Fluctuation spectra of nonuniform atmospheric wind field measured with spatial averaging

V.A. Banakh and A.V. Falits

Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk

Received May 8, 2003

Some examples of simulations of the turbulent wind fields and their spectra reconstructed with different spatial resolution are presented. The effect of wind shear (wind field inhomogeneity) on the spatial spectrum of wind fluctuations is illustrated. Comparison with the experimental spectra obtained from radar data is presented.

It is known that, unlike the measurements with point sensors, lidar and radar wind measurements are conducted over some spatial volume, and in this case one inevitably needs to take into account averaging over the scattering volume, which depends on both the medium parameters and the parameters of a lidar or radar system. When synthetic aperture radars are used for wind measurements by use of a signal due to scattering from sea surface, it is also important to take spatial averaging into account, because the radar signal is formed due to scattering from a finite-size area of the sea surface. In this paper, we present some examples of simulation of turbulent wind fields and their spectra reconstructed with different spatial resolution. The effect of the wind shear (wind field inhomogeneity) on the spatial spectrum of wind fluctuations is illustrated.

Assume that wind velocity fluctuations in the atmosphere $\tilde{V} = V - \langle \tilde{V} \rangle$ are isotropic and the spatial spectrum of turbulent inhomogeneities is described by Karman model.[1] According to this model, one-dimensional spatial spectra $S_u(z, \kappa_z)$ and $S_u(z, \kappa_x)$ of the radial and tangential components of wind velocity and two-dimensional spatial spectrum $S_u(z, \kappa_z, \kappa_x)$ can be written as

$$S_u(z, \kappa_z) = \frac{2\sigma_u^2(z)\, L_u(z)}{[1 + (8.43 L_u(z)\kappa_z)^2]^{5/6}}, \tag{1}$$

$$S_u(z, \kappa_x) = \frac{\sigma_u^2(z)\, L_u(z)}{\{1 + [8.43 L_u(z)\kappa_x]^2\}^{5/6}} \times \left[1 + \frac{5}{3}\frac{[8.43 L_u(z)\kappa_x]^2}{1 + [8.43 L_u(z)\kappa_x]^2}\right], \tag{2}$$

$$S_u(z, \kappa_z, \kappa_x) = \frac{1}{6\pi}\frac{\sigma_u^2(z)\,[8.43 L_u(z)]^2}{[1 + [8.43 L_u(z)]^2(\kappa_z^2 + \kappa_x^2)]^{4/3}} \times \left[1 + \frac{8}{3}\frac{[8.43 L_u(z)\,\kappa_x]^2}{1 + [8.43 L_u(z)]^2(\kappa_z^2 + \kappa_x^2)}\right]. \tag{3}$$

In Eqs. (1)–(3) $\sigma_u^2(z)$ and $L_u(z)$ denote the variance of the wind speed fluctuations and the integral correlation scale of the radial wind velocity component. The scale L_u is related to the outer scale of turbulence L_0 as $L_0 = 1.35 L_u$ (Ref. 2). In the general case, the parameters σ_u^2 and L_u depend on height, so Eqs. (1)–(3) make it possible simulating statistically inhomogeneous wind fluctuations. Equation (1) was used to generate random realizations of the radial wind velocity by the spectral method when analyzing the operation of coherent Doppler wind lidars in the turbulent atmosphere.[3,4]

A 2D turbulent wind field simulated by Eq. (3) and depicted in Fig. 1 on different scales gives an idea of turbulent variations of the wind field in the atmosphere. The simulation has been performed using the parameters corresponding to the altitudes of the atmospheric surface (*a*) and boundary (*b*) layers. The 1D distributions were obtained by crossing the 2D distributions along mutually perpendicular dashed lines. It can be seen that wind velocity fluctuations at high altitudes have larger scale and include inhomogeneities of 0.5 km and larger. Minimum size of the inhomogeneities is about 10 to 20 m.

Figure 2 depicts the calculated spectra of 1D realizations of the wind velocity obtained from the simulated data shown in Fig. 1 with different spatial averaging. It follows from Figs. 2*a* and *b* that, as the averaging scale increases, the high frequency components of the spectrum are cut off, and the spectrum takes the features of a lower-frequency one. The product of the outer scale of turbulence by the variance of wind speed fluctuations determines the level of spectrum saturation in the low-frequency region. Spatial averaging changes the slope of the spectrum (power law, according to which the spectrum decreases in the high-frequency region). If at point measurements the spectrum obeys the –5/3 Kolmogorov–Obukhov power law (curve *1*), then in the case of averaging the spectrum decreases following the –8/3 law.[5,6] The issues of taking into account the effect of spatial averaging on statistics of the wind velocity measured with Doppler lidars have been considered quite thoroughly in many papers (see Refs. 2–6 and references therein).

0235-6880/03/08 649-03 $02.00

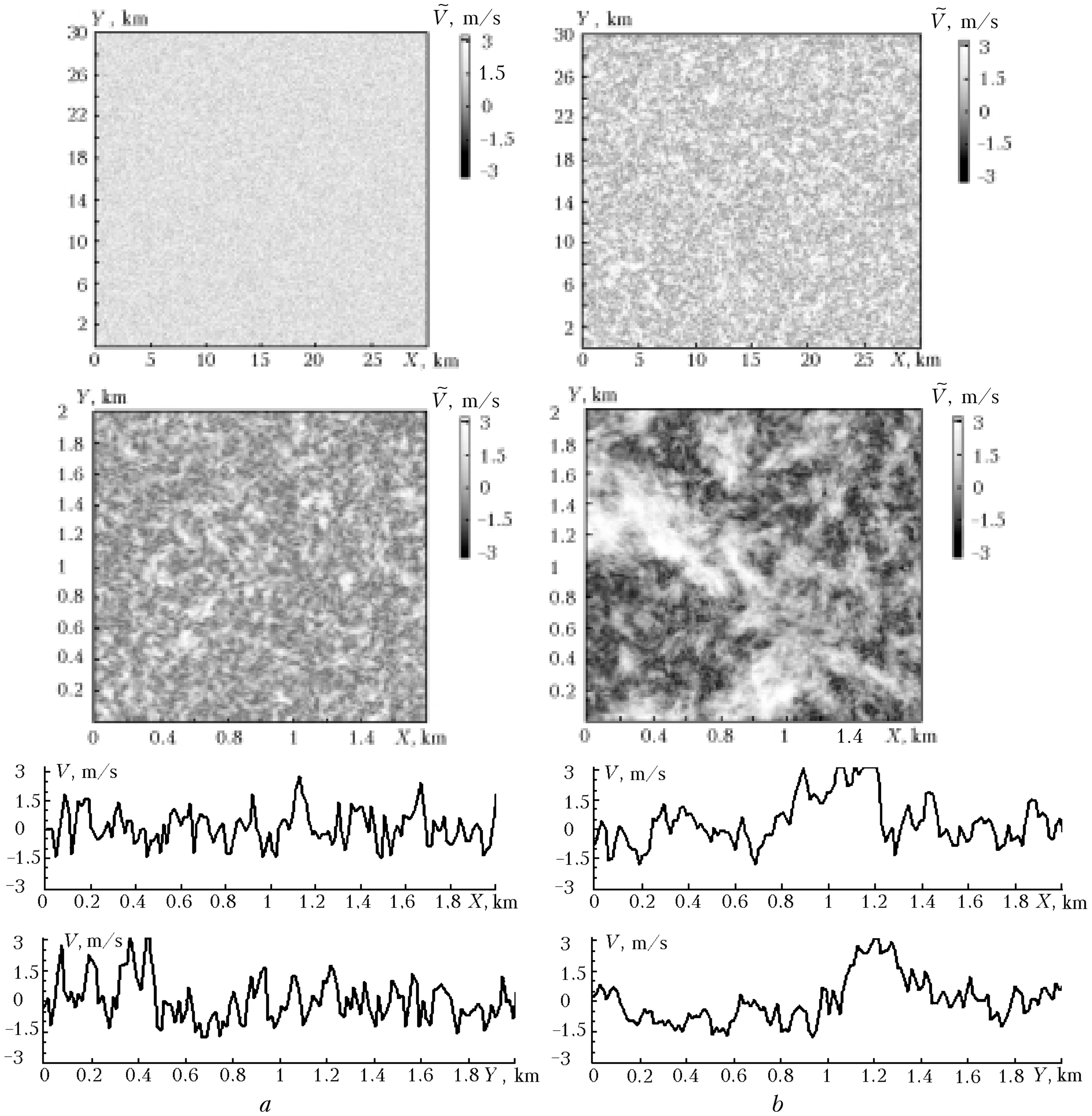

Fig. 1. 2D and 1D distributions of wind speed fluctuations: σ_u = 1 m/s, L_u = 40 m (*a*) and σ_u = 1.5 m/s, L_u = 300 m (*b*).

Wind shears also have a significant effect on the shape of the spectrum. Figures 2*c* and *d* depict the spectra with the same spatial resolution as in Figs. 2*a* and *b* but in the presence of wind shear. It can be seen that the wind shear leads to a significant shift of the spectrum saturation region toward lower frequencies, while the spectrum saturation level increases. Such a transformation of the spectrum that may occur under wind shear conditions should be taken into account when interpreting experimental data, if the spectral measurements are limited to the range of 2–3 orders of magnitude and it is impossible to go farther into the high-frequency region because of the noise. The neglect of the wind shear effect on the spectrum in the low-frequency region can lead to a false conclusion that wind velocity fluctuations in the range of large scales of about several kilometers obey the –5/3 Kolmogorov law, as was obtained in the spectral analysis of wind data retrieved from synthetic aperture radar measurements at ERS-2 (Ref. 7).

Actually, the slope of spectral curves in Figs. 2*c* and *d* in the range of 5–50 km scales and in the high-frequency region (curve *1*) is the same, but physical phenomena causing such a behavior of the spectrum are different.

Figure 3 depicts the wind speed spectra retrieved from radar data obtained from a signal due to scattering from sea surface[8] and wind velocity fluctuations simulated according to Eq. (1) with the spatial resolution determined by the spatial resolution of the measurements.[8] It was just the account of the wind shear observed in the measurements[8] that allowed us to achieve good agreement between the experimental and simulated spectra.

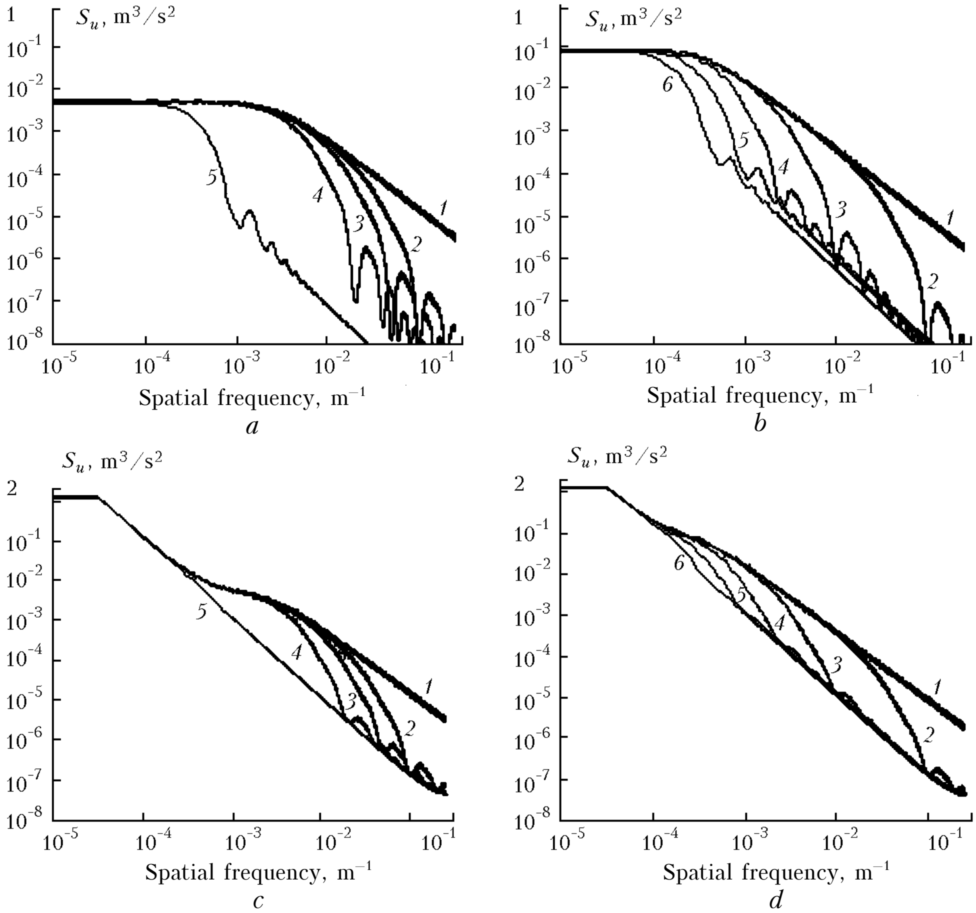

Fig. 2. Spectra of wind velocity fluctuations: zero mean wind (*a*, *b*); mean wind increases linearly from 0 to 5 m/s (*c*, *d*); without spatial averaging (*1*), averaging with the scales of 10, 20, 50, and 1000 m (*2–5*; *a*, *c*); averaging with the scales of 10, 100, 400, 1000, and 2000 m (*2–6*; *b*, *d*).

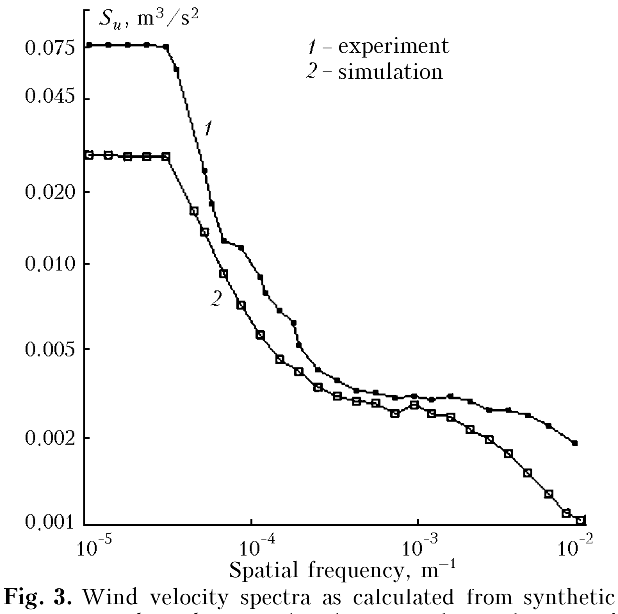

Fig. 3. Wind velocity spectra as calculated from synthetic aperture radar data with the spatial resolution of 12.5 × 12.5 m at the gradient of the mean velocity from 2 to 6 m/s (*1*) and calculated from the model data according to Eq. (3) at $\sigma_u = 0.8$ and $L_u = 30$ with the same averaging and wind shear as in the experiment (*2*).

Acknowledgments

The support from the Russian Foundation for Basic Research (Grant No. 03–05–64194) is acknowledged.

References

1. A.S. Monin and A.M. Yaglom, *Statistical Hydromechanics* (Nauka, Moscow, 1967), Part 2, 720 pp.
2. R. Frehlich and L. Carnman, J. Atmos. Oceanic Technol. **19**, No. 3, 355–366 (2002).
3. R. Frehlich, J. Atmos. Oceanic Technol. **14**, 54–75 (1997).
4. V.A. Banakh and I.N. Smalikho, Atmos. Oceanic Opt. **10**, No. 12, 957–965 (1997).
5. V.A. Banakh and I.N. Smalikho, Atmos. Oceanic Opt. **10**, Nos. 4–5, 295–302 (1997).
6. V.A. Banakh, I.N. Smalikho, F. Köpp, and Ch. Werner, J. Atmos. Oceanic Technol. **16**, 1044–1061 (1999).
7. S. Lehner, J. Horstmann, W. Koch, and W. Rosenthal, J. Geophys. Res. **104**, 7847–7856 (1998).
8. V. Banakh, Ch. Werner, J. Streicher, O. Reitebuch, E. Nagel, T. Schneiderhan, T. König, S. Lehner, A. Dabas, and P. Delville, in: *Proceedings 12th Coherent Laser Radar Conference* (Bar Harbor, Maine, 2003), pp. 191–194.