Influence of the Atmospheric Channel on the Sound Propagation above the Ground Surface

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In this report are presented the results of investigations into the influence of the atmospheric channel on the sound propagation above the ground surface. The algorithms for calculating the sound pressure level and the software package Outdoor Acoustics intended for real-time estimate of the field of the mean sound pressure level from a remote sound source in the ground atmospheric layer have been described. The software package allows for the characteristics of the sound source, vertical profiles of the main meteorological parameters, characteristics of the underlying surface, and the parameters of the atmospheric turbulence. Results of numerical estimation and field tests of this software package for distances from an acoustic source up to 6 km are also presented in the report.

1 Introduction

It is well known that the atmospheric sound pressure level recorded from a stationary source essentially depends on meteorological conditions. This is caused by the high sensitivity of total energetic sound losses to such meteorological parameters as wind, temperature, relative air humidity, and atmospheric pressure. Mean values of air humidity, temperature, and pressure determine not only the coefficient of molecular absorption of the acoustic radiation at a fixed frequency, but also its frequency dependence. Fluctuations of the acoustic refractive index, caused by turbulent pulsations of the meteorological parameters, affect an interference pattern of directly transmitted and reflected acoustic rays and cause the excess turbulent attenuation. In case of near-ground sound propagation at distances more than 1 km, sound attenuation is primarily affected by refraction on gradients of temperature and wind, resulting in the waveguide (Figure 1b) or antiwaveguide (Figure 1c) regime of sound propagation. In the first case, rays bend downward and hence undergo multiple reflections from the ground. Relatively small values of sound attenuation are typical of this regime of sound propagation. In the second case, rays bend upward, and a shadow zone is formed near the ground at certain distances from the source. Only very weak sound, caused by turbulent scattering in the upper atmospheric layers, penetrates into this zone.

In the present report, we describe algorithms for calculating the mean sound pressure level in the surface layer of the atmosphere considering the effect of meteorological conditions on sound propagation. The software package Outdoor Acoustics, developed on the basis of these algorithms, is also outlined in the report.

Figure 1: Ray patterns for sound propagation in the atmosphere under various meteorological conditions: a) neutral regime; b) waveguide regime (only the top–bottom rays are shown); and, c) antiwaveguide regime. Here $S$ is the sound source, $R$ is the receiver (observation point), $\longrightarrow$, direct rays, $\circ\circ\circ\circ\circ$, the scattered rays.
important meteorological factors on sound attenuation.
Some results were presented in our previous papers [1 - 6].

2 Model for calculating the sound pressure level

A regime of weak refraction (called neutral below) is the most simple case of line-of-sight propagation of an acoustic wave to an observation point. In this regime, only two rays come to the observation point: a direct ray and a ray reflected from the ground; in this case, the direct ray does not have any bending point (see Figure 1a). In the neutral regime a ray pattern of sound propagation is characterized by insignificant bending of ray trajectories. It can be observed only for small gradients of wind velocity and temperature or short distances d to the observation point. For the neutral regime, the sound pressure level can be calculated neglecting the effect of refraction. Algorithms for calculation of individual components of sound attenuation are described in the literature in detail (see, for example, [7]). We note that when sound propagates at distances longer than 1 km, the neutral regime is practically not observed.

When analyzing the waveguide sound propagation, the rays which enter the given point for existing wind velocity profiles v(z) and sound velocity in the air c(z) are calculated. This analysis is carried out on the basis of the equation describing the horizontal coordinates r = r(x, y) of each point of a ray which is characterized by the angles of ray departure α and ϕ in two orthogonal planes. In accordance with the ray classification, for the case of waveguide propagation there are four types of rays depending on the portion of the ray trajectory (descending or ascending) at which a source and a receiver are located. In our software package the rays of the type top–bottom (see Figure 1b) provide the basis for calculation of sound pressure level. The characteristics of these rays are calculated by a direct solution of the exact ray path equation with the known number of bending points, while the characteristics of the other rays are calculated from the approximate relations using the results of the base ray calculations. Numerical comparison with the exact ray trajectory shows that the errors of calculations of α_i and ϕ_i are much smaller than the angular width of the directional pattern of a real sound source, and hence have insignificant effect on the results of calculations of sound pressure levels. After the determination of α_i and ϕ_i for all rays whose number \( N_{\text{min}} < i < N_{\text{max}} \) (\( N_{\text{min}} \geq 1, N_{\text{max}} \geq N_{\text{min}} \)), it becomes possible to calculate sound attenuation for all rays.

The algorithm for calculating the sound pressure level in a shadow zone is based on the theory of single scattering of sound in the atmosphere and geometric acoustics equations for moving media.

3 Instrumental-program complex

An instrumental-program complex for investigations of the near-ground atmospheric sound propagation has been developed. It allows real-time calculations to be done and the average sound pressure field in the audible frequency range to be predicted in the lower layer of the atmosphere with consideration of the input parameters including the characteristics of sound sources and the main meteorological parameters of the atmosphere and the Earth’s underlying surface. The instrumental-program complex is capable of:

• estimating the audibility of sound sources in real time,
• determining the amplitude and frequency characteristics of sound sources with allowance for the atmospheric channel of sound propagation;
• mapping the sound pressure level distribution for limited number of sound sources;
• and other.

The instrumental-program complex for predicting the sound pressure level comprises an PC, a meteorological system, and a software in the form of the program complex Outdoor Acoustics. An automated meteorological complex based on ultrasonic measurements of the atmospheric parameters is used as the meteorological system.

Its main computing modules program complex Outdoor Acoustics are subprograms for calculating the neutral, waveguide, and antiwaveguide regimes of sound propagation. The ray trajectories of sound propagation are displayed on the screen for each propagation regime together with some numerical parameters, numerical values of sound pressure levels, and the amplitude-frequency signal characteristics (AFC) at the receiving point.

The characteristics of the sound source, energy losses due to spherical wave divergence, classical and molecular absorption of sound in air, and attenuation by the atmospheric turbulence and the underlying surface were taken into account when the sound pressure level at the receiving point was calculated for the corresponding regime of sound wave propagation. After completion of these calculations, the sound pressure distribution over the area adjacent to the
sound source was calculated and the audibility zones of the sound source were mapped together with zones of recommended location of the sound source relative to the receiving point.

The working version of the program complex Outdoor Acoustics has been realized in the visual programming medium Delphi for the operating system MS Windows.

In the forecast problems, the initial data are the four groups of input parameters: meteorological, underlying surface, source, and propagation path. Among the meteorological parameters, the velocity \(v\) and direction \(\phi_v\) of horizontal wind component, the temperature \(T\) and the relative air humidity \(u\), the atmospheric pressure \(p_a\), the structure constants for turbulent fluctuations of temperature \(C_T^2\) and wind velocity \(C_V^2\) are considered in this package. Diagnostics of sound propagation regime is based here on an analysis of the altitude distribution of the sign of the phase velocity gradient of sound wave.

When calculating the above–considered regimes of sound propagation, the ray patterns are displayed and the amplitude–frequency characteristic of sound at the given point is tabulated for one–third octave intervals on the screen of a monitor. Some parameters characterizing the given regime are also displayed. Moreover, the software package comprises an additional program for calculation and graphics of diagrams of distribution of the sound pressure levels in the neighbourhood of the source.

4 Experimental data

The software package has passed the field tests. In the experiments the sound source radiating a high power of 2 kW and including the array of 24 horn loudspeakers and power amplifier with a standard mixer panel was used. The mean sound pressure level recorded at a distance of 1 m from the source was about 138–147 dB in the frequency range from 315 Hz to 4 kHz. Three stations of acquisition of the data on the sound pressure level measured by operators with the use of a sound level meter and octave filters were organized along the two near–ground paths of sound propagation of length up to 6 km.

An acoustic signal was radiated as a train of 20 pulses whose duration was about 0.5 s and the time intervals between pulse trains were 2 s. This pulse train was repeatedly radiated with one–third octave intervals from 315 Hz up to 4 kHz. Then the first cycle of measurements whose duration was about 25 minutes terminated. In all, 33 cycles of measurements corresponding to the case of waveguide sound propagation and 19 cycles of measurements, when operators were within the acoustic shadow zone, were carried out. In every cycle the values of sound pressure level \(L_r(f)\) averaged over 20 measurements were obtained at all frequencies \(f\) and various distances \(d\) to the point of measurement. The variances and confidence intervals of these values (with a confidence level of 0.95) were also obtained. The error in forecasting \(S(f)\) at the frequency \(f\) was estimated as the difference between the calculated values of \(L_r(f)\) and the measured ones.

The examples of comparison of the calculated values of sound pressure level and experimental ones for one measurement cycle in the case of waveguide and antiwaveguide regimes, respectively, are shown. Due to strong sound attenuation at frequencies above 2 kHz, the signal at these frequencies was typically lower than the level of the ambient noise. Therefore, the experimental data for the given path lengths \(d\) were largely obtained only for the frequency range 315–2000 Hz.

On the whole, the frequency dependences of the calculated and measured values of sound pressure level in this frequency range agree fairly well.

It was found in the experiments that the main source of errors is the inaccuracy in assignment of meteorological information. The revealed errors of assignment of this information can be divided into three groups. First, the meteorological data came from the radar station at relatively large nearly two–hour intervals. The time of acquiring the information about the sound pressure level in one measurement cycle indicated above was larger than the interval usually considered as the period of meteorological field stationarity. Therefore, under unstable meteorological conditions when the mean profiles of the meteorological parameters undergo large and relatively fast variations, the quality of the forecast in our experiments must decrease.

Second, there is a systematic error associated with the assumption of horizontal homogeneity of meteorological fields in the atmosphere. At last, instrumental errors are always present.

In the experiments the stable meteorological conditions predominated. Usually the wind was about 5–7 m/s at an altitude of 2 m. The variance of the wind direction was small. The negative temperature gradient of the order of 8–10 deg/km was typically observed.

The results of experimental estimation of the efficiency of forecast of the sound pressure level in the frequency range 315–2000 Hz for different distances and propagation regimes are summarized in Table I. Here,
$S$ is the error in forecast averaged over all cycles; $P_i$ is the probability that the predicted pressure level is in the confidence interval; $P_6$ is the probability that the error in forecasting is no more than 6 dB. On account of the difficulties of monitoring of meteorological conditions and their variability, the obtained 2–3 dB mean errors of forecast are sufficiently good results.

The dependence of the total attenuation $L$ on the wind component parallel to the direction of sound propagation $v_p$ is shown in Figure 2. Here, the waveguide regime of propagation is realized for $v_p > 0$ and the antiwaveguide regime – for $v_p < 0$. Refraction by wind velocity gradients always results in the increase of sound attenuation. In the waveguide regime of propagation, the increase of $v_p$ is accompanied by a relatively small increase in $|L|$, as a rule, by no more than 6–10 dB, connected with the change of the beam focusing pattern compared with the conventional spherical beam divergence. At the same time, in the antiwaveguide regime of propagation, the excess noise attenuation due to wind is much greater and may even exceed 100 dB. In this case, the sharp increase of $|L|$ by 15–20 dB is first observed as $|v_p|$ increases and the observation point enters the acoustic shadow zone. With the further increase of $|v_p|$, the sound attenuation continues to increase noticeably, because the atmospheric layer, from which a scattered signal comes to the observation point, is displaced upward. The change of the distance from the source $d$ affects insignificantly the form of the dependence $L(v_p)$, but shifts noticeably the absolute values of $L$.

### Table 1: Experimental results

<table>
<thead>
<tr>
<th>Waveguide regime, 33 cycles × 20 pulse trains</th>
<th>Antiwaveguide regime, 19 cycles × 20 pulse trains</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$, m</td>
<td>$S$, dB</td>
</tr>
<tr>
<td>3000</td>
<td>+3.2</td>
</tr>
<tr>
<td>4500</td>
<td>+2.3</td>
</tr>
<tr>
<td>6000</td>
<td>+1.5</td>
</tr>
</tbody>
</table>

### 5 Numerical estimation

An attempt was made to analyze numerically, with the use of this software package, the effect of the meteorological parameters on audibility of sound in the atmosphere. The most interesting results of calculations are shown in Figures 2–4. The values of the main atmospheric parameters at a height of 2 m above the ground are indicated in figure captions. The vertical wind velocity profile was assumed to be logarithmic in character, the air humidity and pressure were constant, the vertical profile of $C^2_n$ was determined by the corresponding profiles of $C^2_T$ and $C^2_V$, and the underlying surface was covered with grass.

Figure 2: Dependence of sound attenuation in the atmosphere, in dB, on the wind component $v_p$ parallel to the direction of sound propagation for $P_a = 750$ mm Hg, $u = 75\%$, $T = 20^\circ C$, $\gamma = 0^\circ /km$, $C^2_n = 10^{-6}$ m$^{-2/3}$, $f = 1000$ Hz, and distances to the source $d = 1$ (1), 3 (2), 6 (3), and 10 km (4) $v_p$, m/s

Figure 3: Sound attenuation in the atmosphere, in dB, as a function of the wind direction $\varphi_v$ for $u = 75\%$, $T = 20^\circ C$, $\gamma = 0^\circ /km$, $C^2_n = 10^{-6}$ m$^{-2/3}$, $f = 1000$ Hz, and $v = |v| = 0$ (1), 5 (2), 10 (3), and 15 m/s (4) $\varphi_v$, deg
Figure 3 shows sound audibility as a function of the wind direction $\phi_v$, counted off from the source-observer direction. Curve 1 was calculated without refraction ($v = 0$). It can be easily seen that at $v = \text{const}$ the change of $\phi_v$ is equivalent to the change of the wind component $v_p$ parallel to the direction of sound propagation. Therefore, curves 2, 3, and 4 exhibit practically the same behavior as in Figure 2. From Figure 3 it follows that the wind component perpendicular to the direction of sound propagation affects insignificantly its audibility.

![Figure 4: Sound attenuation in the atmosphere, in dB, as a function of the wind component $v_p$ parallel to the direction of sound propagation for $u = 75\%$, $T = 20^\circ\text{C}$, $\gamma = 0^\circ/\text{km}$, $f = 1000$ Hz, $d = 6$ km, and $C_n^2 = 10^{-8}$ (1), $10^{-7}$ (2), $10^{-6}$ (3), and $10^{-5}$ m$^{-2/3}$ (4)](image)

Figure 4 shows the dependence of $L$ on $v_p$ for indicated values of the structure parameter of refractive index fluctuations $C_n^2$ that characterize the intensity of the atmospheric turbulence. As expected, $C_n^2$ affects most strongly the sound pressure level in the antiwaveguide regime of propagation. In this case, the recorded pressure level is almost proportional to $C_n^2$.

Because $C_n^2$ varies over a wide range, sound audibility also undergoes large variations. In our case experimental values changed from 2 to 5 km.

In the waveguide regime of propagation, the observed sound pressure level is a sum of pressure levels of individual rays propagating along paths of different lengths. The total pressure level differs qualitatively as a function of amplitude and phase fluctuations of rays.

For small values of $C_n^2$, the amplitude and phase fluctuations of rays are also small and hence can be partly coherent. In this case, because the ray path lengths depend on the $v$ profile, the linear increase of $v_p$ results in the interference sound pressure pattern vividly seen in Figure 4 for curves 1 and 2. For large values of $C_n^2$, the rays are incoherent and interference is not observed. Coherence starts to break at smaller values of $C_n^2$ as the distance between the source and the receiver increases.

The effect of temperature gradient $\gamma$ on sound attenuation in the atmosphere is illustrated too. For $\gamma > 0$, the waveguide regime of sound propagation is realized, as in the case of wind refraction for $v_p > 0$, but in contrast to it, additional beam focusing takes place resulting in sound amplification. Therefore, the presence of temperature inversion in the atmosphere increases the sound level. In calculations, the sound source was at $r_1 = 5$ m above the ground and the observation point was at $r_2 = 1.5$ m. In the antiwaveguide regime of sound propagation, the zone of line-of-sight propagation always exists in the vicinity of the source followed by the acoustic shadow zone. For high source and receive the distance to this shadow zone is determined by the curvature radii of ray paths, which are noticeably smaller in case of refraction by temperature gradients than in case of refraction by wind gradients. Therefore, when $\gamma < 0$ and the observation point is in the shadow zone, the sharp increase of sound attenuation takes place for large absolute values of $\gamma$. The further increase of the sound attenuation in the shadow zone as $|\gamma|$ increases is caused by the upward displacement of the lower boundary of the region of sound scattering, as in the case of wind refraction.

6 Summary

The sound pressure level from a remote source has been estimated. Significance of the influence of different atmospheric parameters also has been demonstrated. Good accuracy of sound pressure level prediction has been obtained in the field test. A wide application area of the above-described algorithms and software package Outdoor Acoustics for routine prediction of the sound pressure level should be emphasized. This software package can be used successively for routine evaluation of the sound pressure level at the observation point, study of the noise background in the atmosphere produced by newly developed devices, calculation of the extension of sanitary zones of industrial objects against the criterion of the noise pressure level produced in the atmosphere, mapping of noise intensity distribution in
populated areas, estimation of audibility of sound sources, etc. One of example calculating sound pressure level for our sound broadcasting station shown in Figure 5.

Figure 5: Example of an angular pattern forecast for range and quality of sound broadcasting over Earth surface at a given wind direction (a – arrow on the left, b – arrow at the bottom): directional sound source is in the center (S); R is a preferable zone for a high-quality broadcasting. Scale marks are in 2-km intervals, chromaticity (color) shows broadcasting qualitative characteristics

References


