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Investigating a simple method of including the effect of turbulence into short to medium range sound propagation prediction schemes.

N. J. Edwards, Y. W. Lam

Department of Applied Acoustics, University of Salford, Salford, M5 4WT, U.K.

1. INTRODUCTION

For many years the presence of turbulence in the atmosphere has been known to influence the propagation of sound outdoors. Simple, accurate methods for including the attenuation effects due to air absorption, spherical spreading and the ground effect are incorporated into most prediction schemes but, despite much research in the area, at present there is no practical way of including the effect of turbulence.

One of the main effects of turbulence on the propagation of sound is to reduce the coherence of the waves. This lessens the destructive effect of interference of the waves. Daigle[1] developed a method of accounting for this. The method is rather involved and, as will be seen in section 2.2, requires the measurement of many parameters and a large amount of data processing. As such it is not suitable for inclusion into outdoor propagation models.

In optics partial coherence theory is used to account for this phenomenon. It stems from the realisation that the concept of a perfect point source is theoretical. Any real physical source is always an approximation to a point source. The overall amplitude and phase of a disturbance emitted from such a source produced by summing the Fourier components fluctuate randomly The amplitude and relative phase of the Fourier components can be considered constant only for a very short time (the coherence time). As sound waves pass through a turbulent medium their relative phases and amplitudes fluctuate and it becomes partially coherent. The Mutual Coherence Function (MCF) is a standard concept in optics and is a measure of partial coherence. With the work of Clifford and Lataitis[2] it is directly applicable to the situation of sound in turbulence and L'Espérance et al[3] use it in their proposed model. Although based on the work of Daigle, the resulting calculations are much simpler, making it more practical for use in a prediction scheme. It does involve some of the same parameters, however, in particular the fluctuating index of refraction, $\langle\mu^2\rangle$.

As will be shown in section 2.2.2, the calculation for $\langle\mu^2\rangle$ requires many detailed measurements to be made and processed to provide the standard deviations of wind and temperature fluctuations and their cross correlation function. These are all relatively inaccessible quantities and a way of calculating $\langle\mu^2\rangle$ from more readily available parameters is needed. Research from the Meteorological Office at Bracknell has suggested an empirical formula which would greatly simplify the calculation of $\langle\mu^2\rangle$[4] as it would depend only on height and wind speed.

This paper investigates the accuracy of this Met. Office simplification by using it in Daigle's method and comparing it in turn with Daigle's own comparisons of his full method with Parkin and Scholes'[5] measurements. In the hope of finding a practical, simple way of including turbulence in outdoor sound prediction models it is used in the MCF suggested by L'Espérance and compared with results of Daigle's method and Parkin and Scholes' data.

2. THEORY

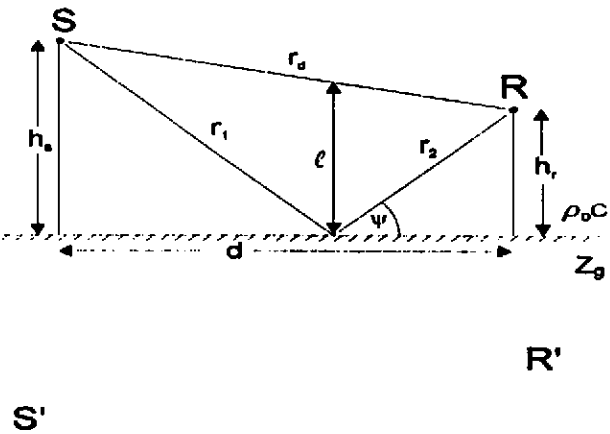


Fig. 1.

2.1 Source receiver topography.

The source-receiver geometry is shown in Fig. 1. The case considered involves non-refractive propagation over flat ground of impedance Z_g and only one reflected path between a point source S and a receiver R. The source and receiver are located at heights hs and hr above ground and separated by a distance d. r_d and $r_r = r_1 + r_2$ are the path lengths of the direct and reflected rays respectively and l is the maximum path separation between the rays.

2.2 Daigle's method.

For the simple case of Fig. 1 the long time average of mean square pressure $\langle \bar{p}^2 \rangle$ at 'R' is (from Ref. 1) :-

$$\langle \bar{p}^2 \rangle = \frac{2}{r_d r_r}\left[\frac{\langle a^2 \rangle}{2}\left(\frac{r_r}{r_d} + |Q|^2 \frac{r_d}{r_r}\right) + \frac{r_r}{2r_d}\left(1 - |Q|\frac{r_d}{r_r}\right)^2 + |Q| + |Q|\left(1 + \langle a^2 \rangle \rho_a\right)\cos(\Phi + \gamma)\exp\left[-\sigma_d^2(1 - \rho_s)\right]\right]$$

where:

$Q = |Q|e^{j\gamma}$ is the spherical reflection coefficient

$\langle \bar{a}^2 \rangle$ is the combined variance the normally distributed amplitude fluctuations of the direct and reflected rays time-averaged over a statistically large number of turbulent fluctuations

σ_d^2 is the combined variance of the normally distributed phase fluctuations of the direct and reflected rays time-averaged over a satistically large number of fluctuations.
ρ_a and ρ_ϕ are the covariance of the amplitude and phase respectively.
$\Phi = k(r_r - r_d)$ and k is the wave number in air.

2.2.1 Calculation of the spherical reflection coefficient.

This is calculated from the plane wave reflection coefficient, R_p, and the boundary loss factor, $F(w)$:-

$$Q = R_p + (1 - R_p)F(w)$$

where:

$$R_p = \frac{\sin\varphi - \rho_0 c / Z_g}{\sin\varphi + \rho_0 c / Z_g} \quad \text{and} \quad F(w) = 1 + j(\pi w)^{\frac{1}{2}} e^{-w} erfc\left(-j\sqrt{w}\right).$$

In this paper the series proposed by Chessel[6] are used to approximate $F(w)$ which is a function of the numerical distance, w, given by:-

$$w = j\frac{kr_r}{2}\left(\sin\psi + \frac{1}{Z_{norm}}\right)^2$$

The single parameter model of Delany and Bazley[7] is used to calculate Z_{norm}, the normal impedance of the ground:-

$$Z_{norm} = \frac{R + jX}{\rho_0 c}$$

where:

$$\frac{R}{\rho_0 c} = 1 + 9.08\left(\frac{1000f}{\sigma}\right)^{-0.75} \quad \text{and} \quad \frac{X}{\rho_0 c} = 11.9\left(\frac{1000f}{\sigma}\right)^{-0.73}$$

and σ is the flow resistivity of the ground in MKS Rayls.

2.2.2 Calculation of $\langle\bar{a}^2\rangle$ and σ_d^2.

These are functions of two quantities I_1 and I_2:-

$$I_1 = \sqrt{\pi}\langle\mu^2\rangle k^2 r_d L$$

$$I_2 = \frac{I_1}{\Delta^2(\Omega + 1)\sqrt{8\Omega}}\left(\frac{\Delta\Omega}{2}\ln\left(\frac{1 + \Delta(2\Omega)^{\frac{1}{2}}}{1 - \Delta(2\Omega)^{\frac{1}{2}}}\right) + \arctan\left(\frac{\Delta\Omega}{1 - \Delta(2\Omega)^{\frac{1}{2}}}\right) + \arctan\left(\frac{\Delta\Omega}{1 + \Delta(2\Omega)^{\frac{1}{2}}}\right)\right)$$

where: .

$$\Omega = \left(1 + \frac{1}{\Delta^2}\right)^{\frac{1}{2}} - 1$$

$$\Delta = \frac{r_d}{kL^2}$$

L in the above equations is the outer scale of the turbulence. $\langle \mu^2 \rangle$ is the fluctuating index of refraction. For an isotropic, homogeneous atmosphere the fluctuating acoustical index of refraction n,where $n = 1 + \mu$ and $\mu \ll 1$,is assumed to have a Gaussian spatial correlation function (as in Ref 1). Typical values of these have been calculated and tabulated for different weather descriptions by Daigle[8] Most conditions will be adequately described by an outer scale of turbulence value of 1.1 but $\langle \mu^2 \rangle$ must be calculated:-

$$\langle \mu^2 \rangle = \left(\frac{\sigma_v \cos\theta}{c_0} \right)^2 + \frac{\sigma_v \sigma_T R_c \cos\theta}{c_0 T_0} + \left(\frac{\sigma_T}{2T_0} \right)^2$$

where

σ_T is the standard deviation of the temperature fluctuations

σ_v is the standard deviation of the wind fluctuations

R_c is the cross correlation between the wind and temperature fluctuations

c_0 is the sound speed at mean temperature T_0

θ is the angle between the wind direction and path of sound propagation.

$\langle \bar{a}^2 \rangle$ and $\sigma_d{}^2$ can then be found form the following:-

$$x = \langle [\ln(1+a)]^2 \rangle = \frac{1}{2}(I_1 - I_2)$$

$$\langle a^2 \rangle = \frac{x}{1 + \frac{11}{4}x} \qquad \text{for } x \le 1$$

$$\langle a^2 \rangle = 0.27x^{0.33} \qquad \text{for } x > 1$$

$$\sigma_d{}^2 = \frac{1}{2}(I_1 + I_2)$$

2.2.3 Calculation of ρ_a and ρ_δ.

$$\rho_a = \rho_\delta = \frac{\Phi\left(\frac{l}{L}\right)}{\frac{l}{L}}$$

where $\Phi\left(\frac{l}{L}\right) = erf\left(\frac{l}{L}\right)$ and $l = \frac{\ell}{2}$ (ℓ is the maximum path separation as shown in Fig. 1).

2.3 The Mutual Coherence Function (MCF).

The use of this further simplifies the calculations needed to be carried out in order to calculate the long-time average of the mean square pressure. The expression given by L'Espérance et al for the MCF is:-

$$\Gamma(R,\rho) = \exp\left[\frac{-\sqrt{\pi}}{2}\langle\mu^2\rangle k^2 RL\left(1 - \frac{\Phi\left(\frac{\rho}{L}\right)}{\frac{\rho}{L}}\right)\right]$$

where:

ρ is equal to half the maximum path separation (half the ℓ in Fig. 1).

R is the horizontal source-receiver separation (d in Fig 1).

The overall equation for the long time average of mean square pressure $\langle\bar{p}^2\rangle$ at the receiver becomes:-

$$\langle p^2\rangle = \frac{1}{R_d^2} + \frac{|Q|^2}{R_r^2} + \frac{2|Q|}{R_d R_r}\cos[k(R_r - R_d) + Arg(Q)]\Gamma$$

This very similar to expressions derived by Daigle and later Clifford and Lataitis. It is directly comparable to Daigle's expression as the MCF contains a term equivalent to l_1 and ρ_δ. It can be seen from the above that it is much simpler to calculate than Daigle's expression as it avoids the lengthy calculations for $\langle\bar{a}^2\rangle$ and σ_d^2, only requiring the relatively simple calculation for the phase covariance. It does still require values for $\langle\mu^2\rangle$ and L however.

3. RESULTS AND DISCUSSION

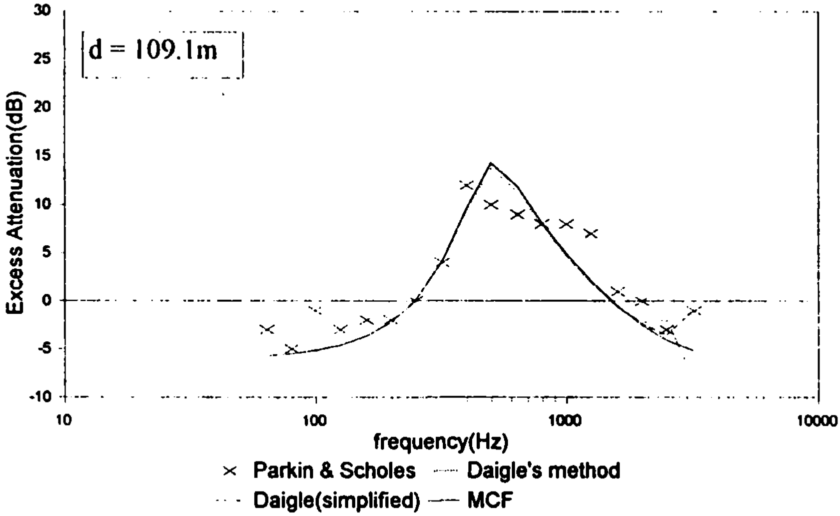
3.1 Results

Non-refractive conditions, classified as having neutral temperature conditions and zero vector wind, are used for comparisons. Two test runs from Parkin and Scholes' data which satisfied these conditions were chosen and these were runs 13 and 17. Run 13 provided the comparison data in Figs. 2 and 3 while run 17 was used in Fig. 4.

Parkin and Scholes' data does not provide enough information to calculate $\langle\mu^2\rangle$ using Daigle's full equation. To make his comparisons he carried out extensive fitting to find a suitable value of $\langle\mu^2\rangle$ and found this to be 2×10^{-6}. His comparison curves from Ref. 1 using this value are reproduced in Figs 2-4 and labelled 'Daigle's method'. They show excess attenuation (attenuation produced by effects other than air absorption and spherical spreading) versus frequency. Parkin and Scholes' data does provide enough information to calculate $\langle\mu^2\rangle$ using the simplified method, namely the wind speed at 10m. A wind speed of $5 fts^{-1}$ ($1.5 ms^{-1}$) was recorded for run 13 and $23 fts^{-1}$ ($7 ms^{-1}$) for run 17. The curves obtained are shown labelled as 'Daigle's (simplified)' in Figs. 2-4. The curves produced using the simplified form of $\langle\mu^2\rangle$ and MCF are labelled 'MCF'.

A ground flow resistivity of 300 CGS Rayls and source and receiver heights of 1.8m and 1.5m respectively were used in all cases.

Figure 2


d = 109.1m
Excess Attenuation(dB)
30
25
20
15
10
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100
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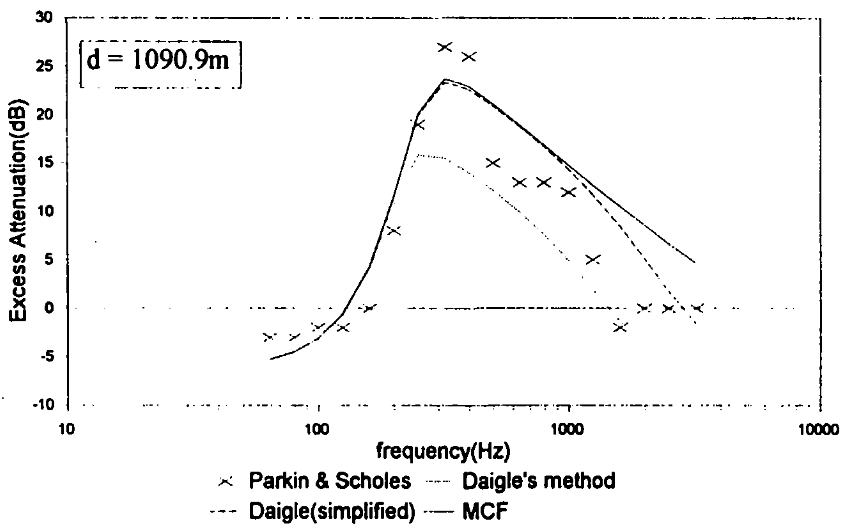
frequency(Hz)
Parkin & Scholes
Daigle's method
Daigle(simplified)
MCF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Excess Attenuation(dB)
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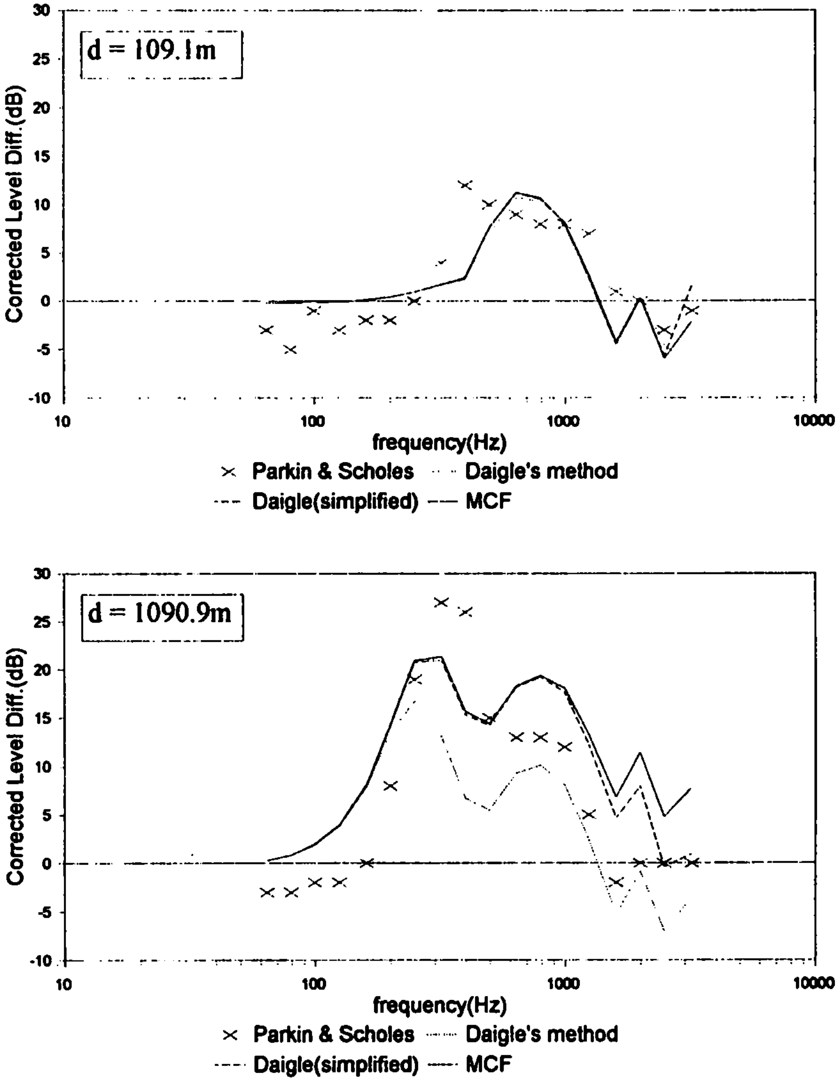
frequency(Hz)
Parkin & Scholes
Daigle's method
Daigle(simplified)
MCF

Figure 3


d = 109.1m
Corrected Level Diff.(dB)
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1000
10000
frequency(Hz)
Parkin & Scholes
Daigle's method
Daigle(simplified)
MCF
d = 1090.9m
Corrected Level Diff.(dB)
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15
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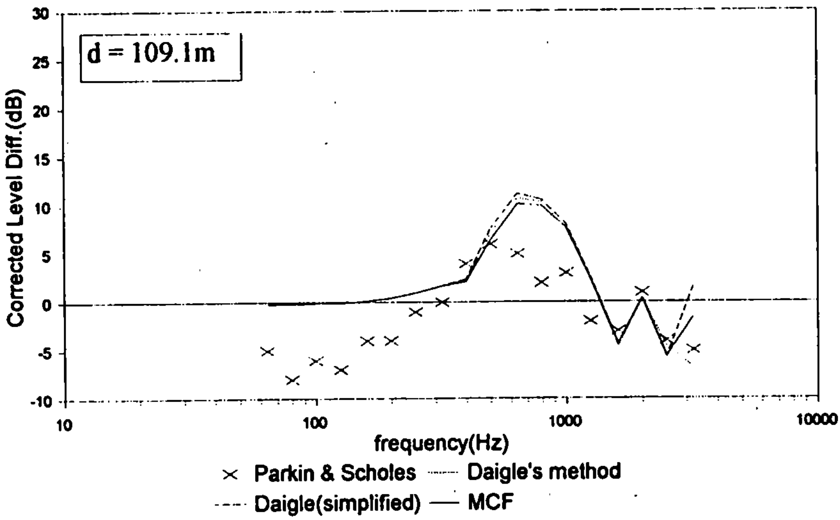
10000
frequency(Hz)
Parkin & Scholes
Daigle's method
Daigle(simplified)
MCF

Figure 4


d = 109.1m
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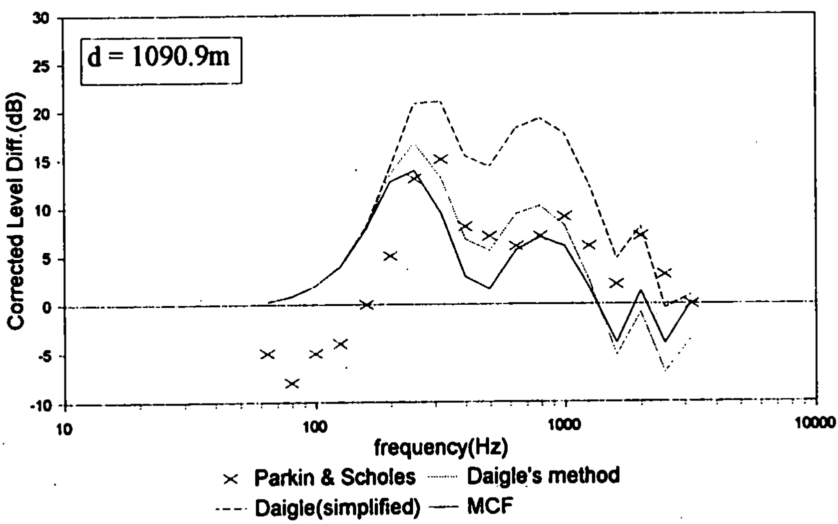
Daigle(simplified)
MCF


d = 1090.9m
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frequency(Hz)
Parkin & Scholes
Daigle's method
Daigle(simplified)
MCF

3.2 Discussion

3.2.1 Results for Run 13 (wind speed = $5fts^{-1}$ ($1.5ms^{-1}$))

3.2.1.1 Fig. 2

Fig. 2 shows excess attenuation versus frequency for 2 different distances as calculated from each of the 3 methods of including turbulence. Parkin and Scholes' measurements for run 13 are also shown. The value of $\langle\mu^2\rangle$ calculated using the simplified formula was 8.6×10^{-7}, a value lower than that chosen by Daigle. The results obtained from all three methods compared well over the whole frequency range for shorter distances. The curves lie very close together at 109.1m but at distances greater than this the curves diverge increasingly with increasing distance. The curves also start to differ noticeably at lower frequencies as the distance becomes larger. The curves using the simplified $\langle\mu^2\rangle$ consistently over estimate the attenuation compared to Daigle's method at longer distances and higher frequencies. All three methods compare fairly well with Parkin and Scholes' data, Daigle's method slightly underestimating the attenuation at higher frequencies where the other methods tend to over estimate.

3.2.1.2 Fig 3

Fig. 3 shows the curves of Fig. 2 normalised to the sound level at 19.4m i.e. the corrected level difference referred to 19.4m versus frequency. 19.4m is the position of the first microphone in the Parkin and Scholes' experiment of Ref. 5 and the level at this point is the level they state as taking as their reference level. In order to be consistent with the measurements of Parkin and Scholes, comparisons with their data should be made using the corrected level difference and not the excess attenuation as used in Ref. 1 and Fig. 2. The curves of Fig. 3 show the same trends as the ones of Fig. 2. but appear to fit the shape of the measurements much better, especially at high frequencies. The corrected level difference will therefore be used as a basis for comparison in subsequent graphs in this paper.

3.2.2 Results for Run 17 (wind speed = $23fts^{-1}$ ($7ms^{-1}$))

Fig. 4. shows the corrected level difference versus frequency for the same 2 distances calculated using the 3 different methods. The measurements of Parkin and Scholes for run 17 are also shown. They show similar trends to those of Fig. 3 in that they lie close together at short distances and diverge increasingly with increasing distance. Divergence starts at a lower frequency at the longer distance. As before, the curve of Daigle's method with simplified $\langle\mu^2\rangle$ consistently over estimates attenuation at higher frequencies and longer distances when compared to the unsimplified version of the method. This time, however, the curve using the MCF and simplified $\langle\mu^2\rangle$ under estimates attenuation compared to Daigle's curves. The empirical value of $\langle\mu^2\rangle$ was 1.8×10^{-5}, a value closer to that chosen by Daigle than in run 13. Since the simplified $\langle\mu^2\rangle$ is proportional to wind speed a possible trend of the MCF method under estimating for high wind speeds and over estimating for low wind speeds may be emerging since the wind speed in this case is much higher than that in run 13. This would need more research, using several different wind speeds to verify this trend. Daigle's and the MCF methods compared best with

Parkin and Scholes' data, the simplified Daigle tending to rather overestimate the attenuation at high frequencies and longer distances.

4. CONCLUSION

The three methods of including turbulent effects into the prediction of outdoor sound levels agreed well with the data of Parkin and Scholes, especially when normalised to the pressure at 19.4m, for shorter ranges. In view of the results obtained it would seem that the loss in accuracy over long ranges is warranted by the simplicity of the empirical formula for the fluctuating index of refraction. The use of the MCF with the empirical formula achieved better comparisons with Parkin and Scholes' data than the simplified method of Daigle at a higher wind speed. The MCF further simplifies the calculations and would be the most practical choice for inclusion into outdoor sound prediction schemes. Its performance over long distances and varying wind speeds needs further examination, however. The possibility of extending this work to account for the effects of turbulence on barrier attenuation will be explored at a later date.

5. REFERENCES

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