ULTRASONIC METHODS FOR ESTIMATION OF ATMOSPHERIC METEOROLOGICAL AND TURBULENCE PARAMETERS

A.Ya. Bogushevich

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
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The capabilities of ultrasonic systems are described as applied to gathering of information needed for estimation of meteorological and turbulence parameters of the surface atmospheric layer. The algorithms and techniques used at the BMK–01 meteorological station for processing the measured data are presented.

INTRODUCTION

The idea to apply ultrasonic methods to estimation of meteorological parameters of the atmosphere arose even in the late 40s because of significant time lag and radiation errors inherent in the standard meteorological instrumentation. The ultrasonic methods are free, to a great degree, of these drawbacks, what is especially valuable for determination of various statistical and turbulence characteristics of atmospheric meteorological fields.

The local acoustic method was initially proposed only for measurements of the air temperature. For the first time, the thermometer utilizing this method was described by Barret and Suomi in 1949 (Ref. 1). In the USSR, the similar device was first described by Fateev in 1955 (Ref. 2). However, these acoustic thermometers have not achieved wide acceptance because of some drawbacks in their design.

A rebirth of interest in ultrasonic methods for atmospheric investigations appeared in the 60s. In that period, they came in use for determination of not only the air temperature, but also different components of the wind velocity vector.[3–5] What is more, in connection with intensive experimental study of the atmospheric turbulence, the ultrasonic methods came to be applied to estimation of different characteristics of turbulent pulsations of the same meteorological parameters.[6–13] Active development of microcircuitry in recent 15 years and the emergence of personal computers gave rise to elaboration of principally new ultrasonic meters with significantly improved performance characteristics (see, for example, Refs. 14–19). Such devices allow long, practically unattended, instantaneous determination of the air temperature and three orthogonal components of wind velocity with the time constant of the order of 10–3 s and the sensitivity about 0.01–0.02 (C or m/s). These data are read out at 0.1 s or longer intervals and stored at the computer hard disk as long time series for each measured meteorological parameter. Upon processed with the specialized software, these series give very extensive information about the state of the surface atmospheric layer. Below we briefly describe the main algorithms and the techniCues used by us for gathering and processing the data obtained at the BMK–01 ultrasonic meteorological station.[18,19]

ALGORITHMS AND MEASUREMENT TECHNIQUE

The method for determination of meteorological parameters in ultrasonic systems is based on the dependence of the group sound velocity on the air temperature and wind velocity[20]:

$$\mathbf{U} = c\,\mathbf{n} + \mathbf{v}, \qquad (1)$$

where $\mathbf{U}$ is the vector of the group sound velocity; $\mathbf{n}$ is the normal to the wave phase front; $\mathbf{v}$ is the wind velocity vector; c is the sound speed in stationary air. As known,[21] the expression for the sound speed in air c can be derived from the linearized eCuations of the hydrodynamics. The following expression can be thus obtained for an ideal, in terms of thermodynamics, gas:

$$c = \sqrt{\frac{\chi R}{\mu} T_k}, \text{ m/s}, \qquad (2)$$

where $\chi = c_p/c_v$ is the specific heat ratio; R is the gas constant (molar); μ is the molecular weight of a gas; T_k is the temperature, in K. For dry air under normal conditions $\chi = 1.402$, $\mu = 28.96$, $R = 8.315\cdot 10^7$ erg/deg. ConseCuently, the following expression can be used in spite of EC. (2):

$$c = 20.067\sqrt{T_k}, \text{ m/s}.$$

The Van der Waals corrections used for real gases contribute negligibly slightly into EC. (2), at least outside the freCuency region of sonic oscillations, at which maximum molecular absorption and sound dispersion are observed. The air molecular weight remains practically constant up to altitudes about 100 km. The parameter $\chi = c_p/c_v$ varies only in its fourth significant digit about its real values in the atmosphere depending on the air temperature.

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Therefore, EC. (2) allows very accurate estimation of the air temperature from c, if the dependence of c on the ratio of the water vapor pressure to the atmospheric pressure e/p_{atm} is also taken into account in it through the following relation[14]:

$$c = 20.067 \sqrt{T_{\text{v}}},\ \text{m/s}\ , \qquad (3)$$

where $T_{\text{v}} = T_k(1 + 0.3192\, e/p_{\text{atm}})$ is the virtual acoustic temperature. The parameter e can be estimated here from the value of the relative air humidity E with regard for the eCuality $e = 6.107^{m-2} E$, where $m = 7.665\, T/(243.33 + T)$, T is the air temperature, in °C.

Ultrasonic systems measure the times t_i of an acoustic signal propagation between a pair of ultrasonic transducers (sensors) separated by a known distance S_i (from 15 to 30 cm) along the chosen directions i. In this case, the relation $U_i = S_i/t_i$ actually estimates the absolute value of the group velocity $U_i = \{c^2 + 2c\, \mathbf{v}\mathbf{n}_i + v^2\}^{1/2}$. Since the wind velocity vector $\mathbf{v}$ is characterized by values of its three orthogonal components v_x, v_y, and v_z, at least four channels of ultrasound propagation in air with different orientation in space are needed for algorithmic separation of contributions from wind and temperature into the values of U_i.

Let us introduce the unit vector $\mathbf{q}_i = \mathbf{U}_i/U_i$, describing the direction of propagation of a sonic wave in the ith channel of the ultrasonic system. This vector is related to the normal $\mathbf{n}_i$ to the wave phase front as follows[22]:

$$\mathbf{n}_i = \mathbf{q}_i \left(\sqrt{1 + (\mathbf{v}\cdot\mathbf{q}_i/c)^2 - (v/c)^2} + \mathbf{v}\cdot\mathbf{q}_i/c \right) - \mathbf{v}/c. \qquad (4)$$

Taking a scalar product of the eCuality (1) through $\mathbf{q}_i$ and considering EC. (4), we have

$$U_i = c\sqrt{1 + (\mathbf{v}\cdot\mathbf{q}_i/c)^2 - (v/c)^2} + \mathbf{v}\cdot\mathbf{q}_i. \qquad (5)$$

To derive the algorithms for calculation of meteorological parameters, EC. (5) can be simplified by expanding its right-hand side into a series in the small parameter $v/c \ll 1$. Thus, for the group sound velocity in the ith channel we obtain the following eCuation:

$$U_i = c + \mathbf{v}\cdot\mathbf{q}_i + (\mathbf{v}\cdot\mathbf{q}_{i\perp})^2/(2c) + (\mathbf{v}\cdot\mathbf{q}_{i\perp})^4/(8c^3) + \dots, \qquad (6)$$

where $\mathbf{q}_{i\perp}$ is the unit vector transverse to $\mathbf{q}_i$. If only two first terms are retained in EC. (4) (the linear approximation), then the contribution from the wind velocity component transverse to the signal propagation direction will be neglected. Numerical estimates show that it is permissible only for the case of a gentle wind $v \le 10$ m/s. Therefore, the measurement algorithms used in ultrasonic systems should take account of the sCuare terms in EC. (6) as well. The particular form of the algorithm depends on the geometrical arrangement of sensors. Let us consider it as applied to the BMK-01 meteorological station.[18,19]

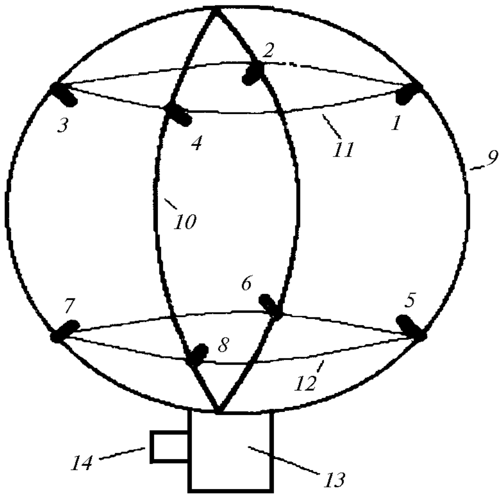

FIG. 1. A schEmE of thE mEasuring systEm of thE BMK-01 ultrasonic mEtEorological station: piEzocEramic sEnsors (1-8); tubE rings (9-10); solid rings (11-12); attachmEnt to thE mEtEorological mast (13); Exit port to thE ElEctronic unit (14).

The ultrasonic system at the BMK-01 station is arranged as a sphere of two orthogonal tube rings of 277 mm in diameter (Fig. 1) with ultrasonic piezoceramic sensors fixed on them. The sensors are arranged in such a way to coincide with vertices of a parallelepiped, whose base lies in the horizontal plane and has a sCuare shape. The sensors *2*, *4*, *5*, and *7* emit acoustic signals, and the sensors *1*, *3*, *6*, and *8* receive them. The space orientation of the sound propagation channels is described by the system of eCuations for unit vectors $\mathbf{q}_i$ (the numbers of the corresponding emitting and receiving channels are given in parentheses):

$$\begin{aligned}
&\mathbf{q}_1 = \mathbf{i}\sin\alpha + \mathbf{k}\cos\alpha, \ (7 \to 1 - \text{for channel No. 1}),\\
&\mathbf{q}_2 = -\mathbf{i}\sin\alpha + \mathbf{k}\cos\alpha, \ (5 \to 3 - \text{for channel No. 2}), \quad (7)\\
&\mathbf{q}_3 = \mathbf{j}\sin\alpha - \mathbf{k}\cos\alpha, \ (4 \to 6 - \text{for channel No. 3}),\\
&\mathbf{q}_4 = -\mathbf{j}\sin\alpha - \mathbf{k}\cos\alpha, \ (2 \to 8 - \text{for channel No. 4}),
\end{aligned}$$

where $\mathbf{i}$, $\mathbf{j}$, and $\mathbf{k}$ are the unit vectors of the Cartesian coordinate system; $\alpha = 45°$. When meteorological parameters are measured at the BMK-01 station, they are first estimated in the linear approximation by the expressions:

$$\begin{aligned}
&\hat{v}_x = \sqrt{2}\,(U_1 - U_2), \quad \hat{v}_y = \sqrt{2}\,(U_3 - U_4),\\
&\hat{v}_z = 2\,(U_1 + U_2 - U_3 - U_4),\\
&\hat{c} = (U_1 + U_2 + U_3 + U_4)/4, \qquad (8)
\end{aligned}$$

where $U_1 = S_1/t_1$; $U_2 = S_2/t_2$; $U_3 = S_3/t_3$; $U_4 = S_4/t_4$ are the values of the group sound velocity for four channels of the ultrasonic system. The caret indicates that a parameter is estimated only in the linear approximation. Then, based on the linear estimates, the corrections of the second approximation are calculated as follows:

$$\delta v_x = \sqrt{2}\ \hat{v}_x\ \hat{v}_z/(2\ \hat{c}),$$
$$\delta v_y = -\sqrt{2}\ \hat{v}_y\ \hat{v}_z/(2\ \hat{c}),$$
$$\delta v_z = \left(\hat{v}_x^2 - \hat{v}_y^2\right)/(4\sqrt{2}\ \hat{c}),$$
$$\delta c = -\left[3\left(\hat{v}_x^2 + \hat{v}_y^2\right) + \hat{v}_z^2\right]/(8\ \hat{c}). \qquad (9)$$

The values $v_x = \hat{v}_x + \delta v_x$, $v_y = \hat{v}_y + \delta v_y$, $v_z = \hat{v}_z + \delta v_z$, and $c = \hat{c} + \delta c$ are considered here as true, and the air temperature is calculated from c with use of EC. (3).

To account for the air humidity and atmospheric pressure in EC. (3), the commercial meteorological sensors with electric output are additionally connected to the ultrasonic system. Besides these sensors, one more pair of sensors is provided for measuring the angles of meteorological mast inclination in two orthogonal planes. Their readings are taken into account when calculating the orthogonal wind velocity components v_x, v_y, and v_z. The account for heat expansion of the measuring system (an increase in the distance S_i with increasing temperature) and shading of the piezoceramic sensors for wind airflow is also taken automatically.[23,24]

The components v_x, v_y, and v_z are calculated from the differences in the average (integral) values of the group sound velocity along paths oriented at an angle to each other and mostly noncoinciding in space (see EC. (8) and Fig. 1). This may result in systematic errors in estimates of turbulent pulsations of wind velocity projections onto the Cartesian coordinates . , 3, and z, if a noticeable violation of anisotropy of the wind velocity field is observed in the atmosphere for spatial scales comparable with the distances between the ultrasonic sensors. The similar meteorological sensors described in Refs. 14–17 use re-emission of signals in the backward direction along each of three propagation paths oriented directly along the . , 3, and z axes. Such measurement techniCue may reduce the above errors. However, it does not eliminate similar errors, caused by anisotropy of meteorological fields, for turbulent pulsation of other wind velocity components, which are usually calculated from the instantaneous values of v_x, v_y, and v_z when determining the parameters of atmospheric turbulence (see below).

STATISTICAL DATA

Statistical processing of time series of instantaneous values of v_x, v_y, v_z, and T measured by the ultrasonic system consists of the following stages. Average values of all measured meteorological parameters are first calculated, along with the absolute value and direction angles of the wind velocity vector **v** and its horizontal component (v_h and φ). At the second stages, the instantaneous values of v_x, v_y, v_z, and T are used for calculation of time series of turbulent pulsations of the temperature T' and wind velocity components (vertical w', longitudinal u', and transverse v' relative to the direction of the mean vector of the horizontal wind v_h; as well as longitudinal $v_{\parallel}'$ and transverse $v_{\perp}'$ relative to the total vector of the mean wind **v**). At the next stage, the standard eCuations of the probability theory (see, for example, Ref. 25) are used for calculation of different numerical characteristics of the above-listed random parameters. Most often calculated characteristics in this case are rms deviations, correlation, asymmetry, and excess coefficients. The last stage includes a calculation of different statistical functions of the meteorological parameters turbulent pulsations: autocorrelation and intercorrelation, probability density distributions (histograms), structured functions, and power spectra (Fig. 2). These functions may be calculated both in time and space scale (using the hypothesis of “frozenB turbulence).

ESTIMATION OF PARAMETERS OF ATMOSPHERIC TURBULENCE

The main advantage of ultrasonic meteorological stations is that their data are directly used in calculation of different parameters of temperature and wind turbulence in the surface atmospheric layer. These calculations follow the well-known eCuations of the theory of atmospheric turbulence (see, for example, Refs. 26–30). In particular, the following parameters are determined at the BMK–01 meteorological station (<.> denotes statistical averaging):

$E_t = \sigma_u^2 + \sigma_v^2 + \sigma_w^2$ is the total energy of turbulent motions (σ_u^2, σ_v^2, σ_w^2 are the dispersions);

$\tau = \langle u'\ w' \rangle$ is the pulse flux (tangent stress);

$H = \langle u'\ T' \rangle$ is the heat flow (temperature flow);

$v^* = \sqrt{-\tau}$ is the friction velocity (wind scale);

$T^* = -H/v^*$ is the temperature scale;

$L^* = \langle T \rangle\ (v^*)^2/(\chi g T^*)$ is the Monin–Obukhov scale ($\chi = 0.4$ and $g = 9.81$ m/s^2);

$C_d = (v^*/\langle v_h \rangle)^2$ is the flow resistance coefficient;

$C_T^2 = \langle [T'(t + \Delta t) - T'(t)]^2 \rangle / (\langle |\mathbf{v}| \rangle\ \Delta t)^{-2/3}$ is the structured constant of temperature fluctuations (Δt is the interval between measurements of instantaneous values of meteorological parameters);

$C_v^2 = \langle [v_{\parallel}'(t + \Delta t) - v_{\parallel}'(t)]^2 \rangle / (\langle |\mathbf{v}| \rangle\ \Delta t)^{-2/3}$ is the structured constant of wind fluctuations;

$C_n^2 = C_T^2/(2\langle T \rangle)^2 + C_v^2/\langle c \rangle^2$ is the structured constant of fluctuations of the acoustic refractive index (c is the sound speed from EC. (3)).

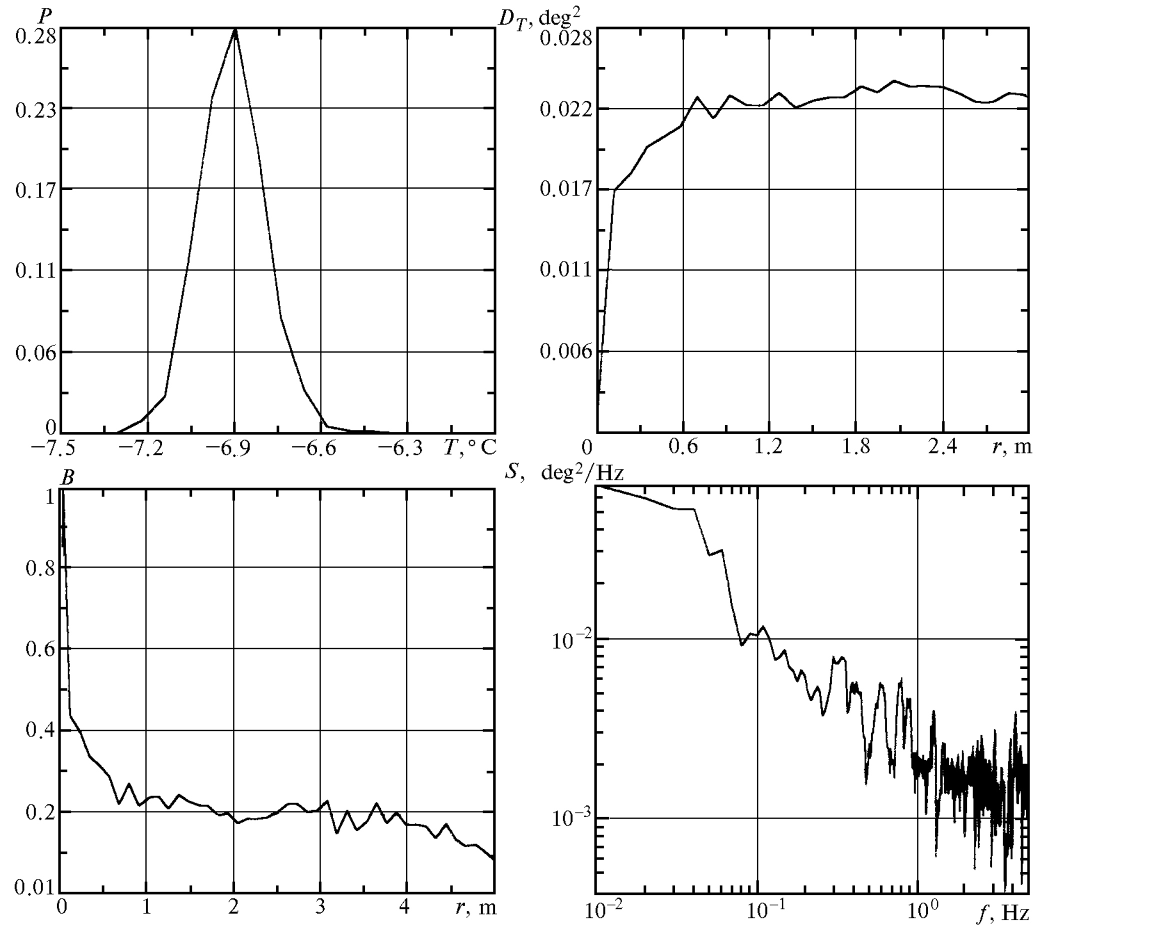

FIG. 2. Histogram (p), structurEd function (D_T), normalizEd autocorrEation function (b), and powEr spEctrum (S) of turbulEnt pulsations of air tEmpEraturE from thE data of thE BMK–01 ultrasonic mEtEorological station.

The listed parameters would suffice to estimate the dynamic mode of the turbulence in the surface atmospheric layer, including determination of the stability class of atmospheric stratification. The following parameters can be predicted by applying the Monin–Obukhov similarity theory (here φ_v and φ_T are the universal similarity functions of the dimensionless altitude $\xi = z/L^*$ for wind and temperature stratification, respectively):

m_s is the altitude of the surface atmospheric layer top;

$\frac{\partial u}{\partial z} = \frac{v^*}{\chi z}\varphi_v\left(\frac{z_{meas}}{L^*}\right)$ is the local wind velocity lapse rate at the measurement altitude z_{meas};

$\frac{\partial \theta}{\partial z} = \frac{T^*}{\chi z}\varphi_T\left(\frac{z_{meas}}{L^*}\right)$ is the local potential temperature lapse rate at the altitude z_{meas};

$\frac{\partial T}{\partial z} = \frac{\partial \theta}{\partial z} - 0.0098$ is the local temperature lapse rate at the altitude z_{meas};

$K_m = (v^*)^2/(\partial u/\partial z)$ is the turbulent exchange coefficient for momentum ;

$K_{heat} = v^*\, T^*/(\partial\theta/\partial z)$ is the turbulent exchange coefficient for heat;

$L_0 = (K_m/|\partial u/\partial z|)^{1/2}$ is the outer scale of turbulence;

$\varepsilon = K_m(\partial u/\partial z)^2 - (g/<T>)\, K_{heat}(\partial\theta/\partial z)$ is the energy dissipation rate of wind fluctuations;

$N = K_{heat}(\partial\theta/\partial z)^2$ is the energy dissipation rate of temperature fluctuations;

$\mathrm{Ri} = (g/<T>)\,(\partial\theta/\partial z)\,(\partial u/\partial z)$ is the Richardson gradient number.

RECONSTRUCTION OF PROFILES OF ATMOSPHERIC PARAMETERS

The universal similarity functions of the dimensionless parameter $\xi = z/L^*$ for the surface atmospheric layer are the following[29]:

$$\varphi_v(\xi) = \begin{cases} 1 + 4.7\xi, & \xi > 0 \\ (1 - 15\xi)^{-1/4}, & \xi < 0 \end{cases}, \quad (10)$$

$$\varphi_T(\xi) = \begin{cases} 0.74 + 4.7\xi, & \xi > 0 \\ 0.74\,(1 - 9\xi)^{-1/2}, & \xi < 0 \end{cases}. \quad (11)$$

The case $\xi > 0$ (or $L^* > 0$) here corresponds to the stable temperature and wind stratification in the surface atmospheric layer, while the case $\xi < 0$ (or $L^* < 0$) corresponds to unstable stratification. The height of the surface atmospheric layer m_s, up to which application of EGs. (10) and (11) is theoretically justified, does not exceed several tens meters in most cases. Only in rare cases, when the atmospheric stratification is close to neutral, m_s is higher than 100 m. With regard for experimental data, it is usually believed that at stable stratification m_s is comparable with L^* ($m_s \sim L^*$), while at unstable stratification $m_s \sim 5|L^*|$. The reconstruction of profiles of atmospheric parameters from the data of ultrasonic meteorological stations obtained at the same fixed altitude $z_{meas} < m_s$ is correct only up to the altitude m_s.

Considering the above eCuations of the atmospheric turbulence theory, it is easy to notice that the similarity functions (10) and (11) allow direct calculation of the altitude profiles of the turbulent exchange coefficients for heat K_{heat} and momentum K_m, the energy dissipation rates of temperature N and wind ε fluctuations, the outer scale of turbulence L_0, and the Richardson gradient number Ri. At the same time, to construct the temperature profile $T(z)$ and the profile of horizontal wind velocity $v_h(z)$ (in the surface layer we assume $\varphi(z) = \text{const}$), it is necessary to integrate the following functions over z:

$$\frac{\partial T(z)}{\partial z} = \frac{T^*}{\chi z}\, \varphi_T \left(\frac{z}{L^*}\right) + \gamma_a , \qquad (12)$$

$$\frac{\partial v_h(z)}{\partial z} = \frac{v^*}{\chi z}\, \varphi_v \left(\frac{z}{L^*}\right) , \qquad (13)$$

where $\gamma_a = -0.0098$ K/m is the dry adiabatic lapse rate. ECuations (12) and (13) can be integrated analytically with regard for the boundary conditions (values of T and v_h on the surface or at the measurement point). The relations obtained in such a way are then used for direct calculations of the profiles $T(z)$ and $v_h(z)$. The BMK-01 station provides the ability to reconstruct the profiles of all listed parameters, as well as the profiles $C_T^2(z)$ and $C_v^2(z)$. In the latter case, to assign to the absolute values, the values of C_T^2 and C_v^2 measured at the altitude z_{meas} are used, and their changes with altitude are determined from the relations between C_T^2 and N and between C_v^2 and ε. The profiles of $T(z)$, $v_h(z)$, C_T^2, and C_v^2 reconstructed from the real data of the ultrasonic meteorological station for the case of stable stratification are exemplified in Fig. 3.

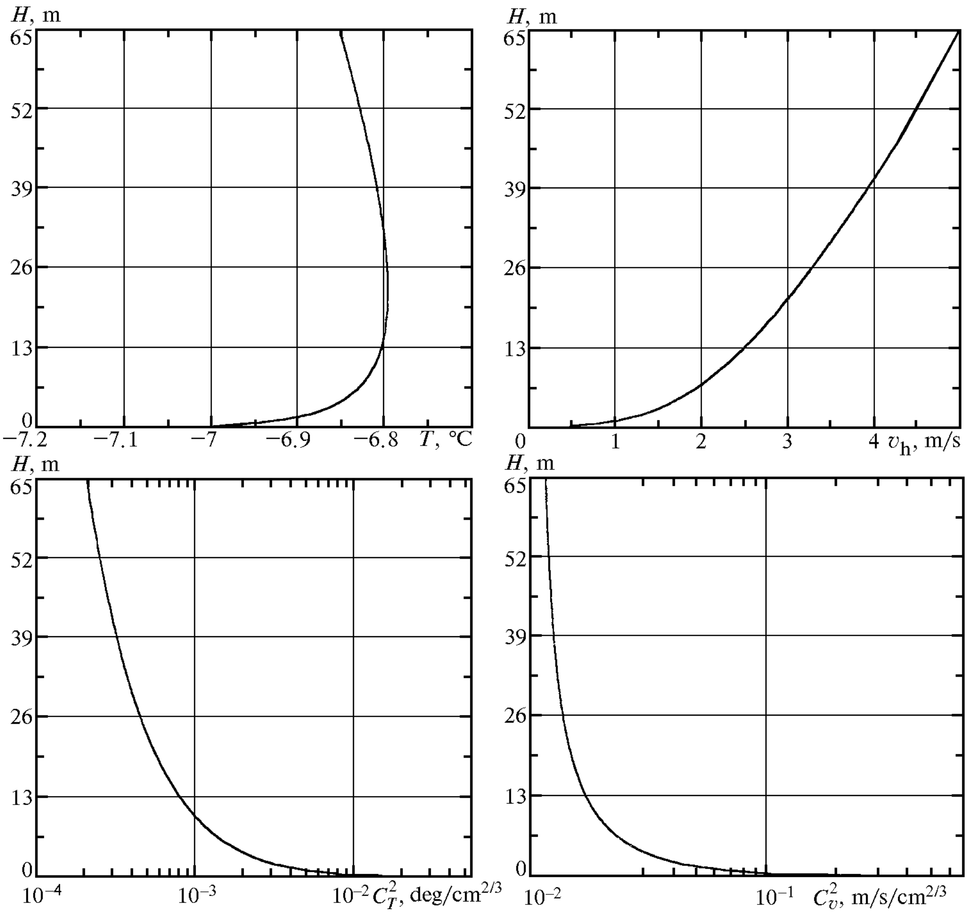

FIG. 3. ProfilEs of air tEmpEraturE (T), horizontal wind vElocity (v_h), structurEd constants of tEmpEraturE (C_T^2) and wind (C_v^2) fluctuations rEconstructEd from thE data of thE BMK-01 ultrasonic mEtEorological station in thE surfacE atmosphEric layEr for thE casE of stablE stratification ($L^* = + 65.2$ m).

The algorithm considered above was completely implemented in the METEO 2.0 MS Windows application.

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REFERENCES

1. W. Barret and E. Suomi, J. Meteorol. **6**, No. 4 (1949).
2. N.P. Fateev, Trudy Gl. Geofiz. Obs., issue 52, 114 (1955).
3. V.M. Bovsheverov and V.P. Voronov, Izv. Akad. Nauk SSSR, Geofiz., No. 6, 882 (1960).
4. M.I. Mordukhovich and V.M. Bovsheverov, Vestnik Akad. Nauk SSSR, No. 9 (1961).
5. M.I. Mordukhovich, Trudy Ins. Atmos. Physics AN, No. 4, 30–80 (1962).
6. A.S. Gurvich, Akustich. Zh. **5**, No. 3, 368 (1959).
7. V.M. Bovsheverov, A.S. Gurvich, M.I. Mordukhovich, and L.R. Tsvang, Trudy Ins. Atmos. Physics AN SSSR, No. 4, 21 (1962).
8. J.S. Kaimal and J.A. Businger, J. Appl. Meteorol. **2**, No. 2, 156–164 (1963).
9. Y. Mitsuta, J. Meteorol. Soc. Japan **44**, No. 1, 12–23 (1966).
10. J.C. Kaimal, J.C. Wyngard, and D.A. Haugen, J. Appl. Meteorol. **5**, No. 10, 827–837 (1968).
11. J.C. Kaimal, Radio Sci. **4**, 1147–1153 (1969).
12. L.V. Antoshkin, O.N. Emaleev, V.P. Lukin, V.M. Sukonkina, V.V. Khatsko, and A.P. Yankov, Prib. Tekh. Eksp., No. 3, 240–241 (1986).
13. L.V. Antoshkin and V.P. Lukin, in: *Abstracts of REports at thE Third Russian–Bulgarian SEminar on LasEr and Radio MEthods for EnvironmEntal Monitoring* (1990), pp. 383–388.
14. T. Hanafusa, T. Fujitani, Y. Koboi, and Y. Mitsuta, Pap. Meteorol. Geophys. **33**, 1–19 (1982).
15. M.V. Anisimov, E.A. Monastyrnyi, G.Ya. Patrushev, and A.P. Rostov, Prib. Tekh. Eksp., No. 4, 196–199 (1988).
16. C.W. Fairall, J.B. Edson, S.E. Larsen, and P.G. Mestayer, J. Atmosph. and Oceanic Technology **7**, No. 6, 425–453 (1990).
17. G.Ya. Patrushev, A.P. Rostov, and A.P. Ivanov, Atmos. Oceanic Opt. **7**, Nos. 11–12, 890–891 (1994).
18. A.A. Azbukin, A.Ya. Bogushevich, V.V. Burkov, et al., in: *Abstracts of REports at thE Third IntErnational Symposium on AtmosphEric and OcEanic Optics,* Tomsk (1996), p. 160.
19. A.Ya. Bogushevich and N.P. Krasnenko, in: *Abstracts of REports at thE Third IntErnational Symposium on AtmosphEric and OcEanic Optics,* Tomsk (1996), p. 167.
20. D.I. Blokhintsev, *Acoustics of an InhomogEnEous Moving MEdium* (Nauka, Moscow, 1981), 206 pp.
21. L.D. Landau and E.M. Lifshits, *MEchanics of Continuous MEdia* (Gostekhteorizdat, Moscow, 1954), 795 pp.
22. V.E. Ostashev, *Sound Propagation in Moving MEdia* (Nauka, Moscow, 1992), 206 pp.
23. J.C. Wyngard and S.F. Zhang, J. Atmosph. and Oceanic Technology **2**, No. 12, 548–558 (1985).
24. S.F. Zhang, J.C. Wyngard, J.A. Businger, and J.C. Oncley, J. Atmosph. and Oceanic Technology **3**, No. 12, 315–323 (1986).
25. E.S. Ventsel', *Probability ThEory* (Nauka, Moscow, 1969).
26. A.M. Obukhov, *TurbulEncE and AtmosphEric Dynamics* (Gidrometeoizdat, Leningrad, 1988), 413 pp.
27. N.L. Byzova, V.N. Ivanov, and E.K. Garger, *TurbulEncE in thE Boundary AtmosphEric LayEr* (Gidrometeoizdat, Leningrad, 1989), 263 pp.
28. V.I. Tatarskii, *WavE Propagation in a TurbulEnt MEdium* (McGraw-Hill, New York, 1961).
29. R.A. Braun, *Analytical MEthods for ModEling of thE PlanEtary Boundary LayEr* (Gidrometeoizdat, Leningrad, 1978), 150 pp.
30. *AtmosphErE Handbook* (Gidrometeoizdat, Leningrad, 1991), 509 pp.