GROUND EFFECT

Together with the measured excess attenuation, figure 1 shows the excess attenuation A_g for isotherm windless conditions as modelled by the Weyl-van der Pol approximation in combination with the variable porosity impedance model [1]. The two parameter values for the impedance model were chosen to make a best fit to the shape and position of the low frequency flank of the ground dip. The choice of the impedance model and the values of the parameters hardly influence the mid- and high frequency part of the curve.

It appeared to be possible to find parameter values that yield reasonable fits to the low frequency part of all measurements for all geometries. In the mid and high frequencies the ground model is clearly insufficient. At 10 m from the source the predicted interference pattern is disturbed, most probably by an overlaying interference pattern caused by reflection at the tree trunks. For pure tones, this pattern is very well audible [5]. At the 100 m range the ground effect is gradually overshadowed by a vegetation effect from a frequency of 500 Hz upwards.

If ground interference is not to be included in the model predictions, the ground model may still be used with the modification that direct and ground-reflected sound are summed incoherently. The resulting 'incoherent excess attenuation' A_i is also drawn in the figure. In the high frequencies, in this experiment from 3000 Hz, where in the forest the ground interference pattern is disturbed, it is certainly more realistic. In the mid and low frequencies the coherent calculation clearly functions better.

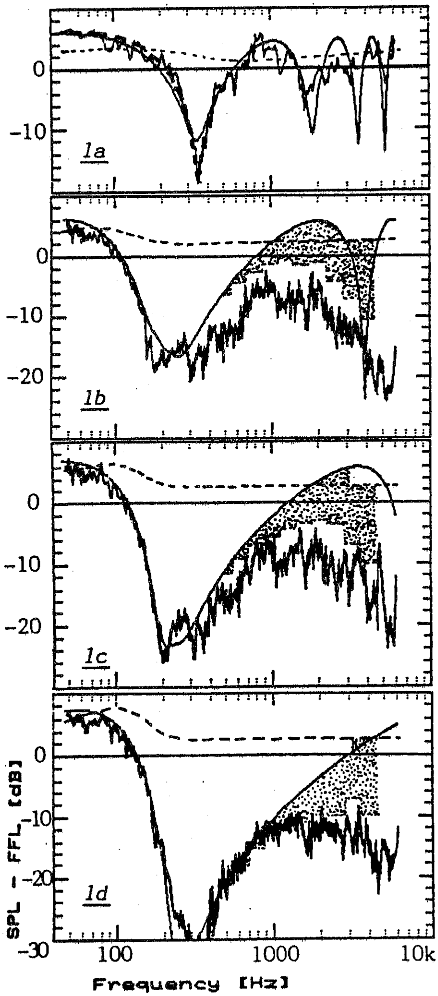


Figure 1 Measured and modelled excess attenuation.

Measurements of a logarithmic pure tone frequency sweep, normalized to free field and corrected for air absorption. Source height 1 m. Clear windless night.
Excess attenuation modelled by ground effect model:
Solid line: coherent (A_g); broken line: incoherent (A_i).
Parameters: Effective flow resistivity σ_e = 30000 Nsm^{-4}; effective rate of exponential change of porosity α_e = 50 m^{-1}.
Line below dotted area: summed attenuation by stochastic scattering model and ground model (incoherent from 3000 Hz).
a Receiver at x_r = 10 m; height 1 m. Average of 4 sweeps. The thick broken line (σ_e = 20000 Nsm^{-4}; α_e = 25 m^{-1}) fits better at this geometry.
b-d: Receivers at x_r = 100m; heights 4.50m (b); 2.50m (c); 1.00m (d). Four sweeps made within ten minutes.

A MODEL OF REVERBERATION BY TREE TRUNKS

The well audible reverberation in a forest demonstrates the scattering effect of the trees and branches. Partly following Kuttruff [8] a model was defined where the forest is represented by a random array of infinitely long parallel cylinders scattering sound particles from a point source. However, instead of calculating algebraicly with probabilities, a stochastic ray tracing program was built [7]. This had the advantage that no secondary assumptions had to be made apart from the usual geometrical acoustics approximation. (The assumptions in [8] necessary to derive the decay equation for a forest are so that it is hardly applicable in practical situations, as is shown in figure 2)

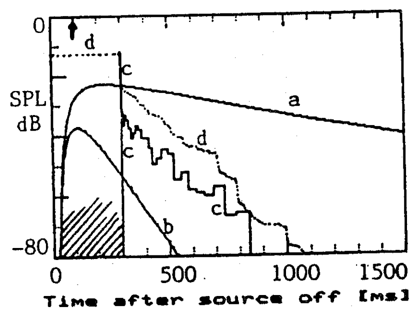
Besides the source-receiver range x_r, four parameters are relevant for the pulse response curve (figure 2). These are the air absorption, to be applied in dB/s; the density of the forest n, in trees/m²; then the effective tree diameter D_e, which will only equal the actual tree diameter in the high frequency limit; and the effective reflection factor R_e, which is the factor of energy loss of a ray after specular reflection on the tree (for ideal hard cylinders, $R_e = 1$).

The pulse response predicted by the stochastic model consists of two parts, the 'direct sound field' and the 'reverberant sound field'. To compute the direct field the numerical technique is not necessary. It is built up by the rays that have not hit any tree before reaching the receiver. These rays all arrive at the same time, which is simply the source-receiver range divided by the sound speed. Therefore, the direct field is a pulse with known energy but undefined intensity since its duration is 0. This energy E_d, normalized to the free field (no trees) energy E_f is found analytically by just accounting for the shielding effect of the trees. It can be expressed in decibel as the direct field attenuation A_d:

$$A_d = 10 \log (E_d / E_f) = 10 \log (\exp (- n D_e x_r)) \quad \text{dB}$$

The reverberant field is built up by rays that have one or more times hit a tree. Its energy is the integral of the pulse response minus the direct field energy. The pulse response shape as well as its energy depend on all four parameters mentioned above. However, the range is hardly important for the reverberant part of the pulse response.

Figure 2 Modelled reverberation
Parameter values: range x_r = 100m; density n = 0.19 trees/m²; scattering diameter D_e = 0.16 m; air absorption 10 dB/s; sound velocity c = 333 m/s.



a+b Pulse response as modelled by [8]. Level normalization is arbitrary. Arrow indicates $t = 1/nD_ec$. Curves should be valid for $t \gg 1/nD_ec$. The hatched area denotes curve parts that are certainly incorrect (no sound can arrive before $t = x_r/c$). Reflection factor: R_e = 1 (a); R_e = 0.1 (b).

c. Pulse response generated by the stochastic ray tracing model. Intensity level is normalized to a free field intensity of one pulse per 5 ms. Reflection factor R_e = 0.1. 20000 rays are computed.

d. Source-off response computed from line c. Source-on level and decay levels are normalized to the free field source-on level. The decay curve gives a good fit to the 4000 Hz measurement.

The total scattering attenuation A_s (that is, due to the thus modelled scattering phenomenon, i.e. without ground effect) is found from the energy of the pulse response E and the free field energy E_f:

$$A_s = 10 \log (E / E_f) \quad \text{dB}$$

By summating a train of pulse responses in time, the response of a source switch on/off sequence is obtained (Fig. 2). The steady source-on level now equals the total scattering attenuation A_s.

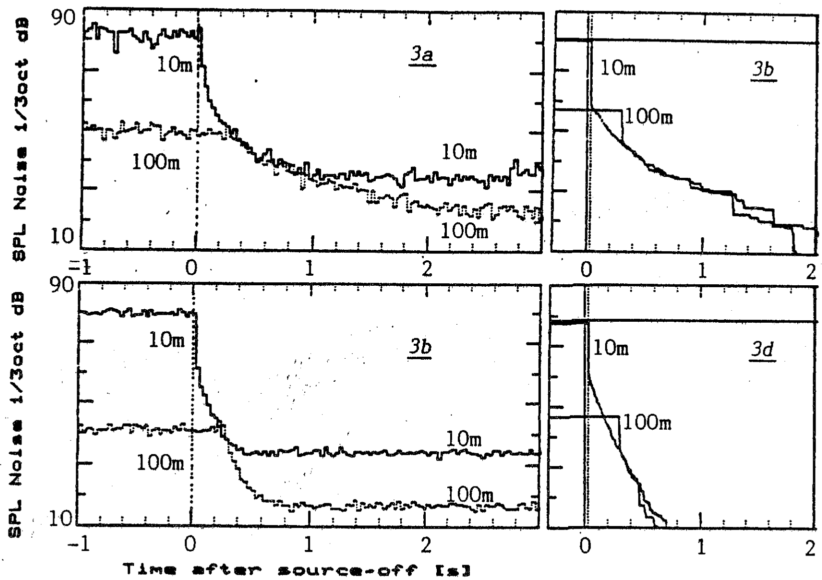


Figure 3 Measured and modelled reverberation.

a+b Simultaneously measured source-off response at range x_r = 10 m (upper lines) and at x_r = 100 m (lower lines), for 1000 Hz (a) and 4000 Hz (b) 1/3 octave band noise, analysed from tape recordings. In the background is apparatus noise of which the apparent level differs for the two receivers because of different microphone amplifications.

c+d Modelled source-off responses fitting to a and b. The parameter values that yielded the fits were found by overlaying model calculations over the adapted source-on level at x_r = 10 m and over the concatenated decay curves at 10 m and 100 m. The adaptation made to the source-on level was the exclusion of ground interference effects.
Parameter values input: n = 0.19 trees/m^2; air absorption 0 dB/s (a) and 10 dB/s (b).
Fitted values: reflection factor R_s = 0.1 (a+b); scattering diameter D_s = 0.04 m (a) and 0.16 m (b).
Also drawn are model predictions for x_r = 100 m with parameter values found for x_r = 10 m.
The difference between measured and modelled source-on levels at x_r = 100m is considered as a ground effect.

ANALYSIS OF MEASURED REVERBERATION

The measured source-off curves at 10m and 100m appear indeed to coincide shortly after the moment that the source-off event reaches the 100m receiver. (Figure 3)

A number of model predictions for x_r = 10m was made with various values for the parameters R_* and D_*, with n equal to the actual forest density. The modelled curves were laid over the measured curves, with the modelled source-on levels at the level of the measurement free field plus 2 dB. In this way the overall sound energy is regarded as the incoherent addition of direct sound and ground-reflected sound; i.e. the interference effect is taken out.

Table 1 summarizes the values for R_* and D_* that fitted best to the 1/3 octave band reverberation measurements. For practical reasons it was not attempted to find fits for all measurements. The decay curves change only slowly and very regularly with frequency, so the missing values may safely be interpolated.

The decrease of D_* with increasing wavelength is quite reasonable (larger wavelengths hardly 'feel' the small trees). However, the value R_* = 0.1 is very low even for the irregular cork-like bark of Pinus nigra. But as pointed out in [2], this parameter also accounts for scattering of sound out of the plane perpendicular to the cylinder axes, that is, for effects caused by the trees not being ideal cylinders.

With the found parameter values new model predictions were made for the range x_r = 100m. The reverberant field fits very well, but the total scattering attenuation A_* underpredicts the measured overall attenuation. This is not surprising, since forests do have a ground which may cause considerable attenuation due to coherent interference of direct and ground-reflected sound, which effect is not included in this essentially incoherent scattering model.

Table 1 Results of stochastic scattering model.

Parameters used for prediction of reverberation at X_r = 10 m:						
Reflection factor R_*	0.1	0.1	0.1	0.1	0.1	
Scattering diameter D_*	.01	.02	.04	.08	.16	m
Air absorption	0	0	0	3	10	dB/s
Fit to measured decay curves of 1/3 oct band:	500	630	1000	2000	4000	Hz
Scattering attenuation predicted for X_r = 100 m						
Total scattering att. A_*	-0.8	-1.6	-3.1	-6.3	-12.8	dB
Direct field atten. A_t	-0.8	-1.7	-3.3	-6.6	-13.2	dB

The low value found for the reflection factor of the trees causes the contribution of the reverberant field to the sound field to be minimal. The sound field even at 100 m is mainly due to the direct field. This may also be deduced from the measured decay curves at 100 m: the source-off event is very marked and causes a deep drop in sound pressure level. Therefore, the treating of the sound propagation in forests as a diffusion problem ([8], [2]) is at least at this range not suitable.

COMBINING THE MODELS

Figure 1 shows the attenuation resulting from addition of the ground model and the scattering model predictions. For the receiver height 1.00 m, the correspondence between predicted and measured is quite good. However, for the highest receiver position, 4.50 m, correspondence in the frequency range 500 Hz to 2000 Hz is disappointing. The results of the other two microphones, 1.50 m (not shown) and 2.50 m, are in between.

In figure 4, results are presented as vegetation effect, either measured directly in an anechoic room, modelled with models neglecting ground effect, or deduced from measurements by subtracting the ground model prediction. From the forest structure, it is very unlikely that such a strong height dependence of the vegetation effect should occur: the pine plantation indeed looks like a random array of equal parallel cylinders (Fig. 5). Foliage effects are to be expected at much higher heights and then mainly in the high frequencies.

Therefore, it is concluded that the ground effect is influenced by the tree scattering to a much greater extent than just loss of coherence in the high frequencies. And since an accurate knowledge of the ground effect is needed to deduce vegetation attenuation from excess attenuation measurements, we cannot empirically verify models of vegetation effect.

A final remark on the old question of using forests to abate traffic noise. Figure 1 shows that the measured attenuations at 100m in the frequency range of interest (around 1000 Hz) are between -6 dB and -12 dB, which values appear to be valid for all meteorological conditions. Currently research is being done on the impact of this observation to traffic noise propagation prediction. This implies at least considering a line source, the traffic noise spectrum, A-weighting, and predicting the open field sound propagation including the there existing meteorologic effects.

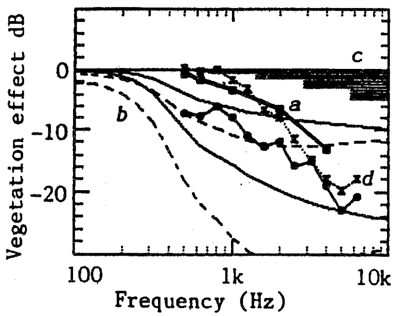


Figure 4. Ground-independent vegetation attenuation.

a Squares: Attenuation A_s predicted by the stochastic ray tracing model (table 1).

b Attenuation predicted by the model by Embleton [3] as implemented by Price et al. [9]. Diameter 0.16 m, density 0.19 trees/m², range 100m.
Solid lines: hard cylinders; broken lines: σ_e = 100000 Nsm^{-4}.
Lower lines: original values; upper lines: reduced to 40% [9].

c Hatched area: Insertion loss by ten 4-year old sawn-off Pinus nigra trees in an anechoic room packed into a 'forest' of 2.00 by 2.80 m, height 1.85m, fresh weight 67 kg, stem diameter at the ground 0.05 m; horizontal transmission of light from source to receiver 0.5 % (= -8.2 dB/m).

d Measured vegetation effect, that is, difference between measured excess attenuation and modelled ground effect A_g (over 3000 Hz: incoherent, A_i)
Crosses: receiver at 1.00m; Circles: receiver at 4.50m.

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The author wishes to thank dr. K. Attenborough and dr. M. Price for the permission to use their multiple scattering program based on [3], and dr. M. Martens, R. Beekwilders and A. Linders for their practical work on the measurements.

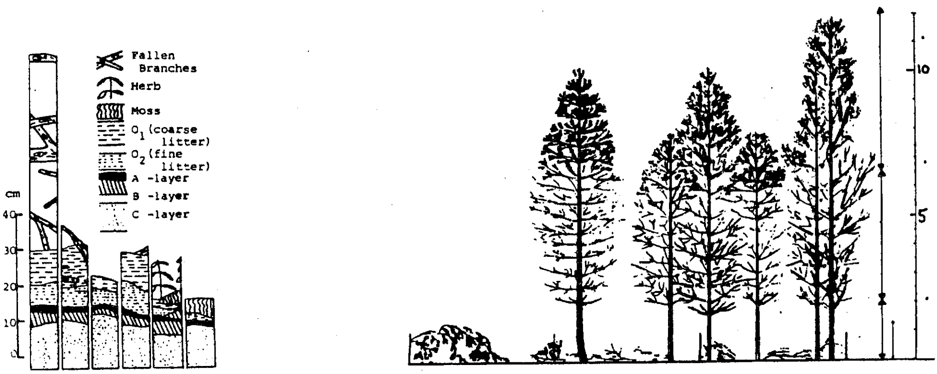

Figure 5. Vegetation structure.

Left: side view of six soil profiles including covering material. Layers A to C are mineral.
Right: side view of a plot of 2m by 15 m with bare trunk zone, dead branches zone, and canopy.