Sodars and their application for investigation of the turbulent structure of the lower atmosphere

N P Krasenko1,2, L G Shamaeva3,4
1Chief Scientific Worker, Institute of Monitoring of Climatic and Ecological Systems SB RAS, Tomsk, Russia
2Professor, Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russia
3Senior Research Scientist, V. E. Zuev Institute of Atmospheric Optics SB RAS, Tomsk, Russia
4Assistant Professor, National Research Tomsk State University, Tomsk, Russia

E-mail: krasenko@imces.ru, sima@iao.ru

Abstract. Possibilities of sodar application for investigation of the spatiotemporal dynamics of three components of wind velocity vector, longitudinal and transverse structural functions of wind velocity field, structural characteristics of temperature and wind velocity, turbulent kinetic energy dissipation rate, and outer scales of temperature and dynamic turbulence in the atmospheric boundary layer are analyzed. The original closed iterative algorithm of sodar data processing taking into account the classical and molecular absorption and the turbulent sound attenuation on the propagation path is used that allows the vertical profiles of the characteristics of temperature and wind velocity field to be reconstructed simultaneously and their interrelations to be investigated. It is demonstrated how the structure of temperature and wind turbulence is visualised in real time.

1. Introduction

Sodars or acoustic radars are widely used all over the world to investigate the structure and dynamics of the atmospheric boundary layer (ABL) [1–18]. The principle of their operation is based on the effect of sound scattering by small-scale turbulent inhomogeneities of the atmosphere. Doppler three-component monostatic sodars that employ the backscattered acoustic signal of audio frequencies are the simplest and most widespread means of ground-based remote sounding of the ABL. They visualise the small-scale structure of atmospheric turbulence, allow the ABL temperature stratification to be elucidated, boundaries of surface and elevated temperature inversions and height of the mixing layer to be determined, and turbulence intermittence and wave motions to be detected.

The knowledge of characteristics of atmospheric turbulence is of fundamental importance for investigation of the structure and dynamics of the atmospheric boundary layer and construction of its mathematical models widely used for synoptic forecast, theoretical analysis, and prediction of electromagnetic and acoustic wave propagation as well as diffusion of pollutants. Characteristics of the atmospheric turbulence depend on the altitude over the Earth surface. Sodars typically measure the characteristics of the atmosphere at altitudes from several meters to several hundred meters.
In the present paper, works of authors [12–18] are generalized, and the possibility of sodar application for simultaneous comprehensive measurements of the vertical profiles of turbulence characteristics is demonstrated. To analyze the random wind velocity field in the atmosphere, the structure functions – the average differences of the squared wind velocity components at two points – are used. The application of sodars allows long time series of observations of the vertical profiles of wind velocity vector to be obtained and the structure functions of the wind velocity field to be calculated for separation of the observation points up to several hundred meters.

The spatiotemporal dynamics of the characteristics of atmospheric turbulence, including three components of wind velocity vector, longitudinal and transverse structure functions of wind velocity field, structure characteristics of temperature and wind velocity, turbulent kinetic energy dissipation rate, and outer scales of temperature and dynamic turbulence are analyzed. The above-indicated characteristics are retrieved from time series of vertical profiles of the wind velocity vector and the backscattered signal power measured with the sodar having a working frequency of 1700 Hz and the minisodar having the working frequency of 4900 Hz. The original closed iterative algorithm of sodar data processing considering the classical and molecular absorption and the turbulent sound extinction on the propagation paths to the scattering volume and back to the receiver is used that allows the vertical profiles of the characteristics of temperature and wind velocity field to be reconstructed simultaneously and their interrelation to be investigated. In the literature, including our papers, only results of measurements of individual turbulence characteristics are described. Many papers are devoted to measurements of the temperature and wind velocity structure characteristics [1–7]; results of acoustic sounding of the turbulent kinetic energy dissipation rate are presented, for example, in [8, 9]; the wind velocity structure functions are considered in [10, 11].

2. Methods of sounding and data processing

Doppler sodars allow long time series of vertical profiles of the backscattered signal power \( P_j(z_k) \) and of the three components of wind velocity vector \( V_{i,j}(z_k) \) to be obtained in vertical strobes \( z_k \), where \( i = x, y, z \), and \( j = 1, \ldots, N \) designates the serial number of the vertical profile in the series of \( N \) measurements, and \( k = 1, \ldots, M \) designates the serial strobe number. They can be used to calculate the temporal longitudinal and transverse structure functions for each strobe \( z_k \):

\[
D_{rr}(z_k, n\Delta t, \langle V(z_k) \rangle) = \frac{1}{N - n - 1} \sum_{j=1}^{N-n-1} [V'_{j+n}(z_k) - V'(z_k)]^2, \quad n = 1, \ldots, N/5, \tag{1}
\]

\[
D_{tt}(z_k, n\Delta t, \langle V_z(z_k) \rangle) = \frac{1}{N - n - 1} \sum_{j=1}^{N-n-1} [V_{z,j+n}(z_k) - V_{z,j}(z_k)]^2, \quad n = 1, \ldots, N/5. \tag{2}
\]

Here

\[
\langle V'_{x}(z_k) \rangle = \sqrt{\langle V'_x(z_k)^2 \rangle + \langle V'_y(z_k)^2 \rangle + \langle V'_z(z_k)^2 \rangle}, \tag{3}
\]

\[
\langle V_{i,j}(z_k) \rangle = \frac{1}{N} \sum_{j=1}^{N} V_{i,j}(z_k), \quad i = x, y, z, \tag{4}
\]

\[
V'_{j+n}(z_k) = \langle V_{x,j}(z_k) \rangle + \langle V_{y,j}(z_k) \rangle + \langle V_{z,j}(z_k) \rangle, \tag{5}
\]

is the longitudinal component of the wind velocity vector retrieved from individual measurement for strobe \( z_k \), and \( \langle V(z_k) \rangle \) is the wind velocity vector for the strobe \( z_k \) averaged over the measurement period \( T = Nt \).
The vertical profiles of the structure characteristic of the wind velocity field \( C^2_V(z_k) \) were calculated from the formula:
\[
C^2_V(z_k) = \left[ \left( V_{z,j}(z_k + r) - V_{z,j}(z_k) \right)^2 \right] \cdot r^{-2/3}.
\] (6)

The separation of the observation points was chosen either in horizontal, or in vertical direction. In the first case, \( C^2_V(z_k) \) was calculated from the vertical component of the wind velocity measured in the strobe \( z_k \) with the time delay \( n_i \Delta t \) (\( n_i = 1, \ldots, N/5 \), \( N \) is the number of measurements in the series, and \( \Delta t \) is the pulse repetition period; in this case, \( r = n_i \Delta t \left( V(z_k) \right) \)). In the second case, \( C^2_V(z_k) \) was calculated from the vertical component of the wind velocity measured in different strobes spaced at the distance \( r = n_i \Delta z \) (here \( \Delta z \) is the strobe length and \( M \) is the number of strobes in the sounding range).

The turbulent kinetic energy dissipation rate \( \varepsilon(z_k) \) was calculated from the wind velocity structure characteristic using the formula:
\[
\varepsilon(z_k) = \left[ \frac{C^2_V(z_k)}{1.97} \right]^{3/2}.
\] (7)

From the backscattered signal power \( P_j(z_k) \), using the iterative algorithm, vertical profiles of the temperature structure characteristic and of the outer scale of temperature turbulence were calculated.

Mathematically, the outer scale of temperature turbulence was calculated using the closed iterative algorithm considering the excess turbulent signal attenuation. The expression for the \( i \)th iteration of the outer scale of temperature turbulence \( L^{(i)}_{OT} \) depending on the altitude \( z_k \) above the underlying surface has the form
\[
L^{(i)}_{OT}(z_k) = \left[ \frac{C^2_T(z_k)}{2.8 \gamma_a^2} \right]^{3/4}.
\] (8)

Here \( \gamma_a \) is the adiabatic temperature gradient, \( C^2_T(z_k) \) is the \( i \)th iteration of the temperature structure characteristic that for the \( j \)th measurement was calculated from the formula
\[
C^2_T(z_k) = \frac{2.7 \cdot 10^{-2} A_c \lambda^{1/3} T^2 z^2 P_j(z_k)}{\gamma_1 \gamma_2 c \tau A_c P_0 L^{(i-1)}_{turb}(z_k)},
\] (9)

\( c \) is the sound velocity, \( \lambda = c/f \) is the wavelength, \( f \) is the working sodar frequency, \( T \) is the surface air temperature, \( \tau \) is the sodar pulse length, \( A_c \) is the instrumental constant, \( A_t \) is the transceiving antenna aperture of the sodar, \( P_j(z_k) \) is the signal power backscattered from altitude \( z_k \) in the \( j \)th measurement, \( j = 1, \ldots, N \), \( P_0 \) is the transmitted signal power, \( \gamma_1 \) and \( \gamma_2 \) are the coefficients of electric signal conversion into the acoustic one and vice versa,
\[
L^{(i)}(z_k) = L_{abs}(z_k) \cdot L_{turb}(z_k)
\] (10)
is the \( i \)th iteration of the extinction coefficient, \( i = 1, \ldots, M \), caused by the classical and molecular absorption of sound waves and their excess turbulent attenuation during propagation from the transmitter to the scattering volume and back to the receiver.
The dependence of the spatial wind velocity structure function on the separation of the observation points $r$ in the inertial ($l_{0V} \ll r \ll L_{0V}$, where $l_{0V}$ is the inner and $L_{0V}$ is the outer scale of dynamic turbulence, respectively) and energy ranges ($L_{0V} \ll r$) is described by following formula:

$$D(z_k, r) = \left\{ \begin{array}{ll}
C_T^2(z_k) r^{2/3}, & l_{0V} \ll r \ll L_{0V}(z_k), \\
C_T^2(z_k) L_{0V}(z_k)^{2/3}, & L_{0V}(z_k) \ll r.
\end{array} \right.$$  \hspace{1em} (11)

It is proportional to $r^{2/3}$ in the inertial range and then is saturated at a constant. It is the inflection point of the dependence of the structure function on the separation of the observation points in power $2/3$ that determines the outer scale $L_{0V}(z_k)$ of the dynamic turbulence. Formulas (1), (2) and (6)–(9) were implemented in the closed iterative computing algorithm.

Measurements were performed with a three-component monostatic Doppler sodar having a working frequency of 1700 Hz, pulse repetition period of 11.5 s, and pulse duration of 150 ms. One receiving sodar antenna was oriented vertically, and two others were tilted at angles of $20^\circ$ to the vertical in mutually orthogonal planes. The normalized backscattered signal power was measured with the altitude resolution $\Delta z = 20$, the minimum sounding altitude changed from 48 to 74 m depending on the surrounding noise level during measurements. Iterations stopped at $z_M$ when they started to diverge. The signal/noise ratio was additionally monitored from facsimile records of sodar signals. Series of $N = 53$ sodar measurements were processed, which provided 10-minute averaging period. The instrumental constants of the sodar entering into formula (11) were determined by sodar calibration from results of independent measurements of $C_T^2$ by an ultrasonic thermometer/anemometer under conditions of developed convection.

Results of measurements with the Doppler minisodar having a working frequency of 4900 Hz, pulse duration $\tau = 60$ ms, and pulse repetition period of 4 s were also processed. Radiation was transmitted and received in three directions – vertical and tilted at the angles $\alpha = 14^\circ$ to the vertical in two mutually orthogonal planes. Vertical profiles of the three wind velocity components $V_{i,j}(z_k), i = x, y, z, j = 1, \ldots, N$ were measured in $M = 40$ strobes $z_k$ of length $\Delta z = 5$ m in the altitude range 5–200 m. Processing of series from $N = 150$ profiles provided the wind velocity structure functions averaged over the 10-minute period.

3. Measurement results

Doppler monostatic sodars are widely used to measure vertical profiles of the wind velocity vector in the atmospheric boundary layer. From their measurements the vertical profiles of the wind velocity structure characteristics $C_V^2$ are also retrieved. Sodars are also used to retrieve vertical profiles of the temperature structure characteristics $C_T^2$ from the backscattered signal intensity. However, a comparison of sodar data with the data of local measurements showed that the divergence of sodar and in situ values of $C_T^2$ is on average equal to 40 % and can reach 2–5 times depending on the atmospheric conditions, which was explained by disregarding of turbulent signal attenuation.

The original method of acoustic sounding of atmospheric turbulence taking into account turbulent signal attenuation allows vertical profiles of the temperature and wind velocity structure characteristics to be retrieved simultaneously.
Figure 1. Temperature and wind velocity structure characteristics.

Figure 1 shows synchronous vertical profiles of the structure characteristics of temperature, $C_T^2(z)$, and wind velocity for the vertical (designated by $C_{Vz}^2$) and horizontal separation of observation points (designated $C_{Vt}^2$) retrieved from sodar measurements in the morning (10:00, $a$ and $b$) and evening hours (16:00, $c$ and $d$). The averaging time was 10 minutes. Asterisks show results of in situ measurements with micropulsation sensors.

Figure 2. $a$–$c$ illustrates synchronous temporal dynamics of the temperature (facsimile records $a$) and wind turbulence (transverse, $D_t(b)$, and longitudinal, $D_l(c)$, wind velocity structure functions) in the lower 200-meter layer of the atmosphere in gradation of artificial colors for two 10-minute series of minisodar measurements. The data of continuous minisodar measurements during 6 days were processed. Thermal plumes characteristic for daytime convection are clearly seen on the facsimile records. Their upper boundary is subject to quasi-periodic fluctuations and has a clearly expressed tendency to an increase in altitude during observation period. Values of the transverse ($b$) and longitudinal ($c$) structure functions, in m$^2$/s$^2$, in gradations of artificial colors, are indicated to the right of the figures. It can be seen that the transverse structure function is much less than the longitudinal one that indicates strong anisotropy of atmospheric fluctuations in the longitudinal and transverse directions and squeezing of the small-scale turbulence in the vertical direction. The behavior of the longitudinal structure function also characterizes the dynamics of the mixing layer height.
Figure 2. Dynamics of the structure of temperature and wind turbulence in the morning at 11:00.

Figure 3, a shows a typical example of the temporal longitudinal wind velocity structure function $D_{rr}(z, \Delta t)$ calculated from formula (1) for sodar measurements in summer from 10:00 till 10:10, local time, and Fig. 3, b shows the spatial structure function $D_{rr}(z, \Delta r)$ corresponding to it calculated using the hypothesis of the frozen turbulence. It can be seen that the temporal structure functions with increasing time delay of observations remain practically unchanged undergoing only local oscillations. Their values increase with sounding altitude. The spatial structure functions first increase with increasing separation between the observation points and then saturate, as predicted by the theory. An analysis of the results obtained demonstrated that the saturation is observed at smaller separations $\Delta r$ with increasing sounding altitude.

Figure 4 shows the longitudinal temporal wind velocity structure function calculated from formula (1). Vertical profiles of the wind velocity vector were measured with the minisodar in summer from 16:00 till 16:10. It can be seen that the wind velocity field is homogeneous with time; it remains almost invariable with increasing time and grows with altitude of the observation point. In this case, when the altitude increases from 30 to 110 m, the structure function increases from $\sim 10$ m$^2$/s$^2$ to $\sim 50$ m$^2$/s$^2$. For higher altitudes, $D_{rr}(z, \Delta t)$ increases faster, reaching $\sim 100$ m$^2$/s$^2$ for $z = 125$ m. Two layers of intensive turbulence in which $D_{rr}(z, \Delta t)$ reached 135 m$^2$/s$^2$ were located at altitudes 125–145 m and 170–180 m. For altitudes above 180 m, the structure function was saturated at $D_{rr}^{\text{sat}}(z, \Delta t) \approx 100$ m$^2$/s$^2$.
Figure 3. Longitudinal temporal (a) and spatial (b) wind velocity structure functions retrieved from sodar measurements.

The corresponding temporal transverse structure function $D_{tt}(z,\Delta t)$ calculated from formula (2) is shown in Fig. 5. It is much less than $D_{tr}(z,\Delta t)$. Strong anisotropy of the time spectra of amplitude fluctuations of sound wave during its longitudinal and transverse propagation relative to the direction of the wind velocity was also pointed out earlier. Moreover, the correlation in the longitudinal direction was much stronger than in the transverse one. The temporal transverse structure function, unlike the longitudinal one, changed with time. It increased with altitude and saturated at $D_{tt}^{\text{sat}}(z,\Delta t) = 0.23$ m$^2$/s$^2$. Small-scale inhomogeneities with lifetimes of the order of 10 s were clearly pronounced.

It should be noted that in addition to the traditional facsimile records of sodars that illustrate the dynamics of temperature turbulence in the atmospheric boundary layer, the results presented here illustrate the dynamics of the wind turbulence indicating layers of more intensive wind turbulence that can be used, for example, to improve aircraft safety.

The diurnal dynamics of the wind velocity structure characteristic is illustrated in Figure 6, where the vertical profiles of $C_{\nu}^2$ calculated from the data of hourly minisodar measurements averaged over 10-minute periods (over 150 individual profiles) on September 13, 2006 from 11:00 till 22:00. Here profiles (a) were measured from 11:10 till 11:20, profiles (b) from 12:10 till 12:20, ..., profiles (l) from 22:10 till 22:20. The red curves are for the vertical separation of the observation points, and the blue curves are for their horizontal separation. Horizontal bars indicate 95 % confidence intervals. The dashed curves illustrate the altitude dependence $C_{\nu}^2(\text{theor})(z) \sim z^{-2/3}$ predicted theoretically for developed convection affixed to the data of surface measurements. From the figures it can be seen that for this series of measurements, $C_{\nu}^2(\text{theor})(1 \text{ m})$ remains constant and equal to 0.18 m$^{4/3}$s$^2$ from 11:00 till 15:00, local time, then at 16:00 it decreases to 0.12 m$^{4/3}$s$^2$, from 17:00 increases from 0.15 m$^{4/3}$s$^2$ to 0.22 m$^{4/3}$s$^2$ at 18:00, reaching a maximum value of 0.25 m$^{4/3}$s$^2$ at 19:00 and 20:00, then decreases to 0.1 m$^{4/3}$s$^2$ at 21:00, and increases again to 0.22 m$^{4/3}$s$^2$ at 22:00.
The temporal dynamics of vertical profiles of turbulent kinetic energy dissipation rate calculated from formula (7) from minisodar data taking into account the excess turbulent attenuation is shown in Figure 7. The month, day, year, and time of the beginning of 10-minute series of sodar measurements are indicated on the right of the figures. For a comparison, asterisks show results of \( \varepsilon \) retrieval from measurements with a 2-micron coherent Doppler lidar.

Good agreement of the results of lidar and acoustic measurements can be seen. Analysis of the results shown in Figure 7 demonstrated that \( \varepsilon(z) \) decreases approximately by an order of magnitude with increasing local measurement time from 01:00 till 09:00, which is in agreement with lidar measurements. It reached a minimum at 11:00. The dissipation rate on September 16 increased by approximately one and a half orders of magnitude when the local measurement time increased from 11:00 till 21:00 and then started to decrease when the measurement time further increased till 23:00. For \( z = 100 \) m on September 17, it decreased from \( \sim 8 \cdot 10^{-4} \text{m}^2/\text{s}^2 \) at 01:00 to \( 1 \cdot 10^{-4} \text{m}^2/\text{s}^2 \) at 05:00.
Figure 6. Hourly dynamics of the structure characteristic of the wind velocity field
Figure 7. Turbulent kinetic energy dissipation rate retrieved from minisodar measurements.

Figure 8 shows the results of measurements of the outer scale of temperature turbulence $L_{OT}(z)$ in developing convection ($a$) in the morning (from 10:00, local time), developed daytime convection ($b$) (from 15:00, local time), and stable stratification ($c$ and $d$). It can be seen that the outer scale of temperature turbulence increases with altitude that is in agreement with its existing models.

Figure 9 shows semidiurnal hourly dynamics of vertical profiles of the outer scale of dynamic turbulence calculated from 10-minute series of minisodar measurements from 11:00 till 23:00, local time. From the figure it can be seen that the outer scale of dynamic turbulence changes in the range from 5 m to 100 m, which is in good agreement with its theoretical estimation and results of aircraft measurements. The general tendency of the outer scale to increase with altitude is also traced. As to
the temporal dynamics, it can be seen that maximal outer scales are observed in the morning and in the evening. Moreover, the outer scale in the morning changes greater than in the daytime and in the evening, and its vertical stratification is also more clearly pronounced in the morning. For a comparison, Figure 9, shows the altitude profiles of the outer scale of dynamic turbulence from night measurements with a 2-micron Doppler lidar from 23:23 till 23:40, local time, retrieved from the azimuthal structure function after spatial filtration of lidar data (circles) and from the radial structure function after spatial filtration of lidar data (diamonds). Good agreement of sodar data with lidar measurements is seen from the figure. Attention is also drawn to the clearly expressed layered structure of the outer scale of dynamic turbulence retrieved from both sodar and lidar data.

Figure 9. Semidiurnal hourly dynamics of vertical profiles of the outer scale of dynamic turbulence retrieved from minisodar measurements. Time of the beginning of 10-minute measurement series is indicated to the right of the figures.

4. Conclusions
The capabilities of sodar application for investigations of the spatiotemporal dynamics of the three components of wind velocity vector, longitudinal and transverse structure functions of wind velocity field, temperature and wind velocity structure characteristics, turbulent kinetic energy dissipation rate, and outer scales of temperature and dynamic turbulence in the atmospheric boundary layer are described. The efficiency of the original closed iterative algorithm of sodar data processing taking into account turbulent sound extinction on the propagation path for simultaneous retrieval of the vertical profiles of the characteristics of temperature and wind velocity fields and investigation of their interrelation is demonstrated. It is demonstrated that sodars are very efficient means for studying and monitoring of the wide range of the above-indicated parameters of the lower atmosphere.

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