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Measurements of Ground Effect Under Downward Refracting Conditions

E. A. Björk
Department of Environmental Science, University of Kuopio, P.O. Box 1627, 70211 Kuopio, Finland. Erkki.Bjork@uku.fi

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Summary

The effects of ground and downward refracting meteorological conditions on the propagation of white noise from two source heights to four receiver heights were measured on an airfield with a view to validating a statistical curved-ray model for noise under downward refracting conditions over flat ground. The measured data supported the model when sound was propagated over an asphalted airstrip, but the model did not work for sound propagated over grassland, perhaps as a result of destructive interference between direct and reflected waves. The method of calculating the ground effect in ISO standard 9613-2 is also evaluated on the basis of the measured data.

1. Introduction

Several noise models and methods have been proposed for computing the attenuation of outdoor noise when propagated near the ground. These computational methods are based on attenuation due to geometrical energy divergence. Geometrical divergence is considered to be spherical in the free field from a point sound source. It is also known that sound can be attenuated by air absorption, ground effect and screening [1].

Determination of the influence of wind and temperature gradients on the propagation of sound over plane ground is an important part of environmental prediction schemes. Such gradients have a substantial influence on sound levels measured at distances exceeding 100 m; therefore, it is necessary to take these influences into account [2].

Björk [3] introduced a statistical curved-ray model for the divergence of noise above flat ground under downward refracting conditions. In this model, the increasing number of downward curving rays with distance leads to the amplification of sound pressure level. The present study was designed to investigate the effects of ground and downward refracting meteorological conditions on the propagation of sound outdoors, with a view to validating this model. The investigation was carried out on an airfield, by measuring the propagation of white noise from two source heights (0.5 and 2 m) to four receiver heights (0.5, 1.5, 3 and 6 m), at a distance up to 1500 m.

2. Measurements and calculations

2.1. Sound source

The source was an omnidirectional Nor-270H loudspeaker (Norsonic AS, Norway) powered by a Nor-260H power amplifier (Norsonic). White noise, at maximum power without equalisation, was produced. The sound power-level of the loudspeaker (L_W) was measured by the Kuopio Regional Institute of Occupational Health, using ISO 3744 standard, in one-third octave bands between 31.5 Hz and 5 kHz. The sound pressure-level in the free field at a distance of 10 m ($L_{10\mathrm{m,source}}$) was computed using the formula:

$$L_{10\mathrm{m,source}} = L_W - 10\log(4\pi \cdot 10^2) \quad (1)$$

and is shown in Figure 1. The A-weighted sound-pressure level at a distance of 10 m in the free field was calculated to be 84.4 dB.

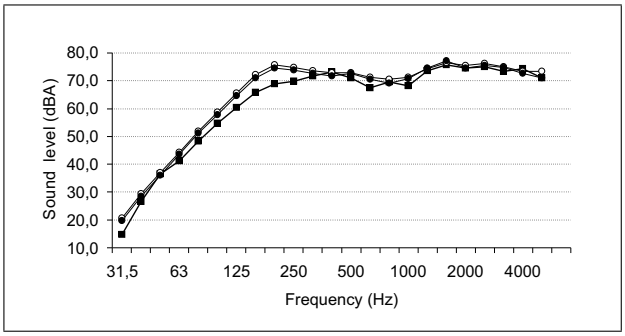


Figure 1. One-third octave band spectrum of the A-weighted sound pressure levels of the sound source in free field at 10 m with respect to the sound power measured in the laboratory (—■—) and at 10 m from measured emissions on asphalt (—○—) and grassland (—●—).

2.2. Measurement site and time

Measurements were carried out on the Kuopio airfield at Rissala over two nights: on 12 August 2004 between 21:00 and 24:00 (night 1) and on 25 and 26 August 2004 between 21:00 and 02:30 (night 2). The source was located on a base, 0.5 and 2 m above the ground, and the receiving microphones were 0.5, 3, 1.5 and 6 m above ground level. The source and the measurement microphones were positioned, in turns, at the centre on an 80-m wide asphalt airstrip and on 40 m of grassland (grass height: ∼0.2 m) at the side of the airstrip.

The nearest building, of any size, was an ∼20-m high airport station, which was ∼300 m from the sound source parallel to the measurement line, i.e. the airstrip. The mirror sound source, caused by this building, was at least twice as far as the primary sound source from any measurement point. Along the line of the measurement points, the ground was relatively flat. There was a 50-m wide transverse asphalted airstrip ∼500 m from the sound source, breaking the continuity of the grassland.

2.3. Determination of the sound ray radius

Mean air temperature, relative humidity, wind speed and direction, and air pressure were measured once a minute at two weather stations (integrated sensory suite with fan-aspirated Radiation Shield; data collected and logged with a Vantage Pro Weather Envoy; Davis Instruments Corp.) at heights of 0.5 (z_1) and 5 m (z_2) above ground level at a point located on the grassland about 200 m from the sound source and 80 m from the airstrip. Meteorological conditions are shown in Table I. The wind direction was nearly downwind on both nights.

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Table I. Mean meteorological conditions during measurements at elevations of 0.5 m and 5 m.

	Temperature (°C)	Humidity (%)	Wind speed (m/s)	Air pressure (hPa)	Cloudiness (8/8)
Night 1	10.4/11.0	86	1.4/2.6	1007	2
Night 2	6.7/8.2	89	0.0/0.1	1016	0

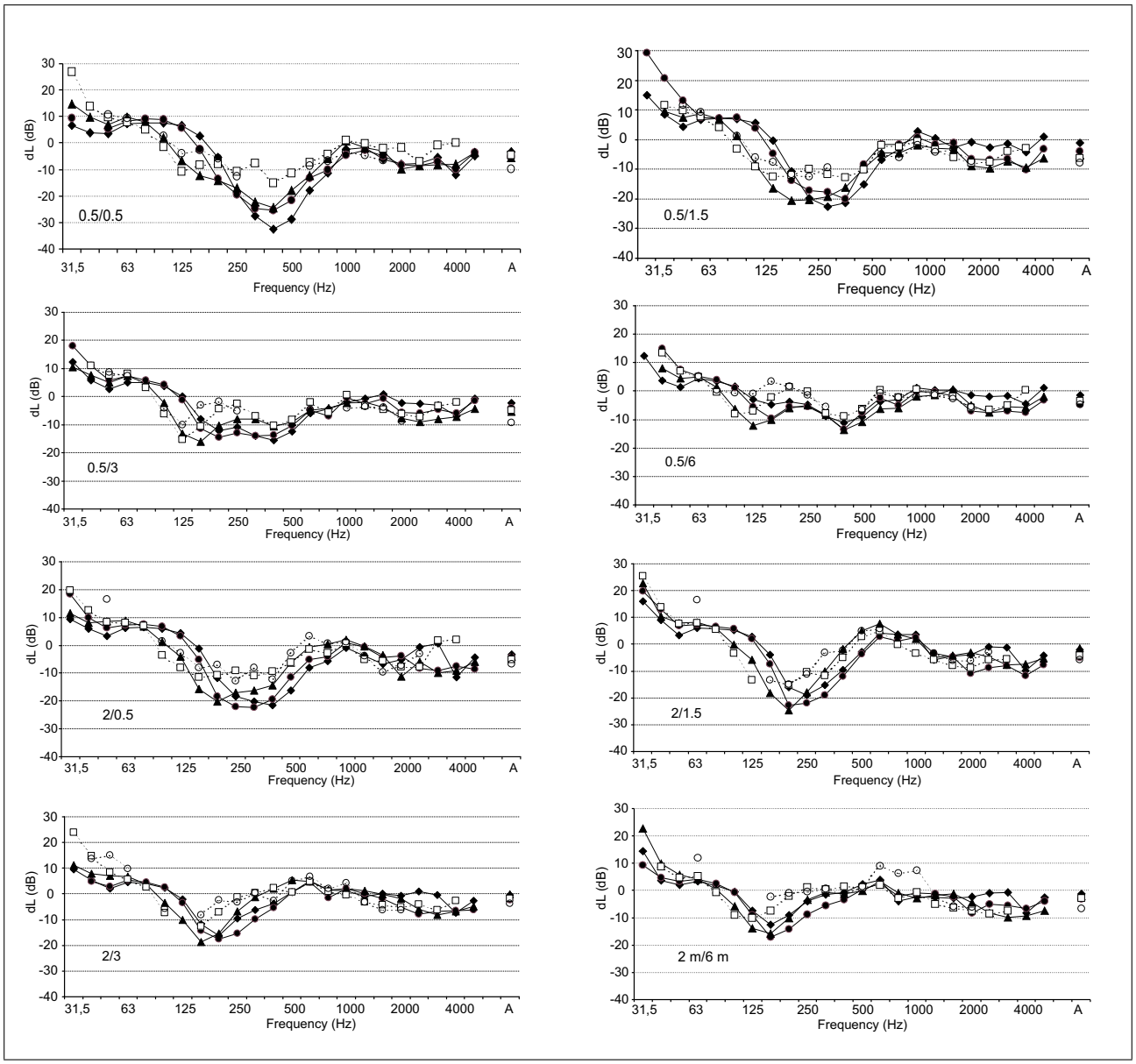


Figure 2. a. Sound pressure levels re free field (dL) on grassland at different distances (—■—, 100 m from source; —●—, 200 m from source; —▲—, 400 m from source; ...□..., 800 m from source; ...○..., 1500 m from source) and at different source/receiver heights.

The radius of sound ray curvature (R) during measurements was computed using the following equation [4]:

$$R = c(1 + u/c)^2 / \left[\frac{10}{\sqrt{T}}\frac{\mathrm{d}T}{\mathrm{d}z} + \frac{\mathrm{d}u}{\mathrm{d}z}\right], \quad (2)$$

where T is the temperature (K), c is the sound velocity (m/s) and u is the component of the wind vector (m/s) in the direction of the ray. Variables C, u and T were determined corresponding to the mean wind velocity and temperature at the two measurement heights (z_1 and z_2) and $\mathrm{d}T/\mathrm{d}z = (T_2 - T_1)/(z_2 - z_1)$ and $\mathrm{d}u/\mathrm{d}z = (u_2 - u_1)/(z_2 - z_1)$. The calculated radius of sound ray curvature, in the direction of the ray, were, on average, 1100 m (min: 900 m/max: 1600 m) on night 1 and 2000 m (min: 1300 m/max: 3100 m) on night 2.

2.4. Measurements and calculations

The sound source was switched on five times for 10 s, with breaks of 10 s, at each trial.

Equal sound pressure levels for every 2 s ($L_{\mathrm{eq.2s}}$) were measured using a two-channel sound analyser (Nor 121; Norsonic) with two microphones: a $^1/_2$" condenser microphone with a wind screen (lower) directed to the sound source and an environmental

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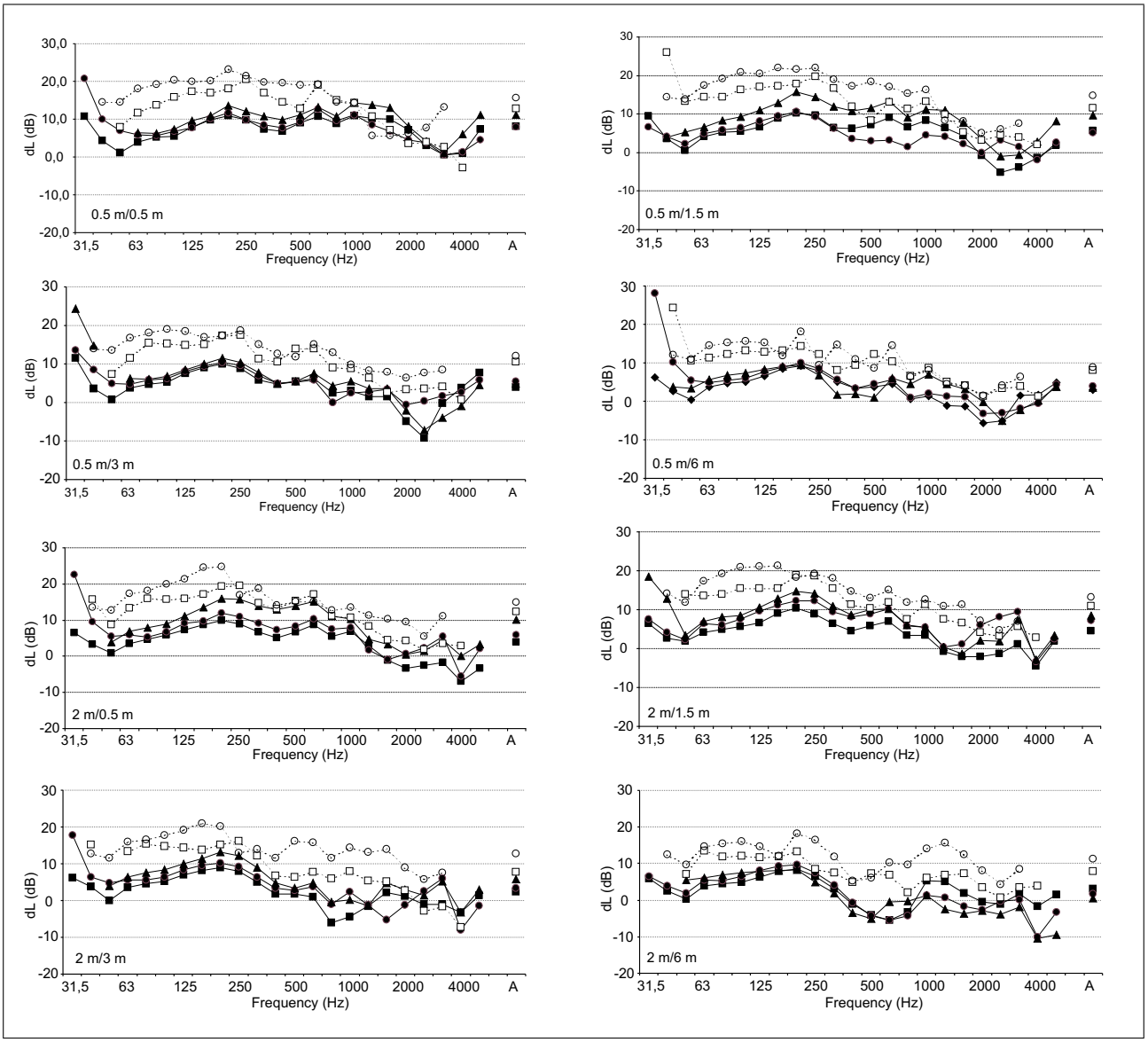


Figure 2. b .Sound pressure levels re free field (dL) on asphalt at different distances (—■—, 100 m from source; —●—, 200 m from source; —▲—, 400 m from source; ...□..., 800 m from source; ...○..., 1500 m from source) and at different source/receiver heights.

microphone system (Nor 1211, upper). The A-weighted sound-pressure and third-octave band sound-pressure levels between 31.5 Hz and 5 kHz were measured. The measurement system was calibrated using a sound level calibrator (Wärtsilä model 5274).

Measurement distances during night 1 were: 10, 100, 200, 400 and 800 m, and on night 2: the same but also at 1500 m.

The background corrected sound-pressure level was obtained by subtracting the background sound-pressure level ($L_{\mathrm{eq,4s}}$ in the middle of the 10-s no-signal period after each 10-s signal period) from the signal sound-pressure level ($L_{\mathrm{eq,4s}}$ in the middle of the signal period). Only measurements with signal-to- noise ratio greater than 5 dB were accepted. If at least three of the five signals yielded acceptable results, the median of the corrected sound-pressure levels was taken as the final figure for the trial (L_{measured}) and used in subsequent analysis.

From the measured sound-pressure levels (L_{measured}) at each distance greater than 10 m, the reversed sound pressure levels at a distance of 10 m ($L_{\mathrm{10m,reversed}}$) were computed, taking into account the attenuations due to geometrical divergence of the point sound-source in the free field [2] and due to air absorption [5].

The sound pressure levels re free field (dL) at each distance greater than 10 m were computed, subtracting the computed sound-pressure levels of the sound source in free field at 10 m with respect to the sound power measured in the laboratory ($L_{\mathrm{10m,source}}$) from the reversed sound-pressure levels ($L_{\mathrm{10m,reversed}}$), i.e.

$$dL = L_{\mathrm{10m,reversed}} - L_{\mathrm{10m,source}}.$$

Furthermore, the sound pressure levels re free field and ground effect (dL_{ground}) were computed taking into account in the computation of $L_{\mathrm{10m,reversed}}$ in addition the attenuations due to ground effects, after the tested model [3] and after the ISO standard [2].

The arithmetic means of the measured A-weighted sound pressure level re free field (dLA) at different distances were computed in order to test the statistical curved-ray model introduced by Björk [3]. For simplicity the averaging was made at two levels. The lower level includes measurements of both source heights at microphone elevations of 0.5 and 1.5 m, and a higher level at microphone elevations of 3 m and 6 m, respectively.

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Table II. Significance levels obtained for the effects of measurement distance, source height, receiver height and radius of sound ray curvature on sound-pressure level re free field for asphalt and grassland.

	Distance	Source height	Receiver height	Radius of sound ray
Asphalt	< 0.001	< 0.001	< 0.001	0.005
Grassland	0.03	0.04	n.s.	n.s.

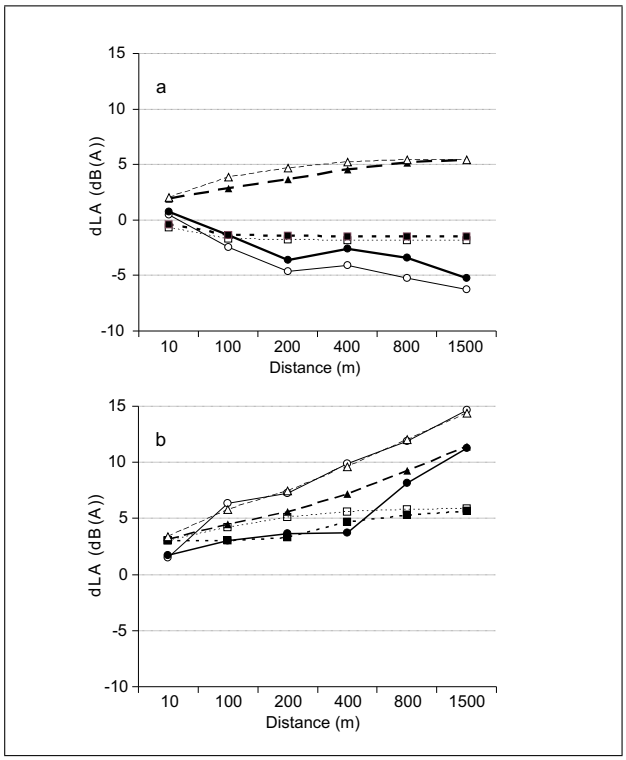


Figure 3. A-weighted sound-pressure level re free field (dLA) on grassland (a) and on asphalt (b) at different distances. Thin lines and open marks stand for lower heights. Heavy lines and solid marks signify higher heights. Solid lines and circles (—●—) stand for measured data. Broken lines and triangles (—▲–) stand for predictions from the tested model and dotted lines and squares (...■...) for the ground effect after the ISO standard. See text for details.

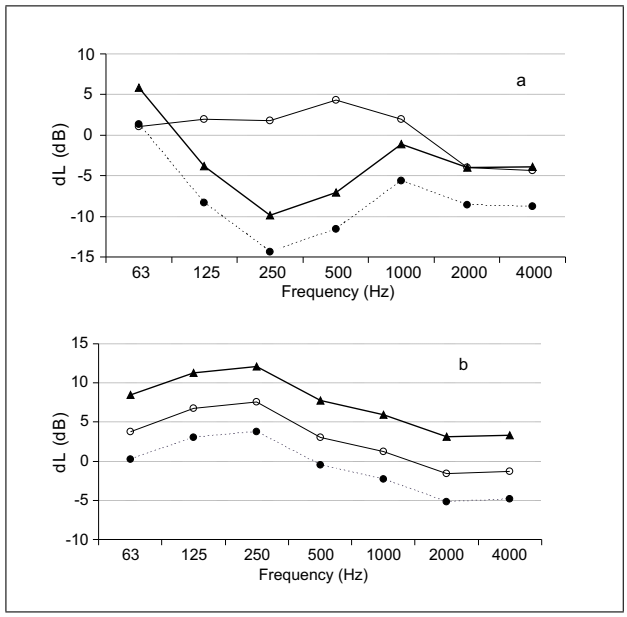


Figure 4. Mean sound pressure levels re free field (dL) and re free field and ground effects (dL_{ground}) on grassland (a) and on asphalt (b) at different frequencies: Heavy line and (—▲—) stands for dL, thin line and (—○—) for dL_{ground} after the ISO standard and thin line and (—●—) for dL_{ground} after the tested model. See text for details.

The A-weighted sound-pressure level re free field, measured at distances equal to or greater than 100 m was analysed separately for grassland and asphalt by an ANOVA of measurement distances (5), source height (2), receiver height (4) and radius of sound ray curvature less of greater than 1500 m (2).

In order to check the sound emission of the used sound source in the field conditions the energetic mean sound- pressure levels in the one-third octave bands between 31.5 Hz and 5 kHz were also determined from the measurements at 10 m.

3. Results and discussion

The one-third octave band spectra of the A-weighted sound-pressure levels measured at 10 m on asphalt and on grassland are shown in Figure 1. At frequencies between 63 and 400 Hz the measured field levels were greater than the free field values computed from the sound power measured in the laboratory.

Sound-pressure levels re free field (dL) in the third octave bands between 31.5 Hz and 5 kHz and A-weighted at different distances, source and receiver heights, are shown in Figures 2a and 2b for grassland and asphalt, respectively. The arithmetic mean values of the two measurements are shown, if both were acceptable.

The arithmetic means of the measured A-weighted sound pressure level re free field at different distances are shown in Figure 3a and 3b for grassland and asphalt, respectively. Figures 3a and 3b show also the corresponding theoretical amplifications, computed from the tested model, using the mean radius of sound ray curvature of 1500 m, mean heights (In this model the maximum height of the source height and the receiver height is a relevant variable.) of 1 m (lower) and 4.5 m (higher), and assumed effective absorption coefficients 0.01 for asphalt and 0.5 for grassland. The corresponding ground effects, computed according to the Standard (ISO 9613-2)[2], using heights for source and receiver of 1 m (lower), and source height 1 m and receiver height 4.5 m (higher), are also shown in Figures 3a and 3b.

The mean sound pressure levels re free field (dL) and re free field and ground effects (dL_{ground}), averaged of measurements at distances equal to or greater than 100 m, are shown in octave bands between 63 Hz and 4 kHz in Figures 4a and 4b for grassland and asphalt, respectively.

The significances of the main effects of measurement distance, source height, receiver height and radius of sound ray curvature on sound-pressure level re free field are shown in Table II. Excess attenuation ($dL < 0$) on grassland increased with increasing measurement distance and decreased with increasing source height. Excess amplification ($dL > 0$) on asphalt increased with

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increasing measurement distance and decreased with increasing source height, receiver height and radius of sound ray.

This data supports the tested statistical curved-ray model when sound is propagating near acoustically hard asphalted ground. The agreement of the measured data with the model was near perfect when the A-weighted sound-pressure level of white noise propagated near the acoustically hard ground; see Figure 3b. Qualitative support was elicited for the effects of all the relevant parameters in ANOVA, i.e. measurement distance, source height, receiver height and radius of sound ray curvature.

In the case when sound was propagating near acoustically non-hard grassland, the agreement between the measured data and the model was poor; see Figure 3a. Measured excess attenuations (Figure 2a) were very similar to those measured by Parkin and Scholes [6] under inversion conditions.

On grassland, there were excess attenuation ($dL < 0$) especially at frequencies between 100 Hz and 1000 Hz; see Figure 2a. The obvious explanation for this disparity is destructive interference between direct and reflected waves i.e. the ground effect. At frequencies lower than 100 Hz where the grassland is acoustically hard and there is no phase change on reflection and destructive interference does not occur, amplifications were present in the measurement data, equally, on grassland and asphalt; see Figures 2a and 2b. Especially at frequencies between 100 Hz and 1000 Hz, the ground effect after the ISO standard predicted the measured attenuation rather good, but the tested model deteriorated the prediction; see Figure 4a.

On acoustically hard asphalt, there was excess amplification ($dL > 0$) at any frequency; see Figure 4b. At frequencies below 1 kHz, the tested model predicted the measured amplification better than would be predicted by ground effect according to the ISO standard. On the other hand the ISO standard predicts the excess amplification better than the tested model at frequencies greater than 1000 Hz.

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