Correlation of the wind velocity components in the atmospheric boundary layer

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The inter-level correlation of the horizontal wind velocity have been estimated based on the data of acoustic sounding of the atmospheric boundary layer in different regions. The relation of the correlation to the type of stratification, the separation between levels, observation intervals, and the time of data pre-averaging has been analyzed. It has been shown, in particular, that the inter-level correlation under the convective conditions is higher than in the case of stable stratification. Sodar observations have been compared with the data of other authors.

The study of the structure of the atmospheric boundary layer (ABL) contains estimation of the statistical characteristics of the wind flow, including the height and time correlations of the wind velocity pulsations. The main results on this problem were obtained at high meteorological towers. To date, there is only one such tower available in Russia. It is situated in Obninsk, 100 km to the south-east from Moscow (it is 312 m high and contains 13 measurement levels). Processing of the data obtained at this tower provides reliable estimation of statistical (including correlation) relations of the random wind flow in the ABL.[1,2] However, these estimates are obtained for a specific region where the tower is operated. So the problem is urgent of the development of mobile technical tools providing the possibility of remotely sensing the ABL structure in any region. The Doppler sodar is one of such tools. The results presented below are based on the experimental data obtained during operation of the "Volna–3", a three-channel Doppler sodar of the IAO SB RAS.[3]

The specific mode of operation of the three-channel Doppler sodar lies in the fact that the data on the wind velocity components come from ABL volumes isolated in space and time. It is related to the peculiarities of monostatic sounding diagrams (united receiver and transmitter of sound). The sodar at such diagrams gives the data on the radial components V_r, i.e., the projections of the wind velocity vector $\mathbf{V} = \mathbf{n}_1 V_1 + \mathbf{n}_2 V_2 + \mathbf{n}_3 V_3$ onto the axes of the antenna polar diagrams. Here $\mathbf{n}_r$ are the basis vectors of the oblique-angled coordinate system.

To determine the vertical profile $\mathbf{V}(Z)$, no less than three measurement channels with different direction are necessary. Usually the sodar antennas are placed next to each other. When using the phase antenna grids with electronic scanning of the polar diagram, all measurement channels have the same transmitter/receiver of sound. As a result, the "fan" of the directions of sounding is formed, which sounds different parts of the ABL. Besides, usual practice of multi-channel acoustic sounding implies a sequential regime of transmitting/receiving the pulsed signals by each measurement channel. These factors ("fan" and sequence of transmission) are responsible for the spatiotemporal separation of the estimates of V_r. Such a technique of sounding imposes some restrictions on the resolution of the sounding system, forming the specific spatiotemporal filter, which does not permit one to estimate the small-scale and short-period pulsations of $\mathbf{V}(Z)$.

The results presented below were obtained using one vertical sounding channel (V_1) and two slant channels (V_2 and V_3) with deviation from zenith by the angle $\varphi = 20°$ and difference between azimuth angles of 90°. Such a diagram corresponds to estimation of V_r at the height Z at the tops of the isosceles triangle with the sides of $l = 0.364\,Z$ (m) and the hypotenuse of $L = 0.515\,Z$ (m). Such is the spatial separation of the observation points. Temporal shifts were determined by the maximum distance (height) of sounding required and were 15–17 s between successive readouts at the height Z in each measurement channel.

It is also necessary to note that the beam width of the Volna-3 sodar was ≈ 8° (at the half-power level). Hence, the signal received at the time moment t is formed in the area with the characteristic cross section $D \approx 0.149\,Z$ (m). The longitudinal section of this area was determined by the duration of the sounding pulse τ and the sound velocity c, and was $d = c\tau/2$. Usual duration of the Volna-3 sodar pulse is $\tau = 0.15$ s. Taking the standard sound velocity $c = 330$ m/s (at temperature of 0°C) we obtain the estimate $d = 25$ m. Thus, at some moment the sodar receives the data from the volume of the atmosphere of about $0.435\,Z^2$ (m^3). If one takes into account that, in order to obtain the estimates of the Doppler shifts in the spectrum of the received signals, it is necessary to have a sample of duration Δt, the longitudinal size increases by some value Δd. The step Δd in the results presented below is 12–15 m.

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This fact allowed us to obtain about 50 estimates of V_r in the height range up to 700 m. The technique for obtaining such estimates is described in Refs. 4 and 5.

In order to reveal the correlation of pulsations of the horizontal component of wind velocity $\mathbf{V}(Z)$ at different heights, the problem was stated on determining their correlation depending on geographical conditions, on the distance between the measurement levels, on the interval of estimates, as well as on time of preliminary averaging. Besides, the inter-level correlations were estimated of the radial components of wind velocity V_r. The data of sounding in different geographical regions were used: in the suburb of Tomsk, at the field site in steppe region, and in the coastal zone of Lake Baikal. To estimate the inter-level correlations, the data were used obtained under relatively stationary conditions, when sharp changes of thermodynamic state of the ABL were absent. The cases were considered of the temperature inversions and developed convection. The typical facsimile records of the amplitude of the sodar signal are shown in Fig. 1 for stable (*a*) and unstable (*b*) temperature stratification. To keep the statistical provision of the data obtained, the height range from 90 up to 300 m was mainly studied. To fill the values rejected for one or another reason from raw profiles $\mathbf{V}(Z)$ at the level Z at the moment t, the procedure was used of linear (inter-level) interpolation preliminary applied to model samples. Examination of the interpolation algorithm has shown that the correlation functions of artificially decimated profile V_r and the profile reconstructed by means the linear regression were in a good agreement with the correlation function of the initial profile.

The inter-level correlations were calculated by the formula:

$$\tilde{\rho}_V(Z_i, Z_l) = \frac{\tilde{K}_V(Z_i, Z_l)}{\sqrt{\tilde{D}(Z_i)\tilde{D}(Z_l)}}, \quad (1)$$

where

$$\tilde{K}_V(Z_i, Z_l) =$$

$$= \frac{1}{n-1}\sum_{k=1}^{n}[V(Z_i, t_k) - \tilde{M}_V(Z_i)][V(Z_l, t_k) - \tilde{M}_V(Z_l)]$$

is the correlation moment for the pair of heights Z_i and Z_l; $\tilde{M}_V(Z_i)$ is the mathematical expectation of wind velocity at the height Z, $\tilde{D}(Z_i)$ is the variance of wind at this height, n is the sample size (it is responsible for the duration of the processed range).

First of all, the results of sodar estimation were compared with the experimental data presented in Ref. 2. To do this, the cross-correlation functions were constructed for each pair of levels Z_i and Z_l in the height range from 90 up to 300 m. The results of comparison of some reference levels at typical stratifications of the ABL are shown in Fig. 2.

As is seen in Fig. 2, coincidence of the results obtained by different tools is quite satisfactory, in spite of the fact that measurements were carried out in different geographical regions. It allows us to believe that the estimate obtained from sodar measurements can provide correct description of the statistical characteristics of the dynamical processes in ABL. One should note that the correlations obtained from sodar measurements not always are similar to that shown in Fig. 2.

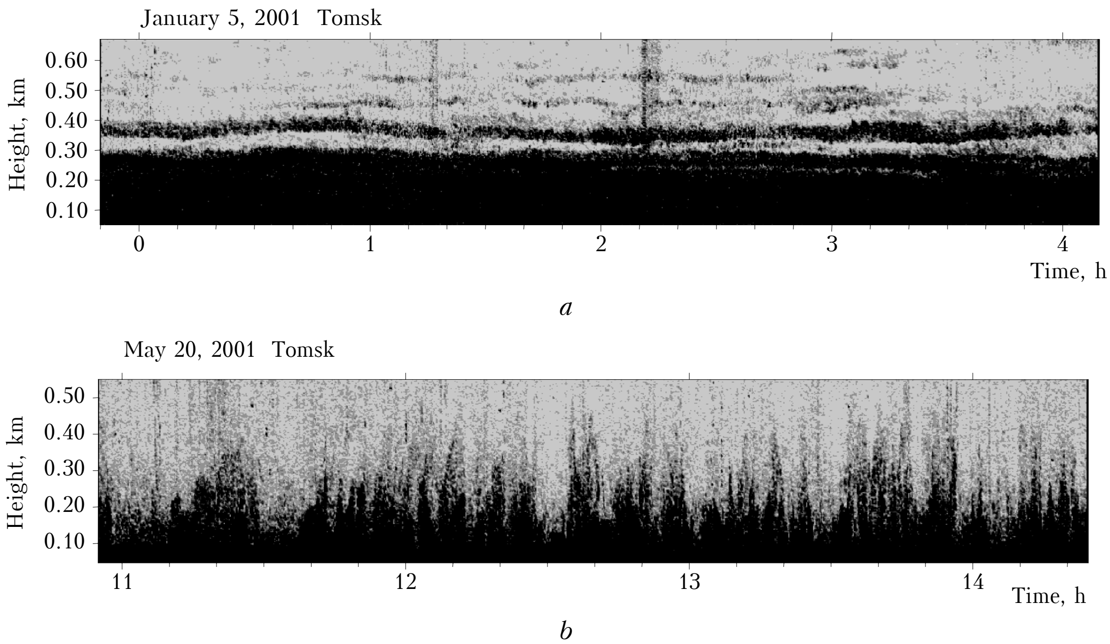

Fig. 1. Typical examples of facsimile records at different stratification types (suburb of Tomsk): winter inversion (*a*), spring convection (*b*).

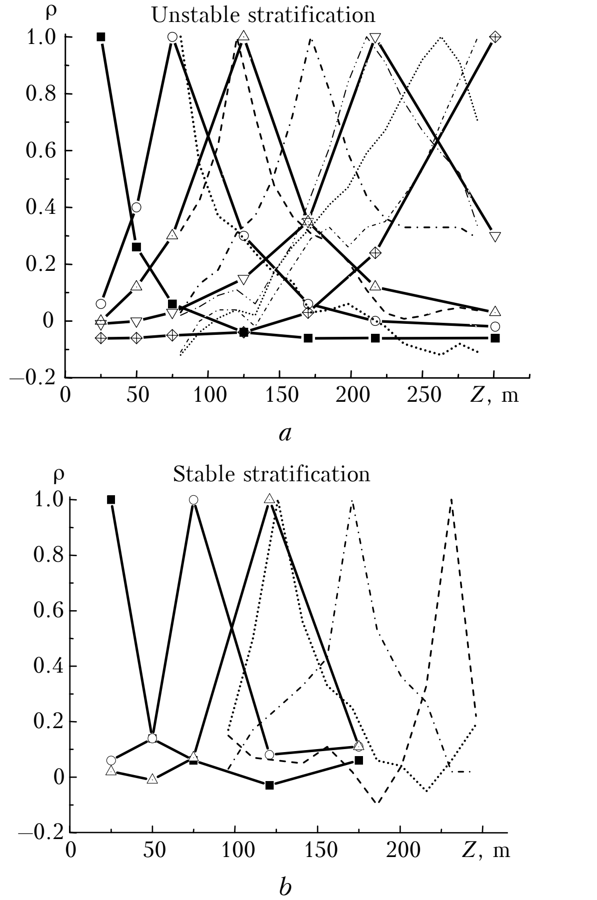

Fig. 2. Correlations of horizontal wind between different levels in the boundary layer of the atmosphere at unstable (*a*) and stable (*b*) stratification assessed from the data of the acoustic sounding (dotted lines of different types) and from the data of meteorological tower in Obninsk (solid lines with symbols).

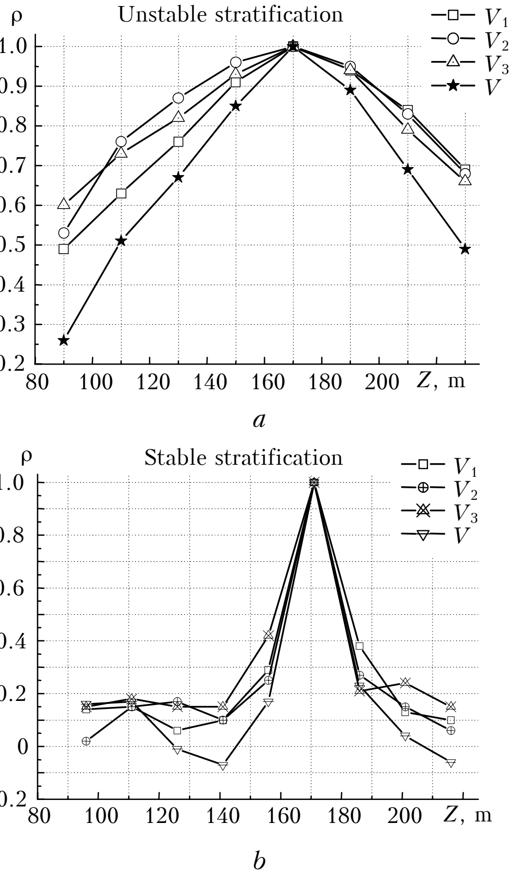

Fig. 3. Comparison of the typical correlation functions of three radial components (V_1 – vertical sounding channel, V_2 and V_3 – slant channels) and horizontal wind V obtained in the time interval of 60 minutes: (*a*) developed convection in steppe region, (*b*) near-ground temperature inversion in suburb of Tomsk.

The inter-level correlation of the radial components of wind velocity were studied using two slant and one vertical measurement channels, and then they were compared with the inter-level correlation of horizontal wind. Typical examples of such a comparison depicted in Fig. 3 show that the correlation of the radial components of wind velocity is a little bit higher in comparison with the horizontal wind. The inter-level correlations of the vertical component of wind velocity are weaker than wind velocity in the slant channels of sounding.

Examination of the relations of correlation properties of the radial components of wind velocity with the direction of the oncoming flow revealed no stable features. For reasons of clarity of the graphical data, Fig. 3 shows the correlation functions related only to one reference level $Z_0 = 170$ m.

The dependence of inter-level correlations on the atmospheric stratification type is well pronounced in all examples considered above: correlation at stable stratification decreases more quickly than under convective conditions. The same conclusion was drawn in Refs. 1 and 2.

One of the important problems in estimation of correlations of the random wind flow is the choice of duration of the interval to be processed for obtaining stable statistical estimates. Calculations of the correlation matrices were performed by formula (1) with different intervals of estimating (sample size n). The intervals were 2, 10, 30, and 60 minutes. Analyzing the results obtained, we have arrived at a conclusion that the shape of the correlation functions depends on the time of estimation, and their scatter decreases with the increase of the interval. In processing 2-minute intervals, quite wide scatter of these functions is observed, while processing of 10-minute and longer intervals, yields more stable correlations. The examples of correlation relative to the height $Z_0 = 170$ m obtained in different time intervals under convective conditions during 1 hour are shown in Fig. 4.

Figure 4*a* shows the calculated results on the correlation matrix (1) over 2-minute intervals. Only some of 30 estimates of the inter-level correlation are presented, as well as their mean value (solid line with symbols). Six estimates over 10-minute intervals are shown in Fig. 4*b*, as well as their mean value (solid line with symbols). Evidently, stability of the estimates in the second case is much higher than that over 2-minute intervals of averaging. The mean values obtained over 2, 10, and 30-minute intervals are shown in Fig. 4*c*, as well as over the entire interval (one hour).

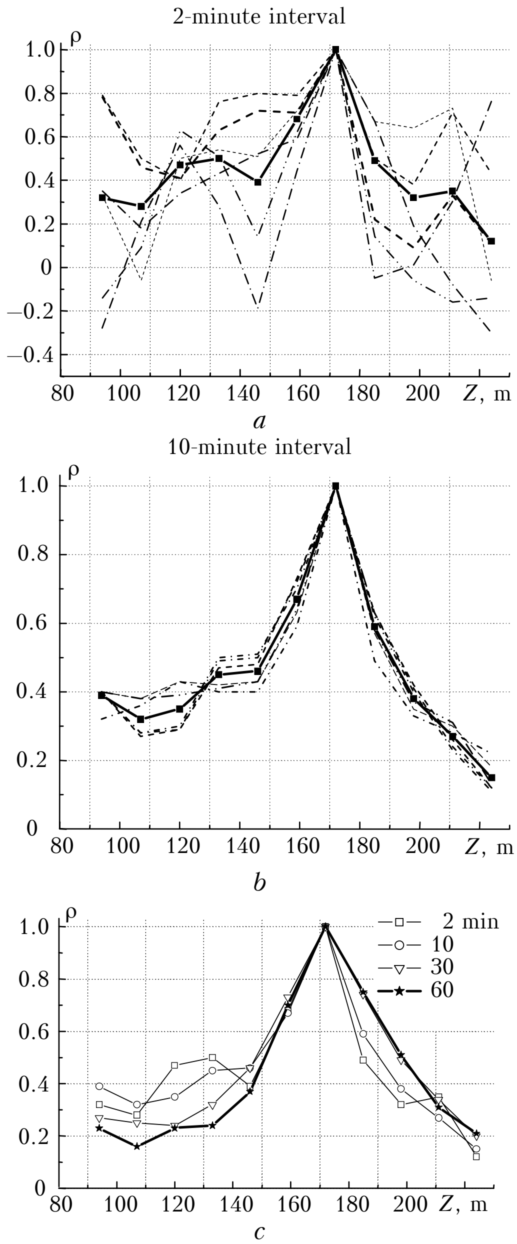

Fig. 4. Examples of the behavior of the correlation curves depending on the interval of estimation under convective conditions (measurements in the suburb of Tomsk).

The aforementioned results characterize the correlations of the wind flow at any height with above and lower laying levels. Correlation matrices have some symmetry relatively to the reference level, though the correlation with lower laying levels is a few greater than correlation with the above laying levels. If not take into account such an asymmetry of the correlation matrices, one can estimate correlations of the pulsations of wind velocity depending on the distance between layers inside ABL. To do it, the mean inter-layer correlation functions of the absolute value of horizontal wind were estimated by the formula

$$B(rh) = \frac{1}{N-r}\sum_{i=1}^{N-r}\tilde{\rho}_V(Z_i,Z_{i+r}),\ \ r=0,1,\ \ldots,(N-1), \quad (2)$$

where h is the height step between layers when estimating the wind velocity, N is the quantity of the considered levels, r is the step number, $\tilde{\rho}_V$ is the element of the correlation matrix calculated by formula (1) estimating the degree of correlation of the pulsations of wind velocity between the levels Z_i and Z_{i+r}. The typical examples of inter-level correlation functions at stable and unstable stratifications in different regions of observations are shown in Fig. 5. Evidently, the correlation under convective conditions is greater than that at inversion.

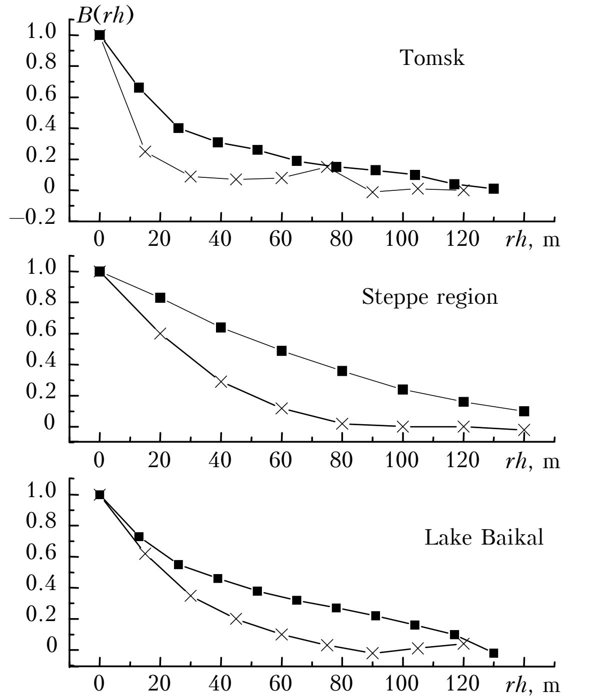

Fig. 5. Correlation functions for stable (crosses) and unstable (squares) stratifications. The interval of estimation of correlations is 60 minutes.

The problem is quite important, how the preliminary averaging of the data affects the correlation. The correlation matrices were obtained in Ref. 6 of the longitudinal wind velocity at stable and unstable state of the atmosphere using the data obtained at Obninsk meteorological tower averaged over 10 minutes. We have performed similar calculations using the sodar data under corresponding geophysical conditions and then have compared our results with the results from Ref. 6. The comparison shows (Fig. 6) that the behavior of the correlation functions is quite the same.

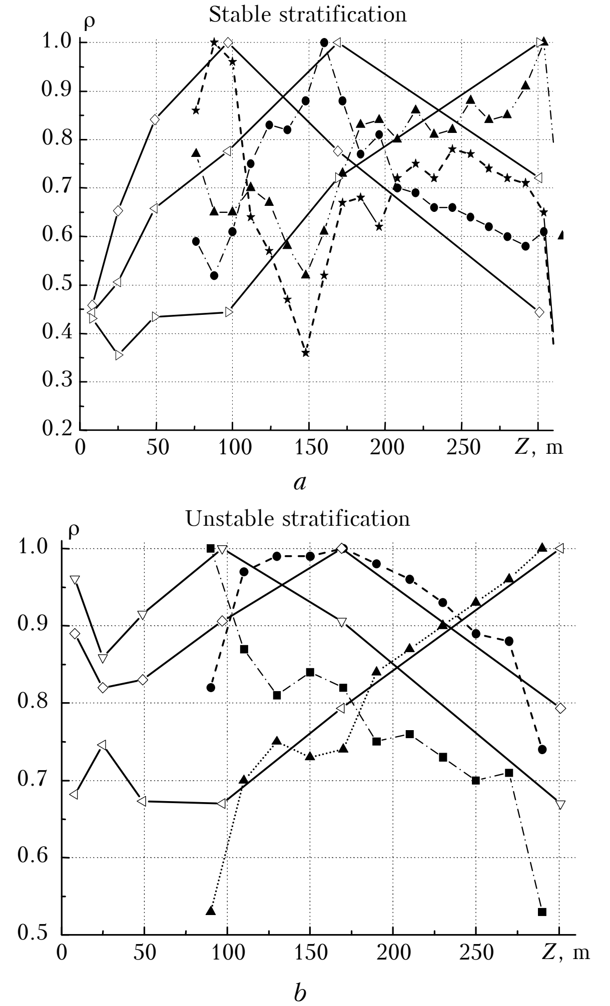

Fig. 6. Correlations of horizontal wind between different levels in the boundary layer of the atmosphere at stable and unstable stratifications according to the data of acoustic sounding averaged over 10 minutes (dotted lines of different types with symbols) and the meteorological tower in Obninsk (solid lines with symbols).

Analysis of the results of processing a large data array is an evidence of the fact that correlations constructed using the averaged data are much higher than that for instantaneous data. It can be easily explained, as in averaging the data we, in fact, filter out small-scale fluctuations, introducing essential random components and decreasing the degree of correlation of wind velocity at different levels. The example of comparison of correlation functions at preliminary 10-minute averaging and without it is shown in Fig. 7.

Summarizing, let us emphasize that at this stage of the work we did not propose the detailed study of inter-level correlations of wind velocity and their parameterization as functions of different geophysical conditions. The main problems were the development of the technique for estimating using sodar data and comparison with the results of other technical tools of diagnostics. Further work will be the search of the parameterization functions and their analysis.

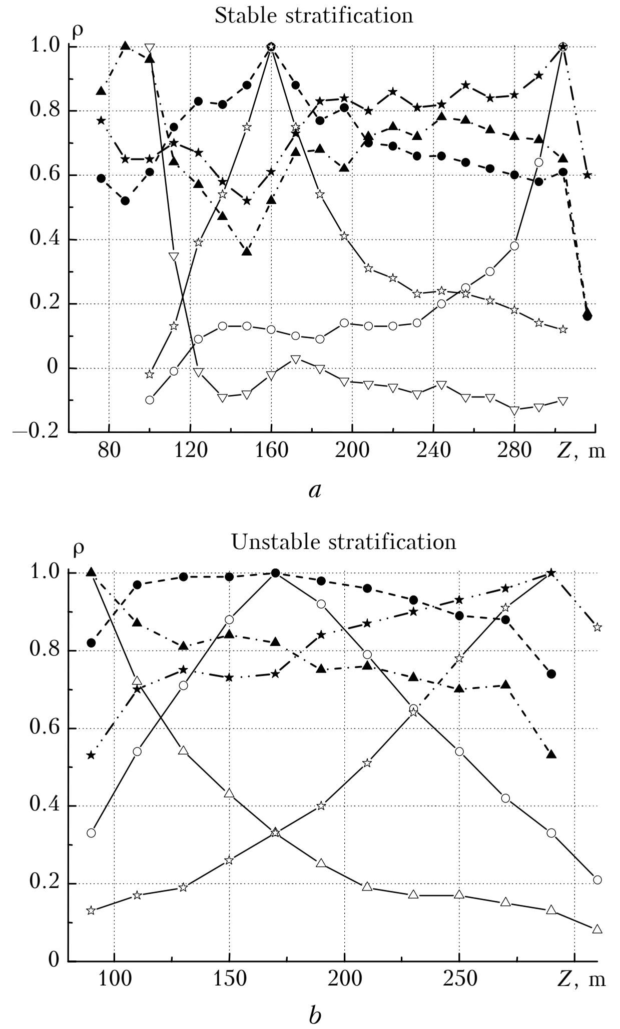

Fig. 7. Correlation functions constructed using the averaged over 10 minutes (dotted lines with symbols) and instantaneous data (solid lines with symbols) on wind velocity under different geophysical conditions. Total interval of estimation is 180 minutes.

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References

1. Z.I. Volkovitskaya and V.N. Ivanov, Meteorol. Gidrol. No. 2, 25–31 (1972).
2. N.L. Byzova, V.N. Ivanov and E.K. Garger, *Turbulence in the Boundary Layer of the Atmosphere* (Gidrometeoizdat, Leningrad, 1989), 264 pp.
3. V.A. Gladkikh, A.E. Makienko, and V.A. Fedorov. Atmos. Oceanic Optics. **12**, No. 5, 422–429 (1999).
4. V.A. Fedorov. Atmos. Oceanic Opt. **16**, No. 2, 141–144 (2003).
5. V.A. Fedorov, Atmos. Oceanic Opt. **12**, No. 10, 836–843 (2003).
6. Yu.M. Bagaev and L.T. Matveev, Meteorol. Gidrol. No. 1, 20–27 (1973).