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MODELS FOR PREDICTING A-WEIGHTED NOISE FROM AIRPORT GROUND OPERATIONS

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Abstract

Measurements made at four distances up to 1158 m from fixed jet engines sources under carefully-monitored meteorological conditions, together with spectra measured around stationary aircraft and engines under test, have been used to derive acoustically-neutral and downwind attenuation rates for A-weighted noise levels from unobstructed airport ground operations. The resulting models for excess attenuation are shown to be consistent with predictions obtained using CONCAWE and ISO9613-2 octave band methods and with predictions based on analytical approximations for propagation from point sources over impedance ground in the presence of atmospheric refraction and turbulence. Close to the source the models presented here will give overestimates of attenuation rates. However extrapolations of the empirical models to ranges up to 3 km are supported by the theoretical predictions. Standard barrier theory has been modified to enable predictions of barrier effects on overall A-weighted levels in the presence of absorbing ground.

1. Introduction

Noise from ground operations including aircraft taxiing, engine testing, aircraft auxiliary power units, ground power units, and other ground equipment including vehicles and mechanical plant at airports plays a significant role in determining community reaction at distances up to 3 km from the source. It is difficult to draw precise lines between ground noise and air noise, however the start of roll, aircraft take-off and landing and reverse thrust are treated usually as air noise rather than ground noise. Apart from wave-front spreading, the attenuation mechanisms for ground noise, which include ground effect, barrier effects and air absorption have strong frequency dependence. The ISO method [5] is an octave band scheme that can be applied to the prediction of noise from airport ground operations. However, it requires knowledge of the source power spectra in octave bands, it predicts levels only under average downwind conditions and is based on data taken 10 years ago or more on industrial rather than aircraft sources. The CONCAWE scheme [6] is an octave band scheme applicable to broad-band sources and enables prediction under several meteorological conditions. Again, however, it requires knowledge of the source power spectra and it is based on data from sources other than aircraft.

The task of aggregating the noise predicted from many aircraft using various taxi routes and stands means that it is useful to derive a scheme that predicts A-weighted levels for taxiing and engine testing noise without requiring knowledge of individual source power spectra. Although such schemes are available for predicting A-weighted levels resulting from various ground transport sources in the UK [3,4] as yet there is no equivalent scheme for airport ground noise. Some authors have suggested "grand mean" attenuation rates determined empirically from *in situ* measurements around airports encompassing "a representative range of topographical and meteorological conditions"[5]. On this basis various attenuation rates for overall A-weighted taxiing levels have been suggested ranging from 11-12 dB per distance doubling [5] to spherical spreading plus 0.02 dB m^{-1} [6]. If suitable meteorological statistics are available, the resulting "mean" attenuation rate may be adjusted for adverse and favourable propagation conditions [6]. Recent years have seen considerable advances in modelling outdoor sound propagation. Where the path from source-to-receiver is not obstructed, the main factors influencing propagation are ground effect, air absorption and atmospheric refraction. There are validated analytical and numerical methods for predicting these effects [see for example ref. 7]. Recently an analytical approximation for predicting A-weighted levels from broad-band sources has been developed that is more useful for routine engineering use [8]. Given that one of the tasks is prediction of noise from jet engine testing, it should be noted also that there are relevant data obtained with single fixed jet engine sources under carefully-monitored meteorological conditions [9-11] out to approximately 1.1 km range. This paper describes how the frequency dependent attenuation rates obtained from these data, together with source spectra averaged over orientations and thrusts for taxiing noise and engine testing noise have been used as the basis for new empirical schemes for predicting A-weighted airport ground noise. Comparison of the resulting models with predictions of the approximate theory [8] indicates the validity of extrapolating to ranges outside the maximum range of the propagation data used to derive the empirical models. The different spectra associated with full-thrust testing and taxiing aircraft result in different mean attenuation rates for overall A-weighted noise levels.

It should be noted that the resulting attenuation rate models are likely to give over-predictions at relatively short ranges. A queue of taxiing aircraft represents a source of finite extent from which the wave-front spreading will be less than from a point source. Moreover there are likely to be appreciable proportions of hard ground along propagation paths at and around airports. The presence of hard ground is known to reduce ground effect compared with that over continuously-soft ground. Close to the source these factors should result in lower attenuation rates than predicted for a single fixed source over continuous soft ground. As range increases so that the finite dimension of the source becomes less important and the proportion of soft ground increases, the empirical models based on airfield data should become more accurate.

In the following sections, available source and propagation data pertinent to engine testing and the ways in which it has been used to predict attenuation rates of A-weighted levels from current aircraft engines under acoustically-neutral and downward refraction conditions are described. Standard barrier theory has been used to determine barrier effects on A-weighted levels. The CONCAWE scheme has been used to derive corrections for the loss of ground effect due to the presence of a barrier.

2. DATA FROM STATIONARY JET ENGINES

Sound level spectra have been measured at a radius of 150 m and at 10° intervals around various modern jet aircraft [12]. The resulting data show different frequency spectra at different orientations. The data for engine testing noise measured over hard ground at 45.7 m radius supplied by Boeing [13] show that these frequency spectra depend on orientation also. The different sets of spectra have been averaged over all orientations for the purpose of the model derivations. Octave band ground effect corrections for acoustically-neutral and various vector wind conditions have been derived by Parkin and Scholes [9,10] from one-third octave band data obtained in a classical series of measurements at 1.5 m high receivers of noise out to 1097 m over a grass covered airfield from a jet engine source (Rolls Royce Avon) fixed with its nozzle at a height of 1.85 m at ranges. Vector wind and temperature were monitored during each test. Similar data have been acquired more recently [11] as narrow band (25 Hz) and one third octave band sound level spectra using a Rolls-Royce Avon single-stream jet engine mounted on a stand such that the centre of the exit nozzle was 2.16 m above the ground. Microphone arrays were deployed over grass at a disused airfield at Hucknall, Notts. along a line at 22.5° to the engine exhaust centre line and at 7.5° to the peak jet noise direction. The source-to-receiver direction was 57° West of South. Each microphone array consisted of microphones at 1.2 m and 6.4 m above the ground and arrays were positioned at 152.4 m, 457.2 m, 762 m and 1158.2 m from the source. Acoustic measurements were made simultaneously at all arrays. Temperature, instantaneous wind speed and direction were measured at 0.025 m and 6.4 m heights at a weather station approximately 500 m from the source. The acoustical data acquired during each trial run, were divided into twenty blocks each approximately 30 s long. The recorded signals were averaged within each of these blocks. The Hucknall trials monitored meteorological conditions to a greater extent than Parkin and Scholes both in respect of the height of the wind profile and turbulence. The importance of turbulence may not have been realised at the time of the Parkin and Scholes trials so it was not monitored. The Hucknall trials yielded levels at each range directly rather than the difference in levels between a reference microphone at 19 m and the remoter microphones quoted in the published Parkin and Scholes data. The data from two consecutive blocks were obtained in conditions that conform most closely to a strict definition of acoustically-neutral conditions, i.e. zero wind, very small temperature gradient and low turbulence. The chosen blocks give rise to the highest attenuation rates for conditions of zero wind and low turbulence.

3. ANALYTICAL APPROXIMATIONS AND THEIR APPLICATION TO FIXED JET ENGINE DATA

The excess attenuation due to ground effect near grazing incidence may be approximated by [11]

$$EA = 20\log\left|1 + Q(r_1 / r_2)exp(ik(r_1 - r_2))\right| \quad (1),$$

where Q is the spherical wave reflection coefficient, $Q = R_p + (1 - R_p)\, F(w)$,

R_p is the plane wave reflection coefficient, $F(w)$ is the boundary loss factor, r_1 and r_2 are direct and specularly reflected path lengths. Equation (1) is accepted widely as an adequate approximation and so it has been used to calculate the ground effect. R_p and $F(w)$ depend on the source-receiver geometry and the ground impedance. The latter may be calculated as a function of frequency by means of a two-parameter model [14].

Turbulence effects may be calculated as suggested by Clifford and Lataitis [15]. Accordingly the excess attenuation in the presence of turbulence is given by

$$\mathrm{EAT} = 20\ \log\left|1 + \frac{r_1^2}{r_2^2}|Q|^2 + 2\frac{r_1}{r_2}\{\cos[k(r_2\text{-}r_1)]\ \mathrm{Re}(Q) - \sin[k(r_2\text{-}r_1)]\ \mathrm{Im}(Q)\}T\right| \quad (2),$$

where, for source and receiver at equal heights separated by a distance d,

$$T = \exp(\alpha\sigma^2(1 - \rho)) \quad (3),$$

$\sigma^2 = \sqrt{\pi}) n^2 \langle k^2 dL_0$, $\alpha = 1$ if $L_0 >> \sqrt{(d/k)}$ and $\alpha = 0.5$ if $L_0 << \sqrt{(d/k)}$, $\langle n^2 \rangle$ is the mean square refractive index, and L_0 is the largest scale of fluctuations. ρ ($0<\rho<1$) describes the lateral correlation between direct and reflected waves and has been set equal to zero in the calculations reported here. The absence of turbulence data and the reporting only of level differences at Hatfield make it impossible to make *direct* comparisons between the Hucknall and Parkin and Scholes data. Nevertheless, use of the theoretical model (equations (1) to (3)) for ground effect has enabled (a) deduction of a source power spectrum for the Avon engine from Hucknall data at 152.4 m range and (b) calculation of the ground effect over 19 m range at Hatfield. The Hucknall and Hatfield data for acoustically-neutral conditions have been fitted by this theoretical model for ground effect in the presence of turbulence. The theoretical model for excess attenuation introduces a total of four parameters. These include two ground impedance parameters (σ_e, α_e)and two turbulence parameters ($\langle n^2 \rangle$,L_0). Values of 30 kPa s m^{-2} and 20 m^{-1} for effective flow resistivity (σ_e)and effective rate of change of porosity with depth (α_e) respectively, and values of 10^{-8} and 1 m for mean squared refractive index and outer scale of turbulence respectively, have been found appropriate for Hucknall data. A similar fitting exercise on Hatfield data has yielded parameters of 65 kPa s m^{-2}, 140 m^{-1}, $10^{-7.5}$ and 1 m, respectively. The fitted parameters have been used to predict narrow-band and third-octave ground effect at 152.4 m at Hucknall and third octave ground effect over 19 m at Hatfield. The Hucknall ground effect predictions have been used with measured 152.4 m data for acoustically-neutral conditions at Hucknall to deduce a narrow-band, third-octave band and octave band source power spectrum for the Avon engine source. The octave band spectra deduced for an Avon engine may be compared in Table 1 with those deduced for average taxiing noise and engine testing noise after correcting 150 m and 45.7 m data [12,13] for spherical spreading and air absorption respectively.

Table 1 Calculated power spectra for Rolls Royce Avon, RB211-524G/H at 100% thrust and average taxiing noise

Octave Band Centre Frequency Hz	Avon spectrum level dB	RB211-524G/H spectrum level dB	Average taxiing noise spectrum level dB
63	157.8	154.7	not available
125	163.8	152.0	108.6
250	162.8	148.6	108.8
500	166.1	145.7	122.1
1000	162.7	143.2	129.4
2000	158.8	141.2	133
4000	148.9	140.0	134.6
8000	135.8	140.2	not available

These results have enabled estimation, from the third octave band data measured at Hatfield, of A-weighted Avon engine levels at Hatfield as a function of distance. The results in Figure 1, indicate that, under zero vector wind and near-zero temperature gradient conditions, the attenuation rate of A-weighted sound levels with distance at Hatfield was somewhat less than that measured at Hucknall. The differences in the fitted ground properties do not influence the predicted attenuation ratcs for A-weighted levels [8] as much as differences in prevailing turbulence (fitted values of $\langle \mu^2 \rangle \approx 10^{-4}$ at Hucknall and $\langle \mu^2 \rangle \approx 10^{-7.5}$ at Hatfield). These values for the mean squared refraction index are smaller than those obtained by other workers [17] from fitting the Hatfield data as a consequence of the fact that these researchers used a non-zero value of ρ (see equation (3)) and a different model for the ground impedance. Recently an analytical approximation for the sound field due to a point source near to an impedance ground in the presence of atmospheric absorption, refraction and turbulence has been developed [8]. It is based on an exponential simulation of the A-weighted source spectrum. For acoustically-neutral conditions, in addition to the source-receiver geometry (h_s, h_r, d), and the four parameters introduced by the more accurate model for excess attenuation described above, the approximate model introduces three parameters (μ, m, P_A) that characterize the exponential simulation of the power spectum and two parameters (a_1, a_2) that characterize the air absorption. The resulting formula for A-weighted sound level in the absence of refraction but the presence of turbulence is

$$L_A = 10\log P_A - 20\log d - 10\log(4\pi) + 10\log\left|S\left(\sigma_e, \alpha_e, \mu, m, P_A, a_1, a_2, \langle n^2 \rangle, L_0, h_s, h_r, d\right)\right| \qquad (4).$$

4. EMPIRICAL MODELS FOR UNOBSTRUCTED PROPAGATION OF TAXIING AND ENGINE TESTING NOISE

The Parkin and Scholes and Hucknall data (see Fig.1) suggest the possibility of 'simple' logarithmic models for unobstructed propagation from aircraft engines under acoustically-neutral meteorological conditions. The logarithmic average A-weighted levels computed from Hucknall data measured at 1.2 m height and due to the Avon engine can be fitted approximately by a 'simple' model of the form 35log(r/150), where r m is the distance from the source. The Avon engine has a rather different spectrum to the engines of current jet aircraft. On the other hand, the octave band attenuation rates deduced from the Hucknall trials represent differences of levels recorded simultaneously. This means that they are determined essentially by the ground and atmosphere at the time of measurement and are independent of the source. The octave band attenuation rates obtained under acoustically-neutral and moderate downwind conditions at Hucknall have been used, together with spectra at 150 m and 47 m [12,13] averaged over orientation to deduce attenuation rates for A-weighted sound levels due to taxiing and engine test noise. The results are shown in table 2. The difference between the octave band attenuation rates for microphones at 1.2 m and 6.4 m height at Hucknall when applied to the averaged engine test and taxiing noise spectra have been used to deduce formulae for correcting predicted levels at 1.5 m to predict A-weighted levels at 4.5 m. The resulting formulae are shown in Table 2 also.

Table 2 Summary of empirical models

Model condition	Taxiing noise	Engine-testing noise
Acoustically-neutral for receiver at 1.5 m	35.2log(r/150)	34.0log(r/150)
Moderate downwind for receiver at 1.5 m	27.3log(r/150)	22.0log(r/150)
Receiver height correction from 1.5 m to 4.5 m	$-0.0054r + 8.3 > 0$	$-0.0058r + 9.9 > 0$

5. EXTRAPOLATION TO LONGER RANGES

The Hatfield and Hucknall data extend only to ranges of a little more than 1 km. However predictions of ground noise are of interest at longer ranges. Support for using the simplified models described in section 4 at longer ranges may be obtained from comparisons with relevant theoretical predictions. Figure 3 shows predictions of the attenuation with respect to the A-weighted sound level at 150 m and 1.2 m height obtained by means of an approximate theory for A-weighted levels including ground effect, atmospheric absorption and turbulence [8]. These predictions are compared with Hucknall data obtained at 1.2 m height under acoustically-neutral conditions. Also shown are predictions of a simple formula of the $x\log(r/150)$ type including a correction for receiver height which is a factor of (6.4/4.5) greater than that detailed in section 4. Although the simple model tends to predict higher attenuation at longer ranges than the approximate theory, it show good fits to the data and a similar trend. Figure 3 indicates also that a formula of the form $x\log(r/150) - y(d - 150)$ would give better agreement with the approximate theory at long ranges.

6. Comparisons with octave band schemes

Implementation of the ISO [1] or CONCAWE [2] schemes requires knowledge of the octave band source power spectra. That deduced for the Avon engine is listed in table 1. The resulting comparison of CONCAWE predictions for the A-weighted levels resulting from the Avon engine spectrum with the Hucknall data for acoustically-neutral conditions is shown in Figure 1. Comparison of ISO predictions with downwind data are shown in Figure 2. Comparison of predictions of attenuation rates for overall A-weighted noise from taxiing aircraft and engine testing indicate that, although the ISO and CONCAWE schemes predict a dependence on range similar to the logarithmic relationships deduced in section 4, the CONCAWE scheme gives rise to lower attenuation rates for acoustically-neutral conditions. The ground effects (K_3 terms) predicted by CONCAWE for the averaged taxiing and engine testing noise spectra may be approximated by $4.651\log(d) - 10.318$ and $4.2697\log(d) - 7.6401$ respectively. Both schemes give similar predictions for downwind conditions.

7. Barriers

The 1997 version of the British Standard Code of practice for construction noise [17] offers "an accurate barrier attenuation" model for the attenuation of A-weighted sound levels that is based on path difference and spectral data. A similar model has been developed for use in predicting and assessing noise from airport ground operations. The potential barrier attenuation of A-weighted taxiing noise, in the absence of ground or meteorological effects, is represented by the expressions in Table 3, where δ = path length difference in metres and $x = \log(\delta)$.

Table 3 Predicted barrier attenuation of A-weighted taxiing noise levels

Shadow zone	$\delta < 0.001$	$0.001 < \delta < 3.0$	
	5	$-0.38x^4 - 3.10x^3 - 6.56x^2 + 2.85x + 20.15$	
Illuminated zone	$0 < \delta < 0.09$	$0.001 < \delta < 0.03$	$0.03 < \delta < 0.09$
	5	$3.84x^3 + 25.05x^2 + 49.26x + 30.68$	0

In the case of bunds or earth banks that may be erected around airfields, there will be some loss of ground attenuation due the the effective increase in mean path height from source to receiver. Moreover barriers used for reducing engine test noise may be a significant distance from the noise source (up to 80 m for a large aircraft) and there may be acoustically-soft ground between source and barrier. Consequently predictions should take account of the loss of ground effect due to the presence of the barrier. One method of predicting this loss is to consider that the top of the barrier acts as a new source and to use the expressions for loss of ground effect due to increase in propagation height on both sides of the barrier for example those given in CONCAWE. Given the significant source-to-barrier-distances involved, there is a need also for predicting the influence of downward refraction.

8. Concluding remarks

Consideration of the noise impact of airport ground operations may involve large ranges up to 3 km. Currently available theories and data have been used to derive models for predicting A-weighted noise levels suitable for routine engineering use. For unobstructed propagation, the models assume point sources and continuous acoustically-soft ground between source and receiver. Consequently they will tend to over-predict the attenuation rate close to the source. More effort is needed to take the high proportion of hard ground near to the source into account and to include downward refraction effects in the presence of barriers.

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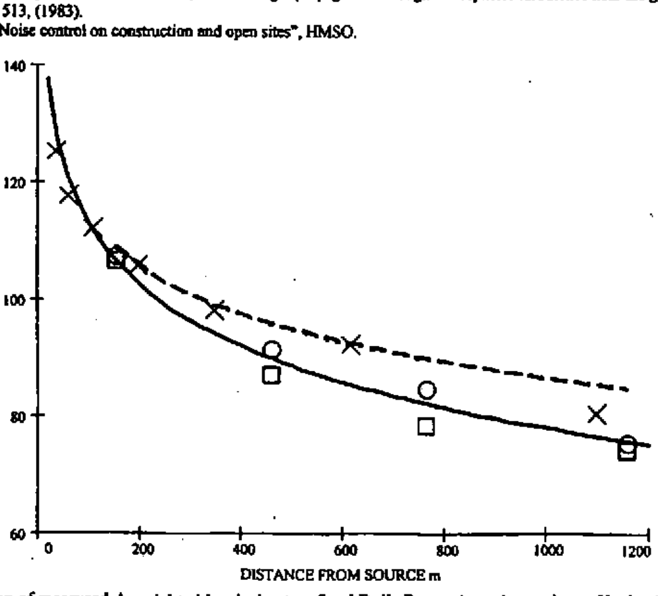

Figure 1 Comparison of measured A-weighted levels due to a fixed Rolls Royce Avon jet engine at Hucknall (Runs 454_20 and 545_19, boxes and circles), levels deduced from Parkin and Scholes (Hatfield) Corrected Level (crosses) including an estimated ground effect at 19 m at Hatfield, and levels predicted using the deduced Avon engine octave band spectrum and the CONCAWE procedure for meteorological category 4 (broken line). Also shown (solid line) is level predicted by the formula:- sound level = (sound level at 150m) - 35log(distance / 150

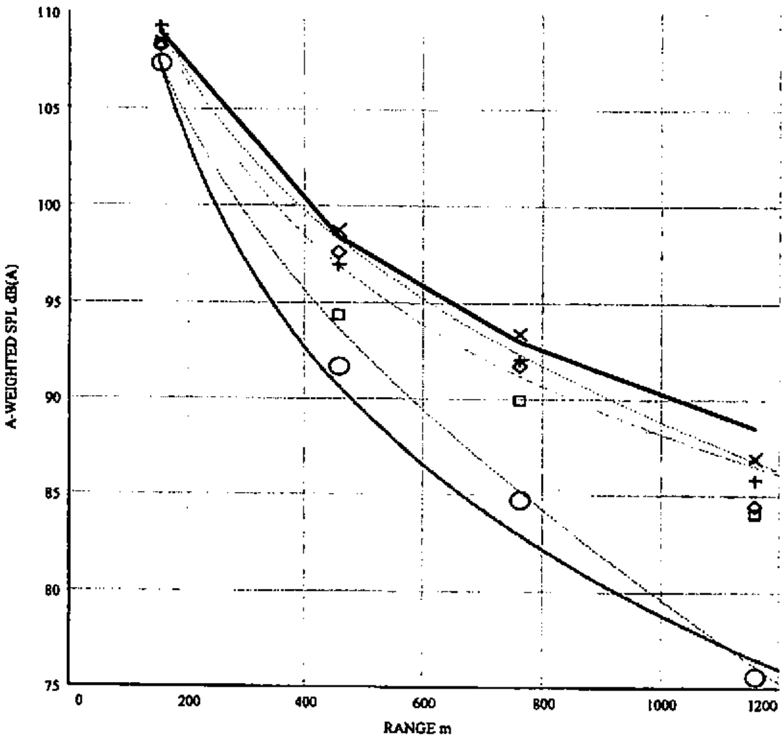

Figure 2 Comparison of measured downwind levels at Hucknall from fixed Avon jet engine (run 453, blocks 3-6: ×,+,◊,□) and measured no wind, low turbulence data (run 454,block 20:O) with predictions based on attenuation rates of the form *x*log(*r*/150) and models involving linear excess attenuation terms. Also shown is the prediction obtained from the Avon power spectrum in Table 1 and the ISO 9613-2 octave band scheme.

KEY

line type	model
	A-weighted level at 152.4 m minus (spherical spreading plus 1.35dB per 100 m)
dash-dot	A-weighted level at 152.4 m minus (Spherical spreading plus 0.5dB per 100 m)
	A-weighted level at 152.4 m minus 26log(*r*/152.4)
	ISO 9613-2 predictions calculated from source power spectrum
	A-weighted level at 152.4 m minus 35log(*r*/152.4)

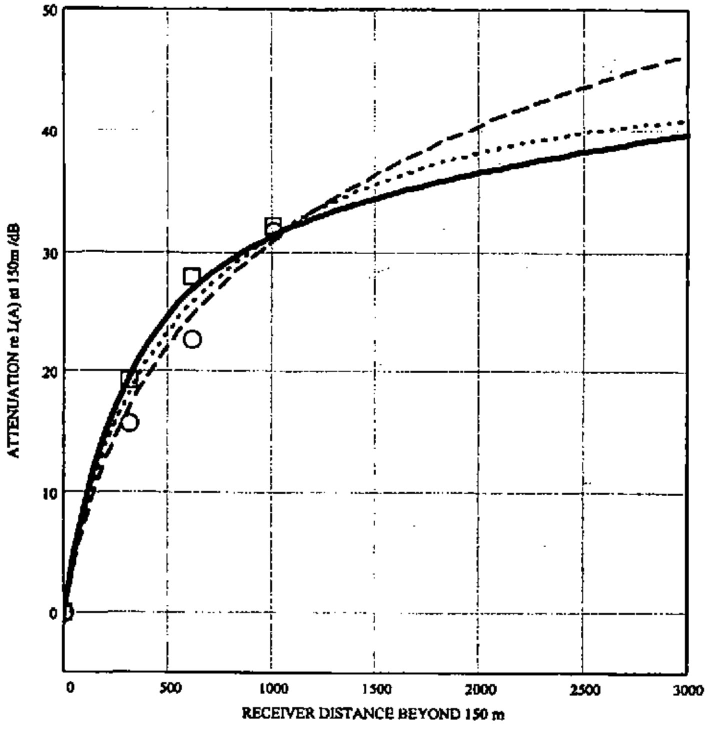

Figure 3 Comparison of approximate predictions (heavy solid line) for the attenuation of A-weighted noise from a fixed jet engine with respect to sound level at 150 m [using $h_s = 2.16$ m, $h_r = 1.2$ m or 6.4 m, $\sigma_e = 30000$, $\alpha_e = 16$, $\langle n^2 \rangle = 10^{-8}$, $L_0 = 1$, $\rho = 0$, $\mu_A = 40.14 \times 10^{-4}$, $m = 2.55$, $a_1 = 4 \times 10^{-7}$, $a_2 = 2 \times 10^{-12}$] with Hucknall data Run 454, blocks 19 (- boxes) and 20 (- circles)) . Also shown are curves corresponding to 35log(d/150) (dashed line) and 40log(d/150) – 0.004(d –150) (dotted line).