Peculiarities in motion of the lower atmospheric layer at passage of the internal gravity waves

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Based on sodar data, this paper exemplifies the complex structure of the turbulent field in the atmospheric boundary layer during passage of the internal gravity waves. The speeds of vertical and horizontal air motions are compared with height oscillations of thin layers characterized by enhanced turbulence coefficient.

Among the wide variety of turbulent fields recorded with acoustic meteorological radars (sodars), there are structures related to the short-period internal gravity waves (IGW) in a stably stratified atmospheric boundary layer (ABL). These are regular vertical motions of rather thin turbulent layers with the periods less than 10–15 min. Manifestation of IGW in the form of oscillation of thermal turbulence layers are caused by random temperature pulsations generated in the zones of increased shear stresses at sharp changes in the motion speed and direction profiles. For example, in Ref. 1 it is stated that significant medium turbulence can arise on crests of internal waves generated because of Kelvin–Helmholtz hydrodynamic instability in the flow of a stratified fluid with the velocity shift. Such layers can be reliably detected and recorded in remote acoustic sensing. However, in spite of vast experimental material published on acoustic sounding of ABL, only some of them include the corresponding episodes.

References 2–4 were among the first papers, in which such episodes were described and analyzed. Later, some more publications on acoustic sensing presented examples of IGW with short periods. Some of them also compared measurements of different meteorological parameters with standard devices and sodar facsimile records. Thus, Refs. 5 and 6 published the results obtained at Boulder Atmospheric Observatory (BAO) demonstrating the wavy structure of some thin layers with the enhanced sound scattering coefficient. These layers oscillate almost in phase. The amplitude of oscillations is from few tens to hundreds of meters. Comparison of oscillations of the ABL turbulent layers measured with a sodar with the results of meteorological measurements at BAO tower showed quite close agreement in estimates of the length, period, and phase of the internal waves. Based on these results, we can state that the use of sodars for diagnostics of short-period IGW considerably enriches our knowledge on the structure of turbulent zones. This is connected, in particular, with the possibility of recording in detail the process with the altitude step of several meters. Such a step can hardly be obtained on meteorological towers, because they usually have only 10–15 measurement levels at the maximum tower height up to 300 m. The limited tower height also restricts the possibility of studying the structure of internal waves in the ABL. It follows, for example, from Ref. 2 and 4, where it was shown that oscillations in the boundary layer developed at the altitudes higher than 400 m.

The capabilities of a sodar to measure different components of the medium velocity vector, as well as estimating the intensity of temperature pulsations allow it to be considered as an important instrument when studying the microstructure of internal waves in the atmospheric boundary layer. Only few papers with the information on simultaneously acquiring such data can be found in the literature. Therefore, even individual experiments on the combined recording of such data can be very useful for a detailed study of the processes of generation, propagation, and destruction of the gravity waves. The importance of this problem is emphasized, for example, in Ref. 7. Attracting attention to the problem of separation of the wavy and turbulent motions of a medium, Byzova, Ivanov, and Garger[7] have mentioned that its solution for short-period internal waves is an extremely difficult task.

Orienting at solution of the problem formulated above, this paper presents some episodes including short-period IGW recorded with a Volna-3 three-channel Doppler sodar of the Institute of Atmospheric Optics SB RAS. Observations were conducted at two sites: Tomsk suburb and southwestern shore of Lake Baikal. Description of the sodar and the techniques for measuring wind velocity components can be found in Ref. 8. The technique of absolute sodar calibration and the procedure of restoration of the structure characteristic of temperature pulsations C_T^2 are presented in Refs. 9 and 10.

Consider first the episode with a short-period gravity waves recorded on May 23, 2001 in Tomsk suburb. Figure 1*a* depicts the facsimile record of the amplitude of the signal received in the vertical sensing channel at the sounding pulse duration τ = 150 ms. The sodar was located at the height of 12 m above the ground. At this level a weak wind up to 2 m/s was observed. The air temperature increased during the episode from 12 to 18°C, and the relative humidity decreased from 55 to 45%. Clouds of *Ac* type with the cloud amount of 7–9 tenth were observed.

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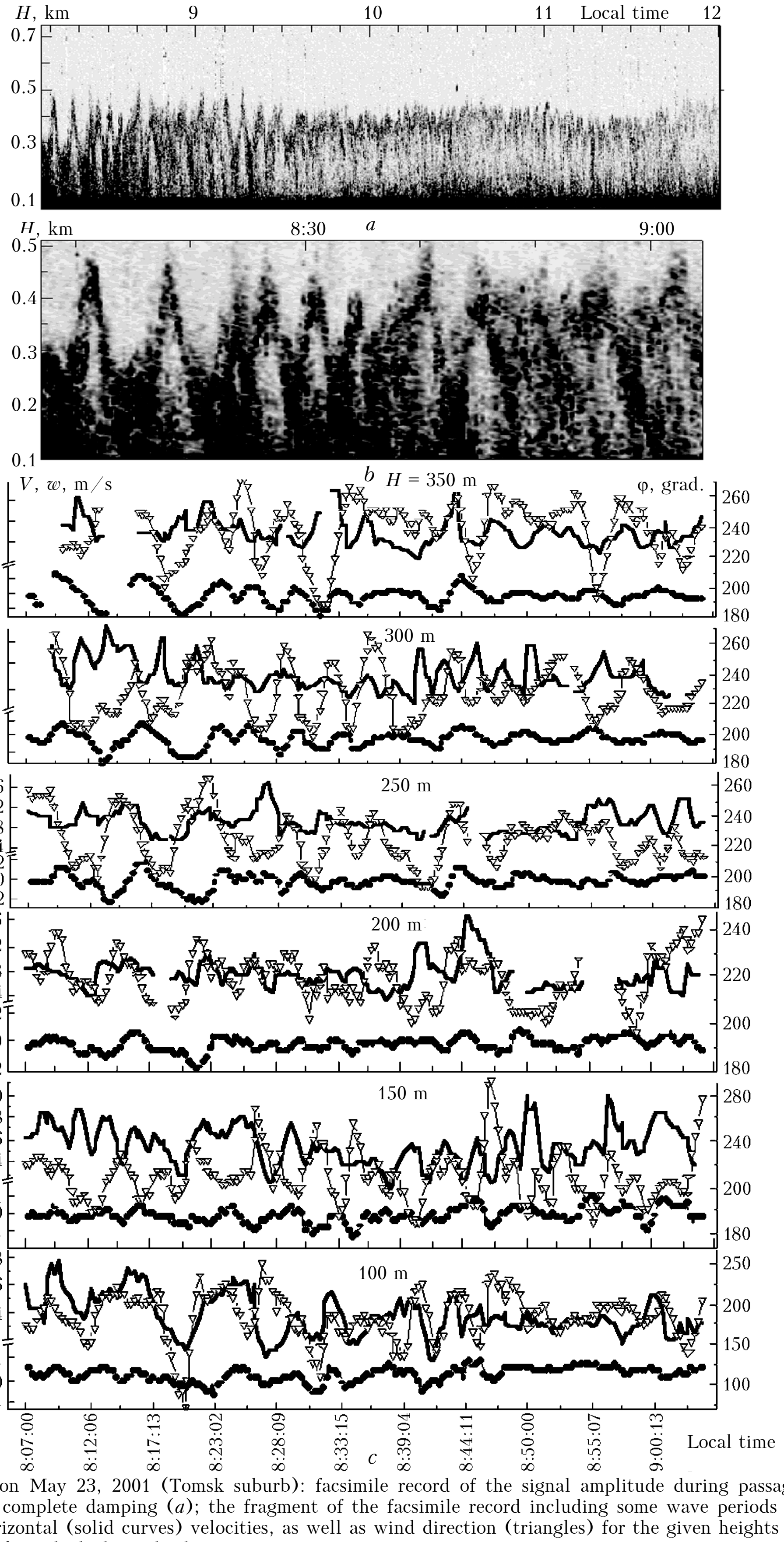

Fig. 1. Measurements on May 23, 2001 (Tomsk suburb): facsimile record of the signal amplitude during passage of an internal gravity wave until its complete damping (*a*); the fragment of the facsimile record including some wave periods (*b*); scans of the vertical (dots) and horizontal (solid curves) velocities, as well as wind direction (triangles) for the given heights (*c*). The velocity scales include breaks, after which the scale changes.

At the beginning of the episode, the sodar recorded vertical motions of a thin scattering layer with the amplitude up to 350–400 m. The period of oscillations was 6–6.5 min. The wave gradually damped with time, and the boundary layer transferred into the mode of weak convection with the thermic height up to 400–450 m. It should be noted that in the period from 8:25 to 9:00 strict periodicity of IGW was distorted. Then the periodicity restored, but the IGW period became shorter – about 5.5–6 min.

This structure of the turbulent field at this observation site was recorded only once. The database incorporating several thousands of observation hours includes no other episodes with such a manifestation of the internal waves. In the majority of cases, they had far longer periods and much smaller oscillation amplitude.

Dynamic processes in the ABL in the presence of an internal wave are considered using, as an example, the fragment shown in Fig. 1*b*, which is the initial stage of the episode shown in Fig. 1*a*. The height-time distribution of the structure characteristic C_T^2, in $K^2 \cdot m^{-2/3}$, for this fragment is given in sufficient detail in Ref. 11. Here it should only be noted that the values of C_T^2 in the oscillating turbulent layer were from 10^{-3} to $5 \cdot 10^{-3}$ $K^2 \cdot m^{-2/3}$. Under this layer, C_T^2 mostly varied from 10^{-4} to $5 \cdot 10^{-4}$ $K^2 \cdot m^{-2/3}$ and by the end of the episode – from 10^{-5} to $5 \cdot 10^{-4}$ $K^2 \cdot m^{-2/3}$. It should be noted that, strictly speaking, the turbulent mode does not satisfy, in this situation, the assumption on homogeneity and isotropy of the temperature field. Therefore, the structure characteristic C_T^2 obtained from sodar measurements can serve only as a very rough approximation in estimates of the intensity of temperature inhomogeneities.

The structure of air motions over the observation site can be retrieved from Fig. 1*c*, which depicts the horizontal and vertical wind velocity components, as well as wind direction. The sodar resolution in measurement of these parameters was 15 m, but Fig. 1*c* shows only time scans with the height step of 50 m. The velocity scale is shown with a break for a reader to easier follow up the vertical component in a more detail.

Analysis of the results shows rather high degree of coherence of the vertical velocity component w and the wind direction φ, especially at the heights $H \geq 200$ m. In the considered episode, the sign of vertical velocity inside the turbulent layer coincides, in general, with the common pattern of its oscillations: $w > 0$ for ascending layer and $w < 0$ for the descending one. The amplitude of w oscillations increases with the increasing height. In addition, it is worth noting significant, up to 60–70°, periodic variations of the wind direction at IGW passage. The horizontal velocity component V has far lower coherence with respect to oscillations connected with the internal wave. However, in the lower atmospheric layer, the synchronism of variation of the wind speed and direction is high, although the correlation with oscillations of the turbulent layer is much lower.

Note the vertical shift of the mean horizontal wind up to 10 m/s at the height change of about 400 m, as well as its significant, with the amplitude of 8–10 m/s, oscillation under the effect of IGW. The turn of the mean flow direction to the right, under the effect of Coriolis force, also holds.

The above results again attract attention to the problem of critical conditions for aircraft takeoff and landing under conditions of such IGW, especially, because the standard ground-based measuring systems are incapable of estimating wind velocity and direction oscillations at the altitudes of decision making for pilots.

Some more episodes with fast oscillations of thermal turbulence layers were obtained during sodar operation on the shore of Lake Baikal (51°54′N, 105°03′E) in summer of 2001. A detailed description of the measurement site and conditions is given in Ref. 2.

The first episode was recorded on July 7 of 2001. The temperature of the surface air decreased slowly from 11 to 9°C in the period from 10:00 to 16:00, and then increased up to 16°C by 20:00. The relative air humidity was 98–100%. The temperature of the near-surface water was about 7°C. In the period from 12:00 to 20:00 the atmospheric pressure quickly increased from 704 to 708 mm Hg. Overcast conditions were observed during the whole episode.

The sodar operating at the sounding pulse duration $\tau = 150$ ms detected temperature turbulence in the layer, whose height-time characteristics resembles an isolated long-period wave. In the final stage, vertical oscillations have developed in this layer likely connected with an IGW. Figure 2*a* depicts the facsimile record of the whole episode of appearance and destruction of the elevated layer of temperature turbulence.

The fragment of the facsimile record including the internal wave is shown in Fig. 2*b*. The period of oscillations of the elevated layer at the beginning of the fragment was equal roughly to 3.5–4 min, and the amplitude achieved 250–300 m. By the end of the episode, the amplitude was 170–200 m with the period of oscillations of about 3 min.

Since the sodar was not verified for signal amplitude characteristics at this observation site, the quantitative data on the structure characteristic C_T^2 are only approximate. We can assume that its value did not exceed 10^{-4} $K^2 \cdot m^{-2/3}$ in the fragment shown in Fig. 2*b*.

The mean horizontal wind at the heights under consideration in the period from 17:00 to 18:00 had relatively low values up to 4–5 m/s and no pronounced periodicity connected with the IGW. The general direction was from the land to water. Periodic oscillations of the horizontal wind direction were also weakly pronounced. To the highest degree, the internal wave manifested itself in the vertical wind component. The distribution of w is shown in Fig. 2*c*. Unlike the case illustrated in Fig. 1, in the considered episode we can see a significant phase shift between the sign of the vertical speed and the direction of the visible layer motion. The same regularity took place for the lower thin layer oscillating in the height range of 100–170 m. This phase shift held by the end of the episode. Such

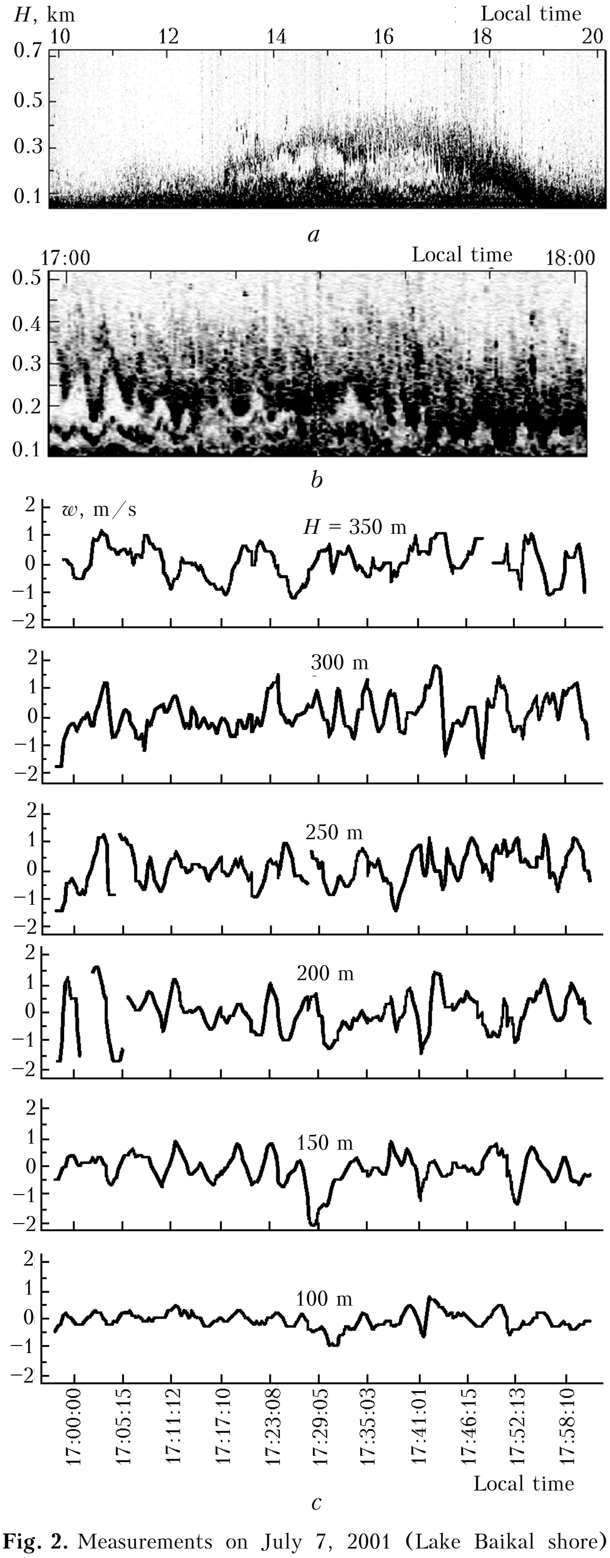

Fig. 2. Measurements on July 7, 2001 (Lake Baikal shore): facsimile record of the signal amplitude during the whole episode of appearance and damping of the internal gravity wave (*a*); fragment of the facsimile record including some wave periods (*b*); scans of the vertical wind velocity component for the given heights (*c*).

phase shifts between the oscillations of different atmospheric parameters in the presence of an IGW were analyzed in detail, for example, in Refs. 5 and 7. Significant misphasing of the layer oscillations recorded by the sodar with the data of microbarographs was noticed in Ref. 13.

It should be also noted that the spectrum of oscillations of the vertical flow component shown in Fig. 2*c* have more harmonics as compared with the visible oscillation of the turbulent layer. This is likely due to the effect of the local orography on the flow, because the height of mountains surrounding the observation site was 200–250 m.

Turbulent fields generated by the IGWs are good indicators of possible nonlinear processes at IGW propagation. In particular, sodar records often detect frequency tuning as the situation evolves. This can be seen, for example, from Fig. 2*b* at the end of the episode. Possibly, nonlinearity of internal waves shows itself as generation of turbulent layers oscillating almost in antiphase. Sodar records of such phenomena are rather rare in the literature. As an example, we can refer to Ref. 4, which presents a facsimile record with the pronounced antiphase oscillation of two very thin layers. The common amplitude of the oscillations achieved 250–300 m with the period of several minutes.

We observed similar turbulent structures on the Lake Baikal shore in 2001. Thus, Fig. 3*a* depicts the facsimile record obtained on July 12 of 2001 in the vertical sensing channel. This record demonstrates close-to-antiphase oscillation of two thin layers by the end of the episode. The sodar operated at $\tau = 150$ ms. The temperature of air was about 12°C, the relative air humidity was 98%, and the temperature of the surface water was about 8°C. Light clouds were observed in the considered period.

Figure 3*b* shows several periods of antiphase oscillations of the turbulent layers in a more detail. The estimated values of C_T^2 in them are roughly from $5 \cdot 10^{-5}$ to 10^{-4} $K^2 \cdot m^{-2/3}$. Attention should be paid to the genesis of this structure. First, there were two independent turbulence areas: near-surface and an elevated one (see Fig. 3*a*), and mean wind directions in them differed markedly: in the lower layer it was about 220° at the speed of 2–4 m/s, and 90° and 4–7 m/s in the upper one, respectively. In the upper layer, in the beginning of the episode, we can see high-frequency small-amplitude oscillations. Then the oscillation amplitude increased, and the lower layer becomes involved in the oscillation process. Roughly at 16:40 the lower layer took off the surface and oscillated almost in antiphase with the upper layer. Unfortunately, at 16:47 a wreck happened in one of the slant sensing channels, and after that we failed to restore the horizontal wind velocity and the wind direction.

The vertical component of the medium velocity measured by the sodar for some heights is shown in Fig. 3*c*. The time interval of this figure corresponds to the fragment shown in Fig. 3*b*. As well as in the episode considered above (see Fig. 2), a phase shift exists between the sign of the vertical velocity and the visible displacement of turbulent layers. However, it should be noted here that there is a possible uncertainty in estimates of the radial – along the axes of antennas direction patterns – flow components. (The vertical component is measured directly by one of the three sodar's antennas.)

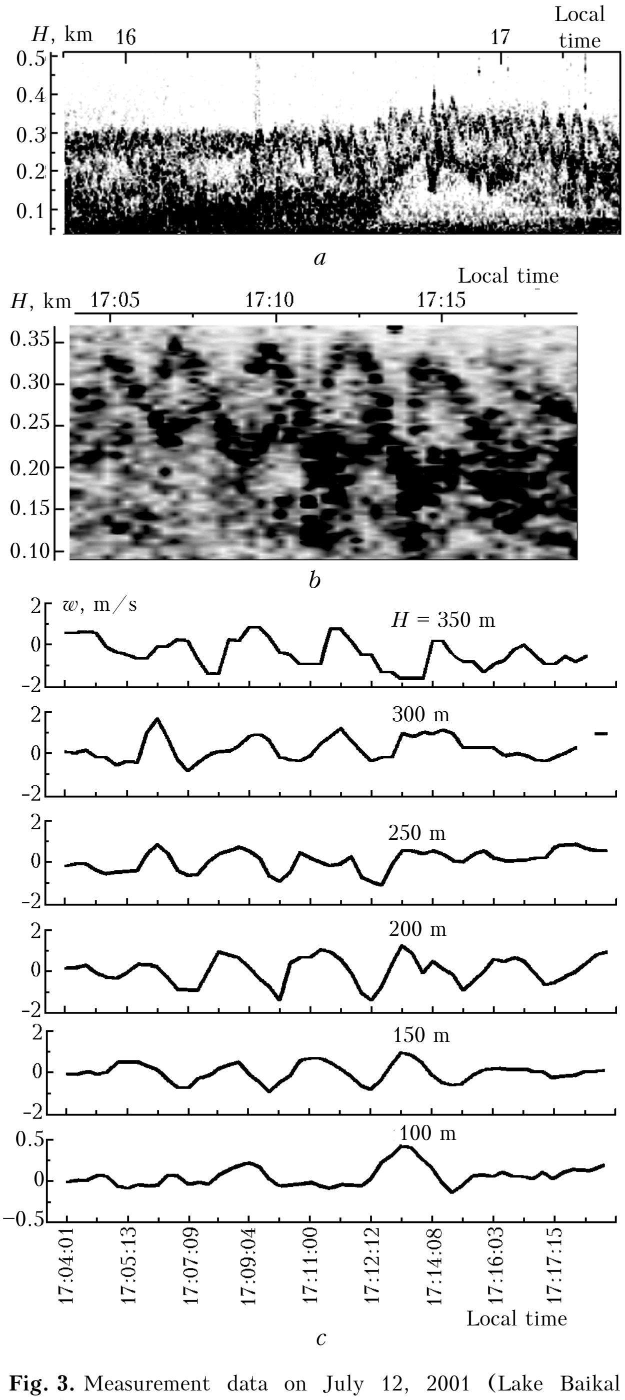

Fig. 3. Measurement data on July 12, 2001 (Lake Baikal shore): facsimile record of the signal amplitude at appearance of antiphase oscillation of layers of temperature turbulence at passage of the internal gravitational wave (*a*); fragment of the facsimile record including several oscillation periods (*b*); scans of the vertical wind velocity component for the given heights (*c*).

According to the technique realized in Volna-3 sodars, the instantaneous velocity is estimated from the maximum in the spectrum of the recorded signal.[8] The characteristic atmospheric volume at the distance H, which forms the signal received at a fixed time, is determined by the longitudinal $L = c\tau/2 \approx 25$ m ($c = 330$ m/s, $\tau = 150$ ms) and cross $l = 2H \tan\Omega \approx 0.14H$ (halfwidth of the direction pattern $\Omega \approx 4°$ (Ref. 9)) dimensions. If we also take into account the need in using a finite sample of N readings for calculating the spectrum, then the longitudinal dimension additionally increases by ΔL. In our case $\Delta L \approx 13$ m. Consequently, the longitudinal dimension of the area forming the signal spectrum will be 35–40 m. Since in the considered case we have complex combinations of motions in limited volumes, it is acceptable to assume the multimode character of spectra and domination of some or other mode can have a random character. Therefore, estimates of the velocity become ambiguous.

The actual shape of the antennas' directional patterns may be an important factor affecting the spectrum of signals under conditions of a complicated structure of the turbulent field. This is caused by the fact that atmospheric areas characterized by higher scattering coefficient and different motion directions as compared with the areas lying along the pattern axes can fall within the field of view of side lobes of the directional patterns (or the periphery of the main lobe). Consequently, the spectrum of the signal can have the main maximum corresponding to the side lobe, rather than the main one. This problem calls for a close study and design, based on it, of correct analytical and engineering solutions.

References

1. N.P. Shakina, *Hydrodynamic Instability in the Atmosphere* (Gidrometeoizdat, Leningrad, 1990), 310 pp.
2. D.W. Beran, W.H. Hooke, and S.F. Clifford, Boundary-Layer Meteorol. **4**, 133–153 (1973).
3. H. Ottersten, K.R. Hardy, and C.G. Little, Boundary-Layer Meteorol. **4**, 48–89 (1973).
4. F.F. Hall, in: *Stat. Meth. and Instru. in Geophys* (Teknologisk Forlag, Oslo, 1971), pp. 167–180.
5. F.F. Finnigan, J. Atmos. Sci. **45**, No. 3, 486–505 (1988).
6. F. Einaudi and J.J. Finnigan, J. Atmos. Sci. **50**, No. 13, 1841–1864 (1993).
7. N.L. Byzova, V.N. Ivanov, and E.K. Garger, *Turbulence in the Atmospheric Boundary Layer* (Gidrometeoizdat, Leningrad, 1989), 264 pp.
8. V.A. Gladkikh, A.E. Makienko, and V.A. Fedorov, Atmos. Oceanic Opt. **12**, No. 5, 422–429 (1999).
9. V.A. Gladkikh and S.L. Odintsov, Atmos. Oceanic Opt. **14**, No. 12, 1050–1053 (2001).
10. I.V. Nevzorova, S.L. Odintsov, and V.A. Fedorov, in: *Proc. of 10th Int. Symp. Acoust. Rem. Sens.* (Auckland, 2000), pp. 312–315.
11. S.L. Odintsov, in: *Proc. of 11th Int. Symp. Acoust. Rem. Sens.* (Rome, 2002), pp. 271–274.
12. S.L. Odintsov, V.A. Gladkikh, and I.V. Nevzorova, in: *Proc. of 11th Int. Symp. Acoust. Rem. Sens.* (Rome, 2002), pp. 393–396.
13. P.S. Anderson, in: *Proc. of 8th Int. Symp. Acoust. Rem. Sens.* (Moscow, 1996), pp. 7.7–7.11.