous atmosphere, at the boundary between two semi-infinite media. This implies zero mean wind and an absence of temperature gradients; however, the loss of coherence between direct and reflected rays arising from turbulence scattering is included. The theory, which is outlined in Section 2 of Appendix A, is that given in Derivation 2 and includes the correction given in Derivation 3. However, the impedance of the ground is modelled using a different ground impedance model from that used in Derivation 2. The ground impedance model used in this Item is described in Derivation 5. The one-third octave band ground-reflection corrections are estimated by making the assumption of white noise (constant spectral density). Results reported in Reference 7 indicate that the assumption of white noise introduces only small errors over a wide range of spectrum slopes.

The effects of source motion, filter characteristics, source distribution and the minimisation of ground reflection effects are discussed in Appendix B.

A computer program, known as ESDUpac A9435*, for estimating the discrete frequency ground-reflection correction and, by combining these corrections, the one-third octave band ground-reflection corrections for all surfaces, is described in Appendix C of this Item. This procedure is applicable to the correction of measured noise spectra to free-field levels for both ground-to-ground and air-to-ground noise measurements.

2.1 Outline of Method of Analysis

The method provides a means of estimating the effect of the reflection of sound waves propagating over any surface between a source and a receiver when source and receiver are located at any height above the ground plane. The ground-reflection corrections are the difference between the measured and free-field spectra. The ground-reflection difference spectrum can either be subtracted from a measured spectrum to obtain free-field levels, or added to a free-field spectrum to obtain the sound pressure levels at the point of measurement. The ground-reflection corrections are calculated for either any set of discrete frequencies at a constant interval using Equation (A.6) or for the standard set of one-third octave bands using Equation (A.7). The method permits the user to take into account the effect of air turbulence by considering the coherence between direct and reflected rays. The correlation of phase and amplitude fluctuations between direct and reflected waves is described in Reference 10.

* The full ESDUpac number has an appended V followed by two digits. These digits indicate the ESDUpac version number. For example, the full ESDUpac number for version 1.0 of ESDUpac A9435 is A94345V10. The version appendage will not be used when referring to ESDUpacs in the text of this Item. See Introduction to ESDUpacs for a full description of the ESDUpac numbering system. The current version of the ESDUpac is given in Appendix C and on the example program output in Section C.2.

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In general, it is necessary to take account of the filter shape in the estimation of the one-third octave band free-field spectrum for a broad-band noise source, as application of the theoretical ground-reflection correction leads to an overcorrection around the primary hollow. To account for this overcorrection, an option is given to include the effect of a practical filter (see Section A.4), as used in the spectrum analysis, on the difference spectrum due to ground-reflection effects. When this filter correction option is exercised, the program estimates the filtered ground-reflection correction.

In practice it is often found that the frequency f^* (see Sketch 2.2), of the measured spectrum is not equal to the value of f^* calculated from the predicted ground-reflection correction spectrum. This discrepancy may result from the non-homogeneity of the atmosphere (see Section 2.2) or from an error in source location.

When a measured spectrum is input, the program automatically aligns the dip in the predicted ground-reflection correction with that in the measured spectrum by finding first the values of f^* for both the measured spectrum and the predicted ground-reflection difference spectrum. The pathlength difference is then multiplied by the correction factor which is calculated from these two frequencies. The program calculates the A-weighted sound pressure level, dBA, the overall sound pressure level, OASPL, and the perceived noise level, PNL, of the measured and free-field spectra. The PNL is calculated using the mathematical formulation of the NOY tables given in Derivation 4.

2.2 Limitations of the Prediction Procedure

The prediction procedure is based on the theory presented in Appendix A, Section A.2, with the additional modifications of Sections A.3, and A.4, which are based on practical considerations. The theoretical approach assumes that the sound waves propagate through a still, homogeneous atmosphere with a spherically divergent wavefront. The effects of refraction due to wind and temperature gradients are not included. Refraction causes the pathlengths of the direct and reflected waves to change from those calculated using the geometrical relationships between the source and receiver. This change in the pathlength difference will alter the phase relationship between the two waves from that calculated using the source receiver geometry and ground impedance. A means of accounting for these effects over short sound propagation ranges is given in Reference 12.

The theory assumes that the ground plane between source and receiver is flat. It also assumes that the sound source radiates equally strongly in the direction of the direct ray and in the direction of the reflected ray before it touches the ground. Both source and receiver are assumed to be stationary.

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3. MAJOR PARAMETERS IN THE CALCULATION OF THE GROUND-REFLECTION CORRECTION

The calculation of the ground-reflection correction covered by this Data Item requires the knowledge of three sets of parameters related to:

i) the source-receiver geometry,
ii) the impedance of the ground surface,
and iii) the prevailing level of air turbulence.

From the source-receiver geometry are required the source and receiver heights and the separating distance between source and receiver. The effects of source distribution are discussed later in Section B.2.

3.1 Ground Impedance

The impedance of the ground surface is calculated using a two-parameter model of the ground. The ground is modelled as a porous layer structure. The model is described in Derivation 5.

The normalised acoustic impedance, Z is given by the equation

$$Z = \left(\frac{\sigma_e}{\gamma\pi\rho f}\right)^{1/2} + \mathrm{i}\left[\left(\frac{\sigma_e}{\gamma\pi\rho f}\right)^{1/2} + \frac{c\alpha}{4\gamma\pi f}\right]. \tag{3.1}$$

The two parameters describing the ground in the above equations are the effective flow resistivity, σ_e and the inverse effective depth of the surface layer, α. Guidance on their selection is provided in Table 5.1. The ranges of values given in this table are typical of those observed from types of the given ground surface (Derivation 5).

3.2 Effects of Air Turbulence

Air turbulence has an important effect on long range sound propagation.

In this Item, the presence of air turbulence is taken into account by considering its effect on the coherence between the direct wave and the reflected wave (see Reference 11). The transverse or mutual coherence function Γ, is given by

$$\Gamma = \exp(-0.25\beta P) \tag{3.2}$$

where $\beta = 0.5$ if $\left(\frac{cD}{\omega}\right)^{1/2} > L$,

$$\beta = 1 \text{ if } \left(\frac{cD}{\omega}\right)^{1/2} \le L \tag{3.3}$$

and

$$P = \langle\mu^2\rangle\left(\frac{\omega}{c}\right)^2 DL\sqrt{\pi}, \tag{3.4}$$

where L is a turbulence scale parameter taken normally to lie between 1.0 and 1.5 m and assumed here as 1.1 m.

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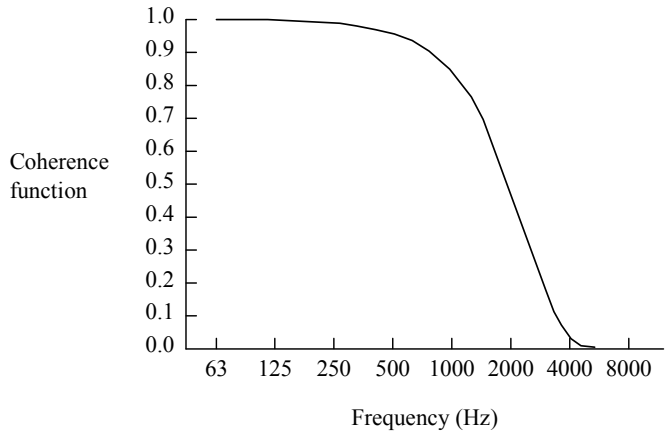
The coherence function, Γ is used in the calculation of the ground reflection correction as shown in Equations (A.6) and (A.7) in Appendix A of this Item. Sketch 3.1 shows the variation of Γ with frequency for the case described in the example in Appendix C.

The input parameter required is the fluctuating index of refraction $<\mu^2>$ which is given by the approximation (Reference 10).

$$<\mu^2> = \frac{\sigma_V^2}{c^2} + \frac{\sigma_T^2}{4T^2} . \tag{3.5}$$

This parameter can be measured accurately only if a fast response system (sampling at over 1 kHz) is used for measurement.

Guidance on selecting $<\mu^2>$ for typical situations is given in Table 5.2.



Sketch 3.1 Variation of coherence function, Γ with frequency

3.3 Selection of Input Parameters

It is obvious that the greater the accuracy with which the input parameters describe the particular situation under consideration, the higher will be the accuracy of prediction. This section contains illustrations of the sensitivity of the model to the different input parameters. Although it is impossible to provide specific guidance for every conceivable situation some broad guidelines based on general trends can be provided.

In the sketches shown in this section, the source height is 2.16 m, the microphone height is 1.2 m and the source-receiver separation is 1100 m. Turbulence has not been taken into account *i.e.* $<\mu^2>$ has been set at zero.

In Sketch 3.2 the effect of varying the effective flow resistivity for grassy surfaces can be seen. In Sketch 3.3 the same general trends can be seen for a hard surface such as concrete. It is apparent that increasing the effective flow resistivity shifts the primary dip higher in frequency.

Varying the inverse effective depth has a similar effect on the primary dip and the slope of the curve below the primary dip. This is shown in Sketch 3.4. However, the model is sensitive to variations in inverse effective depth only for relatively soft surfaces such as grass. For hard surfaces the ground reflection correction depends almost entirely on the effective flow resistance.

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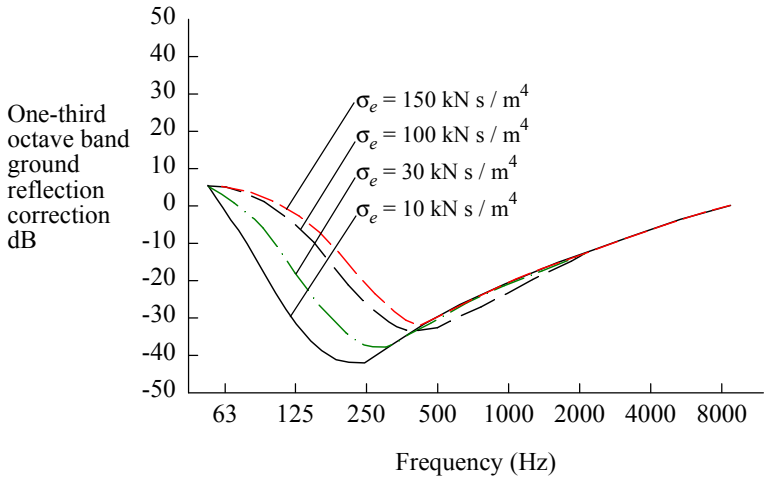
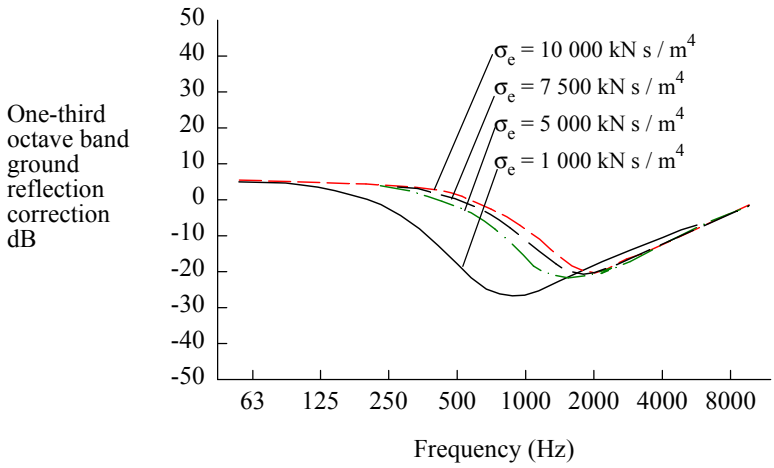
The effect of changing the turbulence parameter $<\mu^2>$ is shown in Sketch 3.5. Increasing the value of $<\mu^2>$, which implies increased turbulence in the air, shifts the frequency of the primary dip downwards and lifts up the prediction at frequencies above the primary dip frequency.

When correcting measured spectra to free-field levels, the input variables should be optimised through trial and error by inspection of the effectiveness of the removal of the primary dip. It is recommended that the effective flow resistivity be varied first around values obtained from Table 5.1. Further fine tuning may then be performed using the other input parameters.



Sketch 3.2 Variation of ground reflection correction with effective flow resistivity, σ_e for grassy surfaces, α set at 20 m^{-1}



Sketch 3.3 Variation of ground reflection correction with effective flow resistivity, σ_e for hard surfaces, α set at 0 m^{-1}

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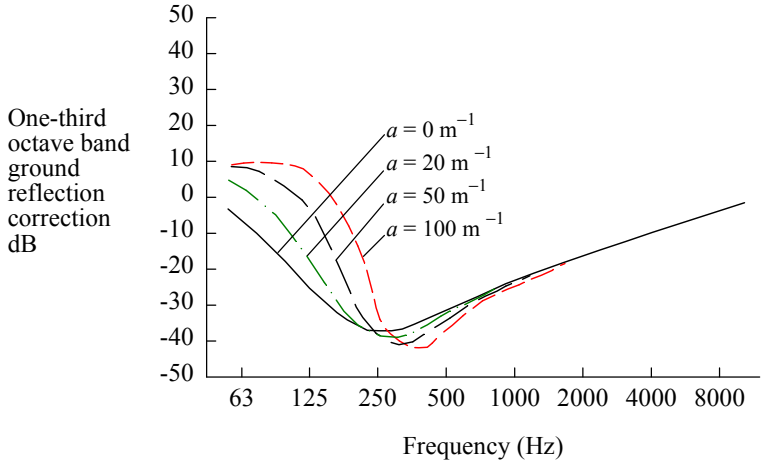
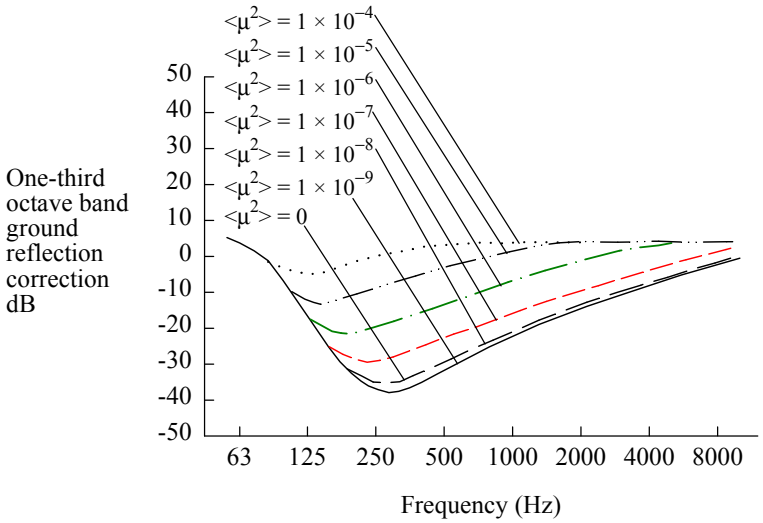


Sketch 3.4 Variation of ground reflection correction with inverse effective depth, σ_e set at 30 kN s/m^4



Sketch 3.5 Variation of ground reflection correction with turbulence parameter $<\mu^2>$,σ_e set at 30 kN s/m^4 and α set at 20 m^{-1}

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4. DERIVATION AND REFERENCES

4.1 Derivation

The derivation lists selected sources that have assisted in the preparation of this Item.

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4.2 References

The references given are a recommended source of information supplementary to that in this Item.

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