A CONTRIBUTION TO THE STUDY OF SOUND PROPAGATION OUTDOORS

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ABSTRACT

Sound propagation in turbulent media has experienced an important theoretical development in the last decades. Several new acoustic statistical moments have been calculated, and these new moments include the vectorial character of the speed of wind. In this paper we compare the new theoretical proposals with experimental data in order to verify the real improvement that these new theoretical calculations produce.

INTRODUCCIÓN

Sound propagation outdoors is affected by many different factors, and the presence of a turbulent atmosphere is one of them. This turbulent phenomena can be described in sound propagation equations by means of several second order moments which have recently been re-calculated by Ostashev [5] in order to take into account the vectorial part of the speed of wind.

In this paper we compare our experimental data to the theoretical results given by Daigle's model [4] together with the modification introduced by the new second order moments calculated by Ostashev [5]. The experimental data have been obtained in several different sets of measurements at the CIBA (Low Atmosphere Investigation Center). We have obtained the meteorological and the acoustical data simultaneously over a flat surface free of potential diffracting objects. The interference region between the direct sound and the reflected sound (where Daigle's model is applicable) is determined according to geometrical acoustics (ray tracing) [7].

THEORETICAL MODEL

Daigle's model for finite impedance surfaces [4] tries to explain the effect of turbulence in a non refractive atmosphere. The purpose of the model is to calculate the mean square pressure which is then used to determine the sound pressure level at a given point. The model assumes that the sound pressure at any point is composed by two spheric waves corresponding to the direct sound and the reflected sound respectively. The sound pressure at the receiver's position *R* when sound is emitted from a point *S,* is given by equation:

$$p = \frac{A_d}{r_d}\exp\left[i\left(k_d r_d - \omega t\right)\right] + Q\frac{A_r}{r_r}\exp\left[i\left(k_r r_r - \omega t\right)\right]$$

where the subscript *d* belongs to the direct sound and the subscript *r* to the reflected (figure 1).

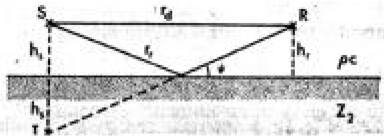

Fig. 1: *Source S and receiver R positions; distances and angles found in the model [4].*

Normalised amplitudes and wave numbers can be written as the addition of two terms:

$$\mathbf{A_d = 1 + a_d} \qquad \mathbf{A_r = 1 + a_r} \qquad \mathbf{k_d r_d = k r_d} + \boldsymbol{\delta}_\mathbf{d} \qquad \mathbf{k_r r_r = k r_r} + \boldsymbol{\delta}_\mathbf{r} \ .$$

The first terms quantify the coherent part (lack of turbulent atmosphere) whereas the second terms introduce the turbulent fluctuations, which are assumed to have a normal distribution and zero average. The average value of the mean square pressure can be written as:

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

Since propagation angles are very small it can be accepted that $r_d / r_r \approx 1$, and thus the amplitude and phase variance of the direct and reflected sound can be considered the same. From now on we shall refer to them as $\left\langle a^2 \right\rangle$ y σ_d^2 respectively. It is also necessary to assume that the fluctuations of direct and reflected phase have a bivariable normal distribution. ρ_a y ρ_d are the amplitude and phase covariance between the direct and reflected rays. The model doesn't consider the correlation between phase and amplitude.

Equation (1) includes (apart from the geometrical distances) a parameter in order to describe the effect of the ground, $Q = |Q| exp\, i\gamma$ and four second order moments which describe the turbulence, $\left\langle a^2 \right\rangle$, σ_d^2, ρ_a y ρ_d. In order to calculate *Q* we have followed Weyl-Van der Pool's model (described, for example, by Rucnick [1]) so that $Q = R_p + \left(1 - R_p\right)F(w)$, where

$$F(w) = 1 + i\sqrt{\pi w}\exp(-w)\,\mathrm{erfc}\left(-i\sqrt{w}\right) \qquad \text{with} \qquad w = \frac{2ik_1 r_r}{\left(1 - R_p\right)^2}\left(\frac{Z_1}{Z_2}\right)^2\left(1 - \left(\frac{k_1}{k_2}\right)^2\cos^2\psi\right) .$$

This function *F(w)* represents the interaction between the spheric wave front and a finite impedance surface; *w* is the numeric distance and R_p is the reflection coefficient for plane waves. Subscript 1 refers to the air and subscript 2 to the ground. ψ is the angle between the ground and the reflected ray. In order to calculate ground impedance and propagation constants we have used Delany and Bazley's model [2]. The real and imaginary parts of the impedance are $\mathrm{R} / \rho c = 1 + 9.08\left(\mathrm{f} / \sigma\right)^{-0.75}$ $\quad \mathrm{X} / \rho c = 11.9\left(\mathrm{f} / \sigma\right)^{-0.73}$ respectively, and the propagation constant is: $\alpha / \mathrm{k} = 1 + 10.8\left(\mathrm{f} / \sigma\right)^{-0.70}$ $\quad \beta / \mathrm{k} = 10.3\left(\mathrm{f} / \sigma\right)^{-0.59}$ in cgs unit system. f, σ, k represent the frequency, flow resistivity and ω / c.

The log-amplitude variance and the phase fluctuation in Daigle's model, aswell as the covariance between the direct and reflected ray, which we represent by:

$$\left\langle \left[\ln\left(1 + \mathrm{a}\right)\right]^2 \right\rangle \qquad \sigma_\mathrm{d}^2 \qquad \rho_\mathrm{a} \qquad \rho_d \tag{2}$$

are calculated according to equations number (12), (13) y (17) in reference [4].

If all four momentum are calculated in this way, the vectorial contribution of the speed of wind is not taken into account. In fact it is only the module of the speed of wind that is considered, so its contribution in the equation is similar to the contribution of the other scalar magnitude which is involved: the temperature. Recently these moments have been calculated by Ostashev, who found the following expressions:

$$\sigma_{\mathrm{d}}^2 = \mathrm{B}_c(0); \quad \left\langle [\ln(1+\mathrm{a})]^2 \right\rangle = \mathrm{B}_d(0); \quad \rho_{\mathrm{a}} = \frac{\mathrm{B}_c(\mathrm{r})}{\mathrm{B}_c(0)}; \quad \rho_d = \frac{\mathrm{B}_d(\mathrm{r})}{\mathrm{B}_d(0)} \qquad (3)$$

where B(r) corresponds to the correlation functions between the log-amplitude and the phase fluctuations given by equations (7.102) y (7.103) in reference [5]. These new moments do take into account the vectorial character of the speed of wind.

This new set of moments is then substituted in the mean square pressure equation (1) in order to compare the new sound pressure level which are found. The correlation length is assumed to be L=1.1m in both cases, according to the estimations performed by Daigle [3].

EXPERIMENTAL SET UP

The experimental measurements took place at the CIBA (Low Atmosphere Investigation Center) which is located in the countryside, about 40 km north west of Valladolid (Spain). The meteorological data where taken from two meteorological towers 12 and 100 m tall respectively. We used as meteorological data the average of the instantaneous values over a five minute period. From these average values we can obtain the phase fluctuations and amplitude variances as well as the covariances of both models by substituting in equations (2) and (3). We also obtained the sound and wind speed profiles for two different refractive conditions in which we measured.

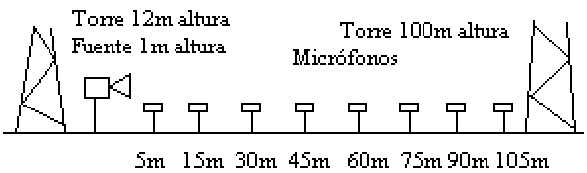

Fig. 2: *Meteorological towers, microphones and source situation.*

The equipment used was composed by a set of seven B&K 4129 microphones, connected to the B&K 2811 multiplexor. The data were sent to the B&K 2143 analyser and saved in third octave bands. As reference microphone we used B&K 2236 Investigator, and the sound source was B&K 4224. We made two different sets of measurements where the source-receiver distances varied from 5 to 105 m. Figure 2 shows the microphones and source distribution for the first set of measurements

DATA ANALYSIS: RESULTS

The meteorological data give information about two important aspects related to sound propagation outdoors: refractive conditions and turbulent parameters. Since Daigle's model applies only for non refracting atmosphere, and in fact it is almost impossible to encounter a non refractive atmosphere, it is very convenient to force measurements under two completely different refractive conditions, in order to validate the model. This measurement technique has already been used, for example in reference [6]. Evidently, the model is not adequate for sound shadow regions. For the first refractive condition we found the following sound and wind profiles: c(z)=347.165-0.307ln(z)m/s y v(z)=2.397+0.359ln(z)m/s; in this case rays are curved upwards creating a sound shadow region starting about 30 m away from the source. From this distance we will not be able to compare the experimental data with those given by the model. For the second refractive condition, sound and wind profiles were: c(z)=347.12-0.114ln(z)m/s y v(z)=2.2732+1.668ln(z)m/s; now rays are curved downwards creating a wave guide (see figure 3). The theory used for the ray tracing is described by Ostashev in reference [5].

The turbulent parameters used in the calculation are the correlation lenght L=1.1m and the standard deviation of temperature and speed of wind. For the first case these parameters turned out to be 0.12K and 1.35m/s respectively and for the second case 0.39K and 1.04m/s. Flow resistivity was σ=95 kNsm^{-4}.

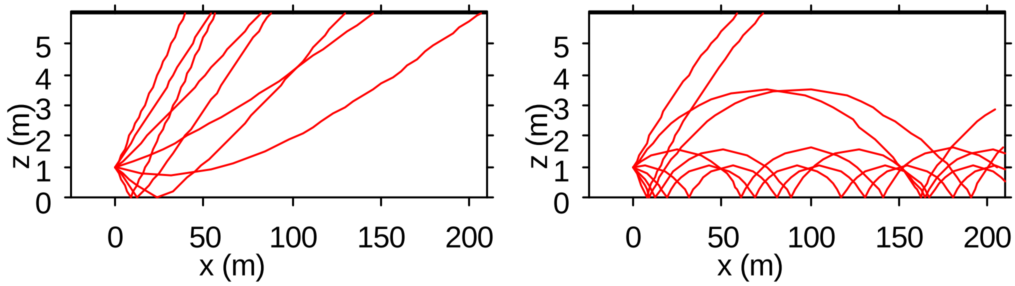

Fig. 3: *Ray tracing for the two different refractive conditions mentioned. In the first one there is a sound shadow region. In the second case the ground becomes a wave guide. The original angle formed by the rays and the horizontal plane varies from 7º y –7º with steps of 2º between them.*

The acoustical data have been measured simultaneously with the meteorological data and then compared with the values given by the model through equation (1). The comparison is made according to the following expression:

$$SPL(P) - SPL(ref) + 20\log(\frac{r_P}{r_{ref}})$$

where the first term corresponds to the sound pressure level at the measurement point *P* and the second to the SPL at a special reference point. The distances from the source to the measurement point and to the reference point are $\mathbf{r_P}$ and $\mathbf{r_{ref}}$ respectively. The last term is included in order to cancel spheric divergence with distance. We will use this expression both for the theoretical and the experimental data.

All results are shown in figure 4. We compare three results: Daigle's model (dotted line), the improvement introduce by the new moments calculated by Ostashev (continuous line) and the experimental data (circles).

The source receiver distances shown are never above 45 m since, as it was mentioned before, the shadow region formed in one of the refractive conditions excluded all data within that region. Due to the fact that source-receiver distances are not too big, the effect of the turbulent parameters in not very important over all the frequency range. Only above 2000Hz and where there are interference maxima or mimima due to the relative source and receiver positions, we can observe differences of about 2 to 3 dB.

The final result is a coherence loss between the direct and reflected ray, which in the end translates into a smoother interference curve. The absolute value of the maxima and minima become smaller. The main reason for this is the standard deviation of the speed of wind; the effect of temperature fluctuations is less important from a numerical point of view.

On the other hand, as it can also be observed in figure 4, in all cases the experimental data fit better the modified model, that is, improved with Ostashev's second order moments. We can thus confirm that the incorporation of these new moments improves the model considerably.

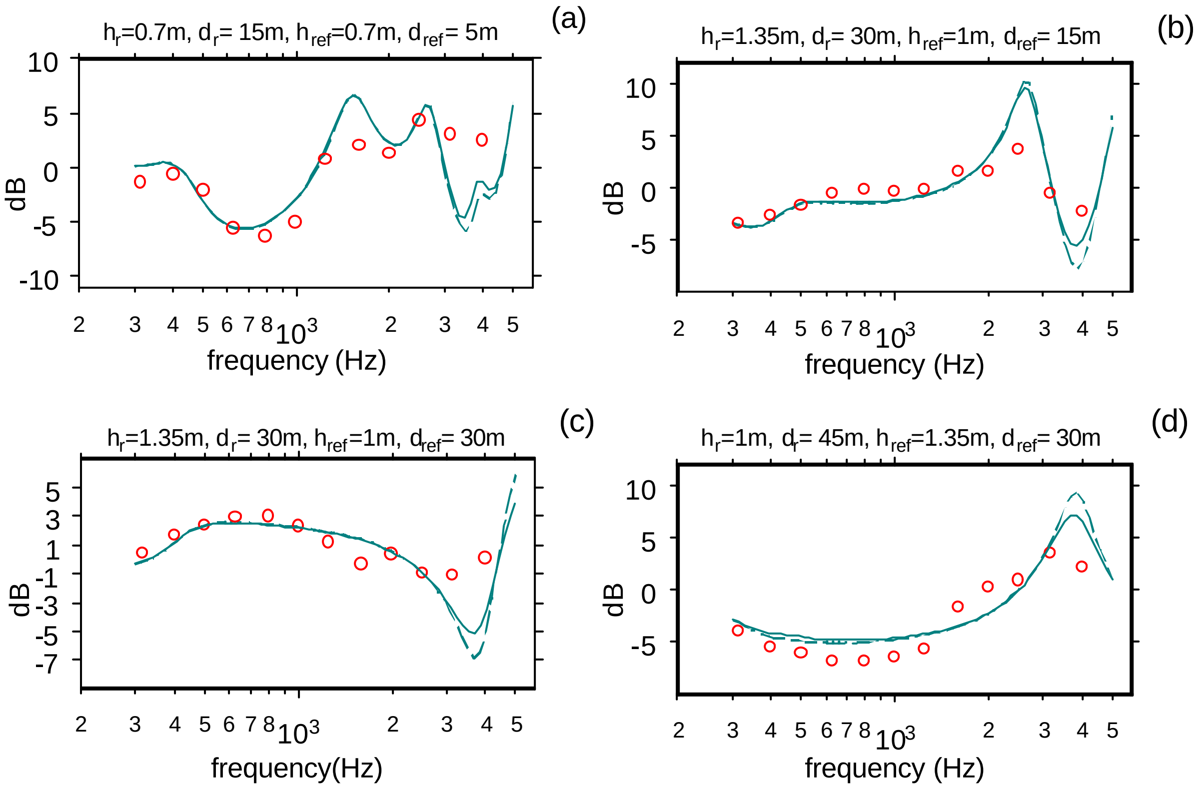

Fig. 4: *Comparison between Daigle's model (dotted line), the same model improved with Ostashev's parameters (continuous line) and our experimental data. Curve (a) corresponds to an upward refracting atmosphere.Curves (b), (c) and (d) to a downward atmosphere. Standard deviation of temperature and wind were 0.12K and1.35m/s in the first case and 0.39K y 1.04m/s in the second case.*

CONCLUSIONS

We have compared the experimental data with Daigle's model and with a modified version of Daigles' model which includes the second order moments calculated by Ostashev. This was done under two different refractive conditions: upward refracting atmosphere and downward refracting atmosphere. The interference region were both models are valid has been calculated using ray tracing theory.

The comparison between Daigle's model and its modification with Ostashev's momentos shows that, for source-receiver distances below 50 m, the difference between both models can reach 3 dB for frequencies above 2000 Hz and when there is a maximum or minimum interference peak. These differences are due to the smaller coherence introduced in the second model, thus resulting into theoretical curves where the direct and reflected ray interference peaks turn out to be much smoother. In this case, due to the relatively short source-receiver distances, the difference between both models is not very important form a quantitative point of view, but in any case the difference is clearly visible..

At high frequencies the modified model fits much better the experimental data, for both refracting atmospheres. We can conclude that at least for high frequencies, the new moments introduced by Ostashev into Daigle's model certainly improve the agreement between the theoretical values and the experimental values.

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