Influence of the outer scales of temperature and dynamic turbulence on the characteristics of transmitted acoustic radiation

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ABSTRACT

In the present work, the problem of propagation of monochromatic acoustic radiation in the lower 500-meter layer of the plain stratified moving turbulent atmosphere is solved by the Monte Carlo method. The influence of the parameters of models of the outer scales of temperature and dynamic turbulence on the intensity of transmitted acoustic radiation intensity is investigated.
Keywords: atmospheric acoustics, Monte Carlo method, outer scales of temperature and dynamic turbulence.

1. INTRODUCTION

In [1, 2] the Monte Carlo method was used to solve the problem of monochromatic acoustic radiation propagation through a 500-meter layer of the plain stratified moving turbulent atmosphere taking into account refraction and statistical estimations of the contribution of multiple scattering to the intensity distribution of transmitted acoustic radiation over zones of the detector depending on the sound frequency and the outer scales of atmospheric turbulence. Calculations were performed for the acoustic model of the atmosphere based on the theoretical estimates of sound scattering by atmospheric turbulence presented in [3] for the von Karman model of the spectra of fluctuations of the atmospheric temperature and wind velocity.

2. MODEL OF THE ATMOSPHERE AND GEOMETRY OF THE NUMERICAL EXPERIMENT

In the given paper, influence of models of the outer scales of temperature and dynamic turbulence on the distribution of the intensity of transmitted radiation over the detector zones is analyzed. Calculations were performed by the Monte Carlo method for a point sound source with acoustic power of 1 W having coordinates x = 0, y = 0, and z = 35 m for radiation frequencies F = 1–4 kHz conventionally used in sodars. The angle of radiation divergence of the source φ = 2.5–25°. The distribution of the intensity of transmitted and multiply scattered radiation was estimated, taking into account the symmetry of the problem, over the horizontal plane of the detector located at an altitude of 500 m depending on the distance H from the vertical axis of the source. The acoustic model of the atmosphere comprised 25 layers 20 m thick each with constant within the layers coefficients of classical and molecular absorption and scattering by fluctuations of the temperature and wind velocity. The underlying surface was considered absolutely absorbing. The outer scales of the temperature (L_{0T}) and dynamic turbulence (L_{0V}) were determined by the Monin–Obukhov length $L_{\mathrm{MO}} = -u_*^2 T_0 / g\kappa T_*$ [4]:

$$L_{0V}(z) = 1.3z \frac{1+0.22(z_i/z)(-z_i/L_{\mathrm{MO}})}{1+0.22(-z_i/L_{\mathrm{MO}})}, \tag{1}$$

$$L_{0T}(z) = 1.5z \frac{1+7.0(-z/L_{\mathrm{MO}})}{1+10(-z/L_{\mathrm{MO}})}, \tag{2}$$

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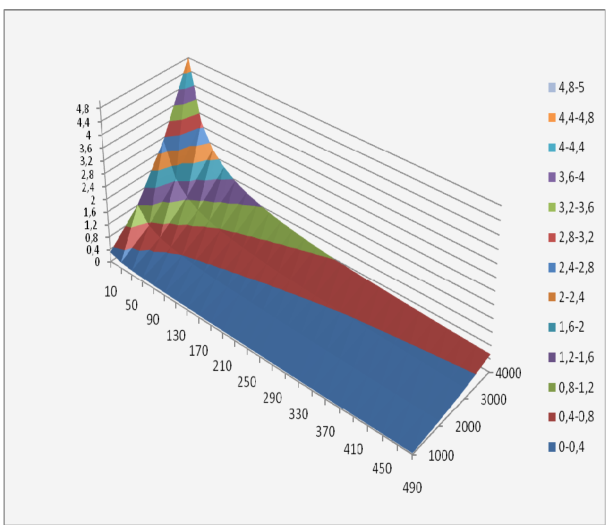
where u_* is the friction velocity, T_* is the surface-layer temperature scale, g is the acceleration of gravity, κ is the von Karman constant, T_0 is the surface temperature, and z_i is the height of the atmospheric boundary layer. Our calculations were performed for the unstable atmospheric stratification with light, moderate, and strong wind under conditions of cloudless (the surface flux $H_s = 200$ W/m^2) and cloudy atmosphere (the surface heat flux $H_s = 40$ W/m^2). The height of the atmospheric boundary layer z_i was set equal to 1000 m. The corresponding values of the parameters u_*, T_*, and L_{MO} for 6 meteorological regimes of the turbulence considered in [4] are given in Table 1.

Table 1. Parameters of 6 benchmark meteorological regimes of the unstable atmosphere according to [4].

H_s, W/m^2	Mean wind velocity	u_*, m/s	T_*, K	L_{MO}, m
200	Light	0.1	–1.6	–0.47
	Moderate	0.3	–0.54	–13
	Strong	0.7	–0.23	–160
40	Light	0.1	–0.33	–2.4
	Moderate	0.3	–0.11	–64
	Strong	0.7	–0. 046	–810

As an example, Fig. 1 shows the altitude dependence of the total sound extinction coefficients (*a*) and the phonon survival probabilities (*b*) for frequencies in the range 400 Hz – 4 kHz and the Monin–Obukhov length $L_{\mathrm{MO}} = -810$ m in the cloudy atmosphere with strong wind. The results of calculations demonstrated that the extinction coefficient in the surface layer increased approximately by an order of magnitude, and the turbulent extinction considerably exceeded the classical and molecular absorption in the entire range of the examined frequencies (the probabilities of the phonon scattering exceeded 0.96).



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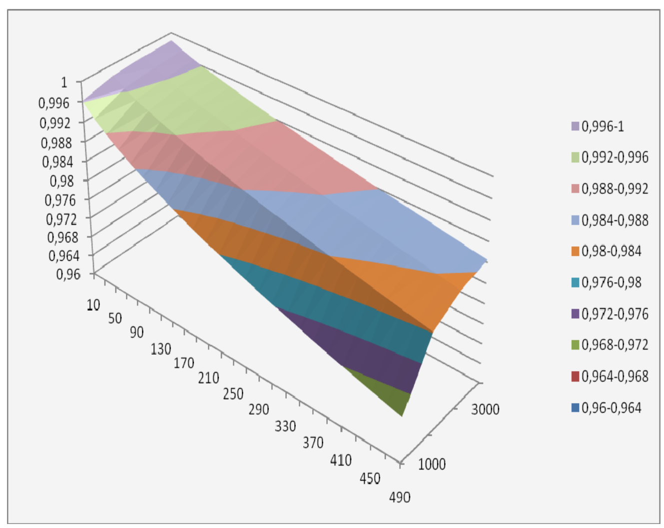

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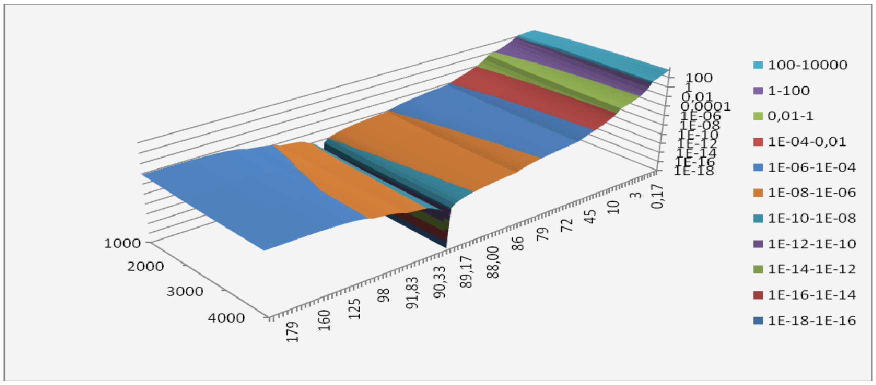
Fig. 1. Altitude dependence of the total sound extinction coefficient (*a*) and of the phonon survival probabilities (*b*) for frequencies F = 1–4 kHz and $L_{\mathrm{MO}} = -810$ m.

Figure 2 shows the normalized phase functions of sound scattering on temperature (*a*) and wind velocity fluctuations (*b*) in cloudless atmosphere with light wind for frequencies F = 1–4 kHz and $L_{\mathrm{MO}} = -0.47$ m. It should be noted that a comparison of the analytical expressions for the total sound extinction coefficients and normalized phase functions of sound scattering by the atmospheric turbulence performed in [3] demonstrated their good agreement with the available experimental data.



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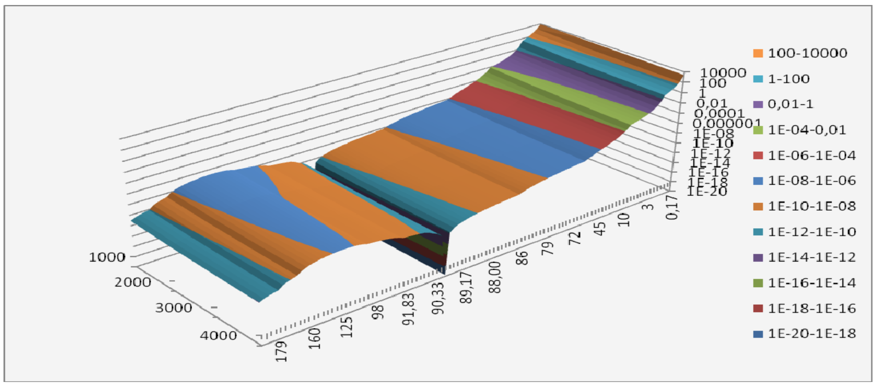

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Fig. 2. Normalized phase functions of sound scattering on the temperature (*a*) and wind velocity fluctuations (*b*) in cloudless atmosphere with light wind for frequencies $F = 1$–4 kHz and $L_{MO} = -0.47$ m.

3. COMPUTATIONAL ALGORITHM

To construct a computational algorithm, both standard computational procedures borrowed from [5] and procedures developed in [6, 7, 8] with allowance for the specifics of sound interaction with the atmosphere were used. The flowchart of the computational algorithm is shown in Fig. 3. We considered a point-sized source of acoustic radiation. A hypothetical receiver was placed above the source at an altitude of 500 m from the ground. The distribution of transmitted radiation over the horizontal plane of the detector was estimated together with the contribution of multiply scattered radiation.

The coordinates of the point of phonon emission (x_0, y_0, z_0) and their directional cosines (ω_1, ω_2, ω_3) were calculated using the procedure described in [5]. The Earth's surface was considered absolutely absorbing, and when the phonon trajectory intersected the plane $z = 0$, the phonon was considered absorbed, and a new phonon history was modeled.

The phonon free path was modeled by the following scheme.

a) Let Δl be the distance passed by the phonon through atmospheric layers with attenuation coefficients $\sigma_{att}[1]$, …, $\sigma_{att}[N]$.

b) By subsequent subtraction, we find the number j of the layer such that

$$\Delta l \sum_{m=1}^{j-1} \sigma_{att}[m] < -\ln(rand) \le \Delta l \sum_{m=1}^{j} \sigma_{att}[m], \tag{3}$$

where *rand* is a random number uniformly distributed in the interval [0,1].

c) If there is no number j satisfying condition (3), it is considered that the phonon have been escaped from the medium; otherwise,

$$l_{\text{free}} = \frac{z_0 - z[1]}{c} + (j-2)\Delta l - \frac{\ln(rand) + \Delta l \sum_{m=1}^{j-1} \sigma_{\text{att}}[m]}{\sigma_{\text{att}}[j]}. \quad (4)$$

The point of the next collision was chosen by the well-known formulas [5].

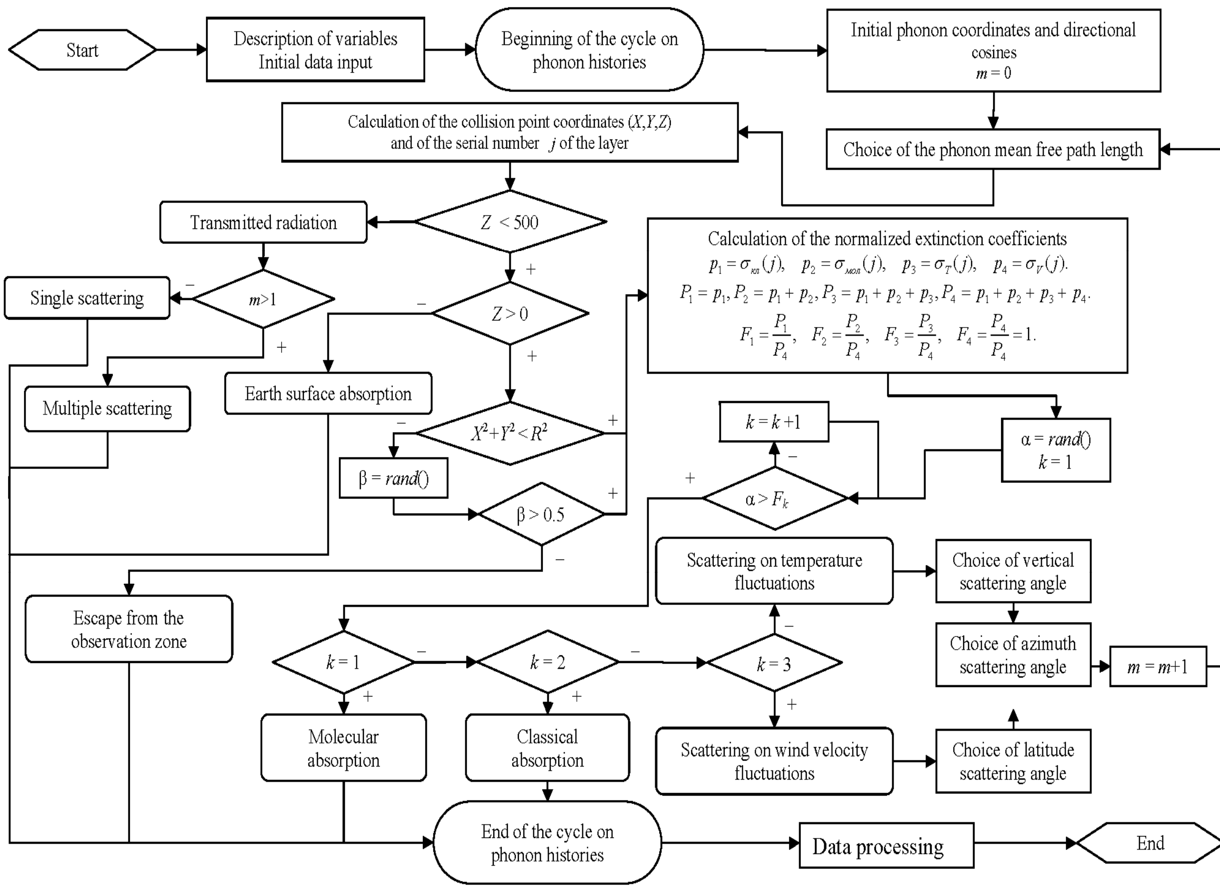

Fig.3. Flowchart of the computational algorithm.

Then the collision type was chosen. For a 500-m standard plane-stratified turbulent atmosphere, the total attenuation coefficient was calculated from the formula

$$\sigma_{\text{att}}(z_i) = \sigma_{\text{cl}} + \sigma_{\text{mol}}(z_i) + \sigma_{\text{T}}(z_i) + \sigma_{\text{V}}(z_i), \quad (5)$$

where σ_{cl} and $\sigma_{\text{mol}}(z_i)$ are the coefficients of classical and molecular absorption, $\sigma_{\text{T}}(z_i)$ and $\sigma_{\text{V}}(z_i)$ are the coefficients of scattering by turbulent temperature and wind velocity fluctuations, $z_i = z_{(i-1)} + dz$, $dz = 20$ m, $i = 1, \ldots, 26$, and $z_0 = 0$.

Then the following procedure was used.

a) $p_1 = \sigma_{\text{cl}}(j), \quad p_2 = \sigma_{\text{mol}}(j), \quad p_3 = \sigma_{\text{T}}(j), \quad p_4 = \sigma_{\text{V}}(j).$

b) $P_1 = p_1, P_2 = p_1 + p_2, P_3 = p_1 + p_2 + p_3, P_4 = p_1 + p_2 + p_3 + p_4.$

c) $F_1 = \frac{P_1}{P_4}, \quad F_2 = \frac{P_2}{P_4}, \quad F_3 = \frac{P_3}{P_4}, \quad F_4 = \frac{P_4}{P_4} = 1.$

d) $k = 1$.

e) $\alpha = rand$.

f) Then if $\alpha > F_k$, go to g); otherwise, $k = k + 1$ and go to e).

g) If k = 1, molecular absorption was simulated; if k = 2, classical absorption; if k = 3, scattering on the wind velocity fluctuations; otherwise, scattering on the temperature fluctuations.
In the case of absorption, the phonon was annihilated, and its statistical weight was added to the element of the array determining the value of the acoustic wave intensity absorbed in the *i*th atmospheric layer. In the case of scattering, the scattering angle was determined by the phase function of scattering by temperature or wind velocity fluctuations. The procedure of simulation of the scattering angle was described in detail in [9].

Distribution of the transmitted radiation intensity over the horizontal plane of the detector was calculated versus the distance H from the vertical source axis (over the annular detector zones with a step of 10 m for H = 10–100 m and then with a step of 50 m up to H = 500 m). The contributions of unscattered, singly scattered, and multiply scattered radiation were also estimated. Calculations were carried out on a personal computer for 10^6 phonon histories, which provided acceptable calculation errors of 3–10%.

4. CALCULATION RESULTS AND THEIR DISCUSSION

The influence of the outer scales is illustrated by Fig. 4, where the distribution of the intensity of transmitted radiation over the detector zones is shown for the frequency F = 1700 Hz and the angle of source divergence of 5 °.
The influence of the angle of divergence of the radiation source is illustrated by Fig. 5. From the figure it can be seen that the dependence of the intensity of transmitted radiation on the angle of source divergence is quadratic in character, which was already indicated by us in [3].

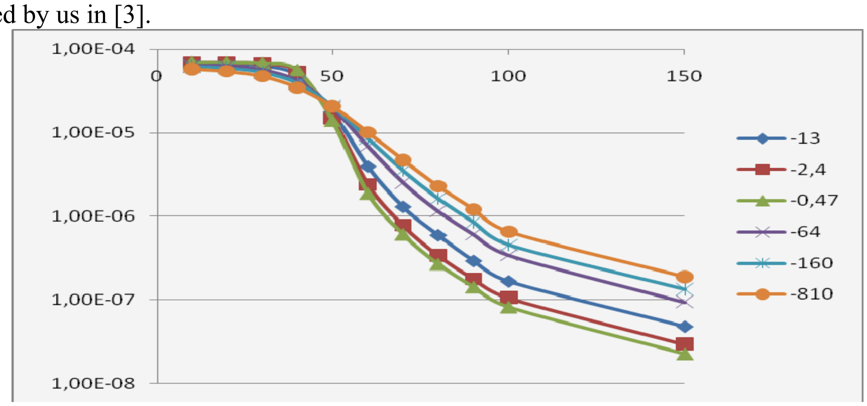

Fig. 4. Influence of the external scales of the atmospheric turbulence on the intensity distribution of the transmitted radiation over zones of the detector for the frequency F = 1700 Hz and the angle of the source divrgence 5°. The Monin–Obukhov length values are indicated on the right of the figure.

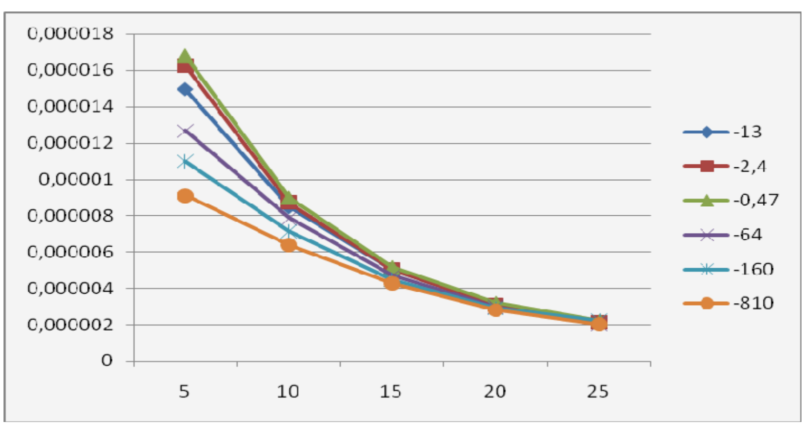

Fig. 5. Influence of the angle of the source radiation divergence on the transmitted radiation intensity for F = 4 kHz.

The analytical approximation of the results of calculations by the Monte Carlo method shown in Fig. 5 using polynomial, power-law, and logarithmic dependences has demonstrated that they are well described by a power-law dependence

$$I_{\mathrm{tr}}\left(0^{\circ},\varphi\right)=A\varphi^{2}-B\varphi+C\,, \tag{6}$$

where $I_{\mathrm{tr}}\left(0^{\circ},\varphi\right)$ is expressed in W/m^2, φ is in degrees, with the correlation coefficient close to 1. In Table 2, values of the approximation constants for the considered Monin–Obukhov lengths are presented.

Table 2. Values of the approximation constants.

L_{MO}	A	B	C
–0.47	$4{\cdot}10^{-8}$	$2{\cdot}10^{-6}$	$2{\cdot}10^{-5}$
–13	$4{\cdot}10^{-8}$	$2{\cdot}10^{-6}$	$2{\cdot}10^{-5}$
–160	$4{\cdot}10^{-8}$	$2{\cdot}10^{-6}$	$3{\cdot}10^{-5}$
–2.4	$3{\cdot}10^{-8}$	$1{\cdot}10^{-6}$	$2{\cdot}10^{-5}$
–64	$2{\cdot}10^{-8}$	$1{\cdot}10^{-6}$	$2{\cdot}10^{-5}$
–810	$1{\cdot}10^{-8}$	$7{\cdot}10^{-7}$	$1{\cdot}10^{-5}$

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