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EXPERIMENTAL INVESTIGATION INTO COHERENCE OF ACOUSTIC
WAVES PROPAGATING ALONG SURFACE PATHS

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This paper discusses the results of analysis of experimental data on the coherence function of acoustic waves, propagating in the randomly inhomogeneous atmosphere along short surface paths. The cases of the coherence longitudinal and transversal to the propagation path are considered. The relation between the coherence and the observed structure of turbulence in the surface layer is estimated. Theoretical assumptions are compared with the experimental results.

Acoustic signals propagating in the atmosphere as a randomly inhomogeneous stratified medium undergo the transformation. In particular, the coherence of the wave field is disturbed. The theoretical analysis of this problem, performed, for example, in a series of papers by V. E. Ostashev with co-authors [1–6], has revealed the basic relations and established the regularities, determining the spatiotemporal change of the initially coherent acoustic wave under the effect of inhomogeneities in the propagation medium. However, these theoretical conclusions did not receive the complete experimental confirmation yet (see, for example, [7–9]).

To study the coherence of acoustic waves, the Atmospheric Acoustics Group of the Institute of Atmospheric Optics SB RAS has made an experimental setup for open-path field measurements. This setup consists of a source of signals of the needed power, a multichannel receiver, a unit for digitization of recorded signals, a software, allowing the coherence function to be analyzed at different combinations of receiving channels, as well as an ultrasonic meter of temperature and wind direction and speed, which provides for the estimation of average and turbulent characteristics. The setup operated in the automatic mode under the control from a personal computer by the specially developed software.

For processing of the data, the technique of analysis of multichannel systems was applied [10]. The realization of this technique assumes the estimation of the mutual spectrum $G_{xy}(f)$ and autospectra $G_x(f)$ and $G_y(f)$ of two random processes $x(t)$ and $y(t)$. Then the estimates obtained are used to determine the coherence function

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_x(f)G_y(f)}. \quad (1)$$

The coherence function is a dimensionless measure of correlation ($0 \leq \gamma_{xy}^2(f) \leq 1$) of two time series in the frequency region. The estimates $\tilde{G}_{xy}(f)$, $\tilde{G}_x(f)$, $\tilde{G}_y(f)$, and $\tilde{\gamma}_{xy}^2(f)$ were calculated on the basis of the prior division of the initial realizations $x(t)$ and $y(t)$ into N_{seg} equal segments, the discrete Fourier transform of these segments, and the averaging of the obtained spectra. The duration of one segment $T=N\Delta t$ (where N is the number of readings in a segment, Δt is the discretization interval) was selected from the needed spectral resolution (acceptable systematic error), while the number of segments N_{seg} was selected from the acceptable random error.

The measurements were carried out at the experimental site of the Institute of Atmospheric Optics SB RAS in Tomsk suburbs. The surface at the experimental site was a relatively flat field covered by low grass. The receiving microphones were arranged in several different ways. The separation between the microphones, arranged on a line perpendicular to the sound propagation path, varied from several centimeters to 24 m. The range from the source to this line was from 48 to 58 m in different experiments. The wind-proof microphones were installed at a height of 1 to 10 cm. Continuous signals with different frequency spectra were emitted. The height of the sound source varied from 5 to 7.5 m. The measurements were carried out by different time schemes, in particular, for many days with the interval of 1–2 h (the measurements took 5–10 minutes at the beginning of every hour). The weather station was located at a height of 3.2 m near the path and operated continuously (up to 10 readings per second).

During the digitization of the recorded signals (with the discretization frequency of 20–30 kHz), samples of 4096 or 8192 readings were collected. For one session, 1000 to 2000 samples were accumulated. The processing of the experimental data involved the segmentation of the samples with 50%

overlap. The segment length N was equal to 1024 or 2048 readings. This allowed the spectra to be averaged over 7–15 segments, providing for the acceptable systematic and random errors in the estimates of the coherence function.

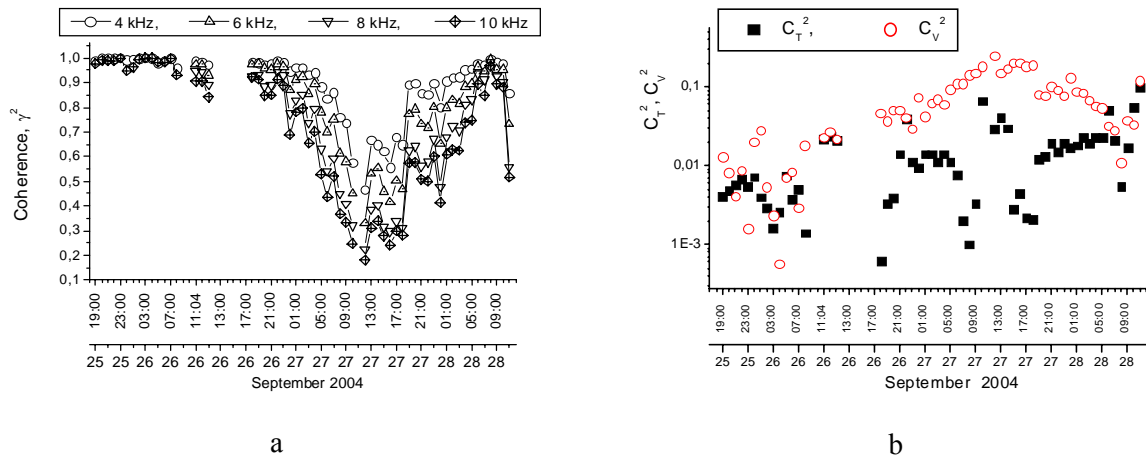


Fig. 1. Diurnal behavior of the coherence (a) and structure characteristics of temperature and wind pulsations (b). The receiving microphones are separated by 24 m.

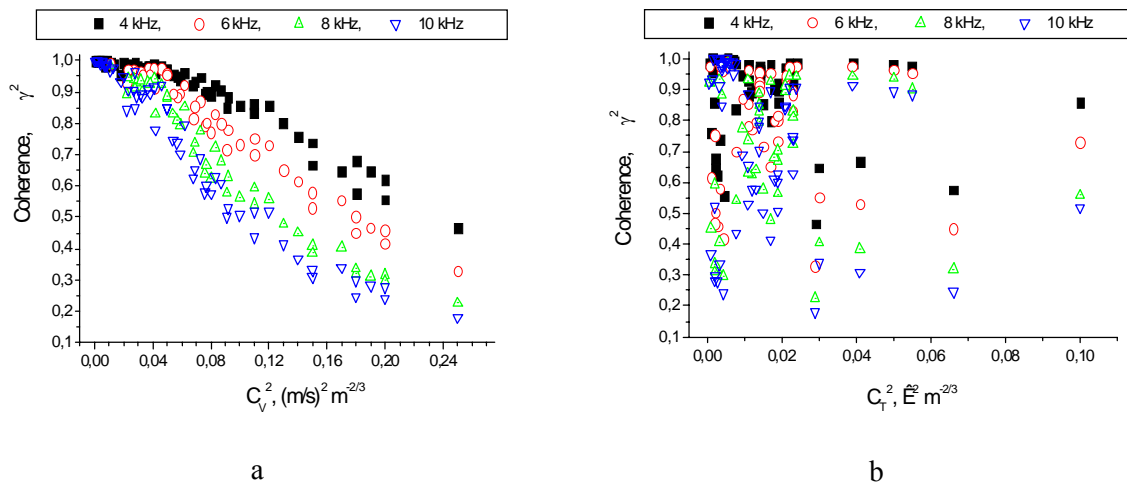


Fig. 2. Dependence of the coherence on the structure characteristics of wind velocity (a) and temperature (b) pulsations. The receiving microphones are separated by 24 m.

As an example, Fig. 1a shows the coherence in hourly measurements (1000 samples at the beginning of every hour), while Fig. 1b depicts the plots of the structure characteristics of wind (C_V^2) and temperature (C_T^2) pulsations. Four frequencies: 4, 6, 8, and 10 kHz, were emitted simultaneously. Comparing the values of $\gamma^2(f_i)$ and the diurnal behavior of C_V^2 and C_T^2 , we can conclude that the coherence depends mostly on the wind velocity pulsations. This would be especially clearly seen from the dependences $\gamma^2(f_i, C_V^2)$ and $\gamma^2(f_i, C_T^2)$. Figure 2 shows the experimental data from Fig. 1a, but systematized with respect to C_V^2 and C_T^2 . Obviously, wind pulsations are major contributors to the disturbance of the coherence of acoustic waves, because only for them $\gamma^2(f_i)$ decreases regularly with the increase of C_V^2 (Fig. 2a). For temperature pulsations, such a regularity is absent (Fig. 2b). This is also confirmed by theoretical conclusions.

Since the temperature pulsations only weakly affect the coherence, the further analysis was performed taking into account only C_V^2 . In particular, the ratio

$$W = \ln \gamma^2(f_i) / \ln \gamma^2(f_j) \quad (2)$$

was considered. The interest to the estimation of this ratio is explained by the fact that the existing theory of sound propagation in the turbulent atmosphere postulates the relation between the coherence and the sound frequency in the form

$$\gamma^2(f) \sim \exp(-f^2 G), \quad (3)$$

where G depends on many parameters (in particular, C_v^2), but does not depend on the frequency. According to Eq. (3), the values of W should be constant at variations of G , but different for different frequency pairs. This can be checked quite easily in the experiment. Figure 3 shows the dependence of experimentally obtained W on C_v^2 for frequency pairs of 4 and 8 kHz ($W=0.25$) and 4 and 10 kHz ($W=0.16$). At relatively small C_v^2 , the theory and the experiment are in a good agreement, but with the increase of C_v^2 the dependence (3) is violated markedly in the frequency region. The cause for this is still to be revealed.

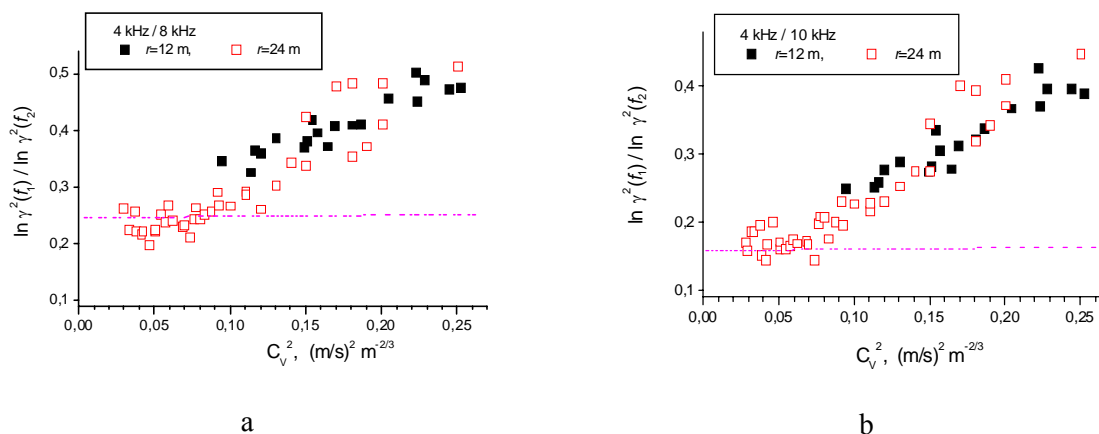


Fig. 3. Dependence of the log coherence ratio for the frequency pairs of 4 and 8 kHz (a) and 4 and 10 kHz (b) on the structure characteristics of wind pulsations. The results were obtained for the receiving microphones separated by 12 (closed squares) and 24 m (open squares).

The longitudinal (along the sound propagation path) coherence was estimated as well. The measurement points were separated by 40–45 m. As expected from the theory, the longitudinal coherence was much higher than the transversal coherence at the same distances between the measurement points and the same turbulent conditions.

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