Estimates of turbulence parameters from measurements of wind velocity with a pulsed coherent Doppler lidar

V.A. Banakh, A.V. Falits, I.N. Smalikho, and S. Rahm*

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk, Russia
**Institute for Atmospheric Physics, Oberpfaffenhofen, Germany*

Received October 12, 2005

We discuss some results on the parameters of turbulent wind field in the atmospheric boundary layer retrieved from wind velocity measurements with a coherent pulse Doppler lidar. The data obtained demonstrate a possibility of studying the atmospheric turbulence with the use of commercial coherent Doppler lidar systems.

Numerous papers can now be found in the literature that analyze the possibilities of estimating the turbulence parameters from wind velocity measured with coherent Doppler lidars. The methods and specific features of the techniques of turbulence parameters retrieval from wind velocity measurements with both CW and pulsed Doppler lidar systems have been thoroughly considered. The results of these investigations can be found among the cited papers (e.g., Ref. 1).

Note that to achieve this goal, in the planetary boundary layer coherent Doppler CW-laser-based lidars can successfully be used. Thus in Ref. 2, one can find examples of retrieval of the altitude profiles of the turbulence kinetic energy dissipation rate from the estimates of wind velocity acquired with a lidar using a CW CO_2 laser.

In Refs. 3 to 6 a possibility is discussed of retrieving parameters of the wind turbulence from the wind velocity estimated using data acquired with a coherent pulsed lidar. In particular, the method of a parametric fitting has been developed for determining the dissipation rate of the kinetic energy of turbulence from the spatial structure function of wind velocity.[6] In this paper, we present some results of retrieval of the dissipation rate of the turbulence kinetic energy and other turbulence parameters from wind velocity measurements using a pulsed Doppler lidar operated at 2-μm wavelength.

The experimental data that we used for retrieval of the dissipation rate of turbulent energy are obtained with a 2 μm pulsed lidar developed at *Coherent Technologies, Inc.* (CTI, Louisville, CO 80027 USA, Ref. 7). The measurements were carried out in May and June 2002 near Toulouse, France. The lidar was operated at a pulse repetition rate of 500 Hz, the total pulse length was 400 ns, while being about 120 ns at the e^{-1} level. Examples of the sounding pulse and the pulsed signal scattered by aerosol are shown in Fig. 1.

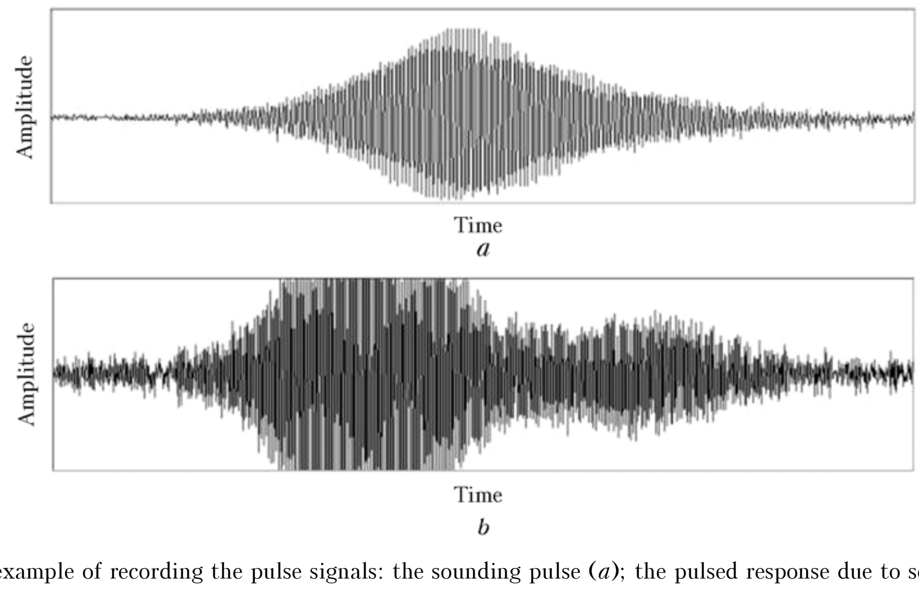

Fig. 1. An example of recording the pulse signals: the sounding pulse (*a*); the pulsed response due to scattering (*b*).

As is clear from the calculations (Ref. 5), such characteristics of the sensing pulse allow us to estimate the radial (along the sensing beam) component of wind velocity $\hat{V}_D(R)$ averaged over the volume sounded, the latter being 51 m long at the level of e^{-1}, at the distances R_i, $i = n, n + 1, ...$ (where n is an integer) spaced by 0.3 m from each other. Near the lidar, there is a 500-m long blind zone.

Geometry of measurements and an example of a 2-D pattern of the wind velocity estimates obtained with a Doppler lidar are shown in Fig. 2. Scanning was performed in a vertical plane within the elevation angles φ from zero to 30° at a scanning rate of 2° per second, so that the time of a single scan was approximately 15 seconds.

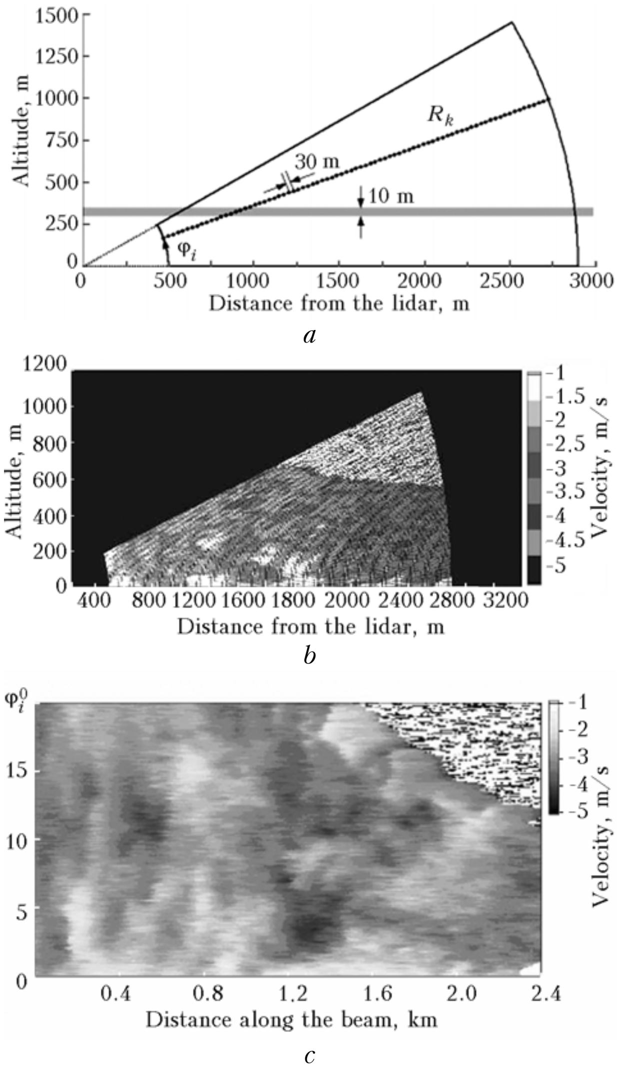

Fig. 2. Schematic presentation of the experiment and examples of 2-D patterns of the wind velocity estimates obtained with lidar.

Normally, 25 laser shots were needed for estimating a single velocity value, so in the experiment, we estimated wind velocity at a rate of 20 Hz with the spatial resolution R_k of 30 m. Figure 2*c* shows an example of a 2-D distribution of the wind velocity estimates along the direction of sounding in the vertical plane for a scanning time of 10 s, obtained at averaging over 25 laser shots. In the upper right corner of the figure one can see the cloud boundary.

Three methods are known for determining the dissipation rate of turbulent energy ε from wind velocity measured with a coherent Doppler lidar:

a) from the width of the Doppler spectrum (Refs. 2 and 8):

$$\hat{\varepsilon} = \frac{1}{\Delta z}\left[\frac{<\sigma_{ft}^2>_E}{(2/\lambda)^2 0.247 C_{\mathrm{K}}}\right]^{3/2}, \tag{1}$$

where $<\sigma_{ft}^2>_E$ is the ensemble and time average of the turbulent broadening of the Doppler spectrum, Δz is the length of the sounding volume, λ is the wavelength of laser radiation, $C_{\mathrm{K}} \approx 2$ is the Kolmogorov constant.

b) from the difference between the spatial structure functions of the wind velocity measured with lidar (Ref. 5)

$$\hat{\varepsilon} = \left[\frac{\hat{D}_{\hat{V}_D}(r_2) - \hat{D}_{\hat{V}_D}(r_1)}{C_{\mathrm{K}}\left(r_2^{2/3} - r_1^{2/3}\right)}\right]^{3/2}, \tag{2}$$

where

$$\hat{D}_{\hat{V}_D}(r_i) = <[\hat{V}_D(R_k + r_i) - \hat{V}_D(R_k)]^2>_E$$

is the experimental estimate of the structure function of wind velocity; $i = 1,2$; r_1 and r_2 are the spacing between the points of velocity measurements, $r_2 > r_1$.

c) from spatial structure functions of wind velocity measured with lidar, which are fitted to the functions simulated with the account of experimental conditions at different values of the outer scale of turbulence by means of minimizing the functional

$$\sum_i \left[\overline{\hat{D}_a(r)} - \overline{D_a(L_{V_i}, r)}\right]^2, \tag{3}$$

where

$$\overline{\hat{D}_a(r)} = \hat{D}_{\hat{V}_D}(r) / \hat{D}_{\hat{V}_D}(r_{\max})$$

is the normalized estimate of the spatial structure function obtained from the experimental data;

$$\overline{D_a(L_{V_i}, r)} = D_{V_D}(L_{V_i}, r) / D_{V_D}(L_{V_i} = \infty, r)$$

is the spatial structure function of wind velocity in a turbulent atmosphere simulated at different values of the outer scale of turbulence L_{V_i}.

Applicability of method (b) is restricted by the distance between the points r_i of wind velocity measurements, which does not exceed the outer scale of turbulence; method (a), as is shown in Ref. 9, also needs to be corrected with respect to the outer scale of turbulence. So, we used method (c) to determine ε from lidar data to retrieve the altitude profile of the kinetic energy dissipation rate, which is free of these restrictions. Adjustment of the parameters of the measured wind velocity structure functions to the simulated ones at different outer scales of turbulence by Eq. (3) allows us to determine the outer scale at the altitudes, where we estimate the structure function. An example of the family of simulated normalized spatial structure functions is shown in Fig. 3.

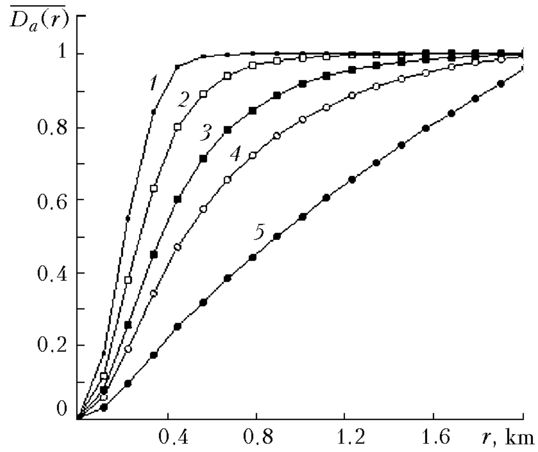

Fig. 3. Calculated normalized spatial structure functions: L_V = 50 (*1*); 150 (*2*); 300 (*3*); 500 (*4*); 1000 (*5*).

The following formula is known from the theory of turbulence

$$\varepsilon = \frac{1.887}{C_K^{3/2}} \frac{\sigma_V^3}{L_V}, \tag{4}$$

that relates the dissipation rate of turbulent kinetic energy ε to the outer scale L_V, and to the variance of the wind velocity fluctuations σ_V^2. When the outer scale of the wind velocity fluctuations has been estimated, we can find the normalization coefficient and thus obtain the estimate of the variance of the wind velocity fluctuations σ_V^2 (Ref. 6). Then, using Eq. (4), we can estimate the dissipation rate of the kinetic energy.

To determine the altitude profiles of the turbulence parameters, we have divided the lidar scanning sector into 10-m thick layers. All the estimates of the structure function for the distributions that vertically fall within the chosen layer refer to this thickness. Thus, for each layer, there is a structure function, and it determines the outer scale, the variance, and the rate of the turbulence kinetic energy dissipation. The division into layers of the scanning sector allows us to build up the altitude profiles of the turbulence parameters.

Figure 4 presents the altitude profiles of the outer scale, of the variance of wind velocity fluctuations, and the dissipation rate of kinetic energy found from averaging over all realizations of these profiles retrieved using the above technique from the array of lidar data received from 14:52 to 16:40 LT on May 30, 2002. Regardless that the experimental data on wind velocity lidar were obtained up to an altitude of 2.5 km because of the scanning geometry, statistically provided profiles of turbulence parameters can be retrieved only up to the altitude of 500 m.

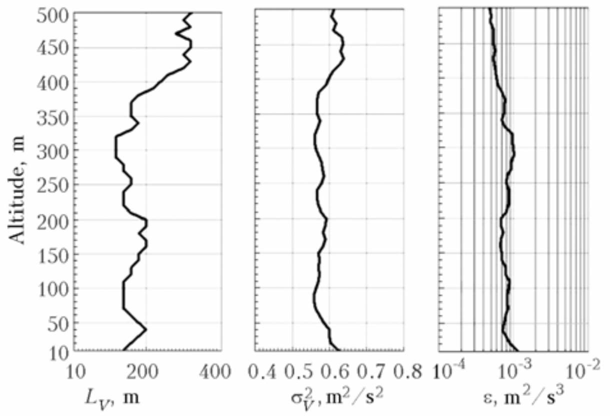

Fig. 4. Altitude profiles of the outer scale of turbulence L_V, variance of the wind velocity fluctuations σ_V^2, and dissipation rate of turbulent energy ε.

The profiles obtained do not contradict the behavior of the atmospheric turbulence parameters in the planetary boundary layer and illustrate the capabilities of modern coherent lidars in the studies of atmospheric turbulence.

Acknowledgments

The work was partly supported by the Russian Foundation for Basic Research, grant No. 03–05–64194.

References

1. V.A. Banakh and Ch. Werner, Opt. Engin. **4**, No. 7, 071205-1–071205-19 (2005).
2. V.A. Banakh, F. Köpp, Ch. Werner, and I.N. Smalikho, J. Atmos. Ocean. Technol. **16**, No. 8, 1044–1061 (1999).
3. R. Frehlich, S. Hannon, and S. Henderson, Bound.-Layer Meteorol. **86**, 233–256 (1998).
4. R.G. Frehlich and L. Cornman, J. Atmos. Ocean. Technol. **19**, 355–366 (2002).
5. V.A. Banakh and I.N. Smalikho, Atmos. Oceanic Opt. **10**, No. 12, 957–965 (1997).
6. V.A. Banakh and A.V. Falits, Atmos. Oceanic Opt. **17**, No. 4, 260–267 (2004).
7. S.M. Hannon, P. Gatt, S.W. Henderson, and R.M. Huffaker, in: *Proc. 12th Coherent Laser Radar Conf.* (Bar Harbor Maine, US), 2003, pp. 86–89.
8. R.L. Doviak and D.C. Zrnic, *Doppler Radar and Weather Observations* (Academic Press, 1993), 562 pp.
9. I. Smalikho, F. Köpp, and S. Rahm, J. Atmos. Ocean. Technol. **22**, No. 11, 1733–1748 (2005).