

# Methods and algorithms for statistical processing of instantaneous meteorological parameters from ultrasonic measurements

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**Abstract.** This paper describes a software system designed to support atmospheric studies with ultrasonic thermo-anemometer data processing. The system is capable of processing files containing sets of immediate values of temperature, three orthogonal wind velocity components, humidity, and pressure. The paper presents a technological scheme for selecting the necessary meteorological parameters depending on the observation time, the averaging interval, and the period between the immediate values. The data processing consists of three stages. At the initial stage, a query for the necessary meteorological parameters is executed. At the second stage, the system calculates the standard statistical characteristics of the meteorological fields, such as mean values, dispersion, standard deviation, asymmetric coefficients, kurtosis, correlation, etc. The third stage prepares to compute the atmospheric turbulence parameters. The system creates new arrays of data to process and calculate the second order statistical moments that are important for solving problems of atmospheric surface layer physics, predicting the pollutant dispersion in the atmosphere, etc. The calculation results are visualized and stored on a hard disk.

## 1. Introduction

The meteorological measurements are an essential part of scientific and applied knowledge on the atmosphere properties. The measurement data allows researchers to learn the specifics of physical and chemical processes in the atmosphere, to determine its composition and structure, to find out its thermal conditions and moisture exchange, research the formation conditions for a variety of optical and acoustical phenomena and, most importantly, modeling weather and climate forecasts.

Weather data is obtained by a complex of various equipment for meteorological measurements [1]. Ultrasonic anemometer is one of the most up-to-date devices used at weather stations [2-12]. The idea of using ultrasonic methods for atmosphere meteorological parameters estimation has appeared in the late 1940s. Ultrasonic methods are largely free of such drawbacks as inertia, radiation error etc. It allows researchers to accurately estimate the turbulent characteristics that describe the small-scale high-frequency spectral structure of meteorological observations.

This work presents a software that extends the functionality of the meteorological complex AMK-03, including its modifications (developed by Tomsk Scientific Center SB RAS). The principle of



ultrasonic anemometer operation is based on measuring the sound speed, which varies depending on air flow (wind direction) vector orientation relative to sound propagation path. A standard implementation of an automatic ultrasonic weather station allows to measure such parameters as air temperature (T), various components of the wind velocity ( $v_s$ ,  $v_e$ ,  $w$ ), pressure (P), humidity ( $r$ ). The immediate values of the meteorological properties are calculated during the preparation stage for processing raw measurement data obtained by ultrasonic thermo-anemometer and stored at the local PC, directly connected to the device. The preparation stage includes:

- reading the raw measurement data stream from the device;
- testing the raw measurement data on operation and transmit failures, quality accessing;
- real-time calculation of the immediate meteorological values, such as temperature, horizontal wind velocity, horizontal wind direction, vertical wind velocity, relative air humidity, atmospheric pressure;
- automatically storing the meteorological value calculation results on the PC hard drive as files of various types, indexed by the measurement date.

Those files are stored in a special archive and they allow to calculate various meteorological parameters for any past period of time, including measurement means and statistic functions for atmosphere temperature as well as wind fields. Traditionally, they are used for analysis of the thermo dynamical condition of the ground layer of atmosphere and numerical estimations of the conventional atmospheric turbulence characteristics.

## 2. Stages of processing

The presented work describes a mathematical processing of meteorological parameters obtained from standard ultrasonic weather station. The data is stored in files and structured as ten minute observation periods with 12.5 millisecond measurement intervals. The meteorological values undergo a standard statistical processing, based upon existing formulae. Authors of this work are responsible for developing the necessary algorithms for analysis described below and implementing them in Java programming language. The statistical processing is done for all of the measurements, filtered by the registration time according to observation time and data statistical analysis (averaging) interval. The goal of the processing is to create informative atmosphere characteristic timelines that reflect statistically stable value trends for longer time periods compared to the initial one (day, month, year). The developed software allows to select data from any observation time and for any averaging interval, as well as to set the period between immediate values of meteorological parameters.

The application form screenshots that illustrate query processing are shown in Figures 1 and 2.



**Figure 1.** Setting the observation time.



**Figure 2.** Setting the averaging interval.

The initial data for processing is measured from  $t_{\text{per}} - t_{\text{avg}}$  to  $t_{\text{per}}$  points of time according statistical data analysis interval selected according to some criteria.

Stage 1. Calculating averages for meteorological values and other physical parameters describing the quasi-equilibrium atmosphere state at measurement location for the given time period.

The initial immediate values ( $T$ ,  $v_s$ ,  $v_e$ ,  $w$ ,  $r$  and  $P$ ) are obtained from binary files containing ultrasonic thermo-anemometer observation results. They are used to calculate the averages of meteorological values for the given observation time  $t_{\text{per}}$  and analysis interval  $t_{\text{avg}}$  (while accounting for requirements set by World meteorological organization and Roshydromet). The calculation results are also used to evaluate other atmosphere air physical parameters that are necessary for the numerical analysis of atmospheric turbulence and related tasks, but usually ignored at standard weather stations.

Stage 2. Preparing to calculate the atmosphere turbulence parameters, creating new data arrays for processing and calculating the statistical moments of second order (or higher).

Stage 3. Calculating the atmosphere turbulence parameters.

The basic mathematical equations used for the initial data processing and repeated for every selected  $t_{\text{H}}$  time interval are listed below.

The averages and dispersion for  $\xi(t)$  random process are calculated for  $T$ ,  $v_s$ ,  $v_e$ ,  $w$ ,  $r$  and  $P$  meteorological values describing the quasi-equilibrium (for a specific  $t_{\text{avg}}$  time interval) state at the measurement location for the given time period.

In the case of ultrasonic weather station, for each meteorological  $\xi_i$  value ( $i$  stands for value type) we only have a set of its discrete samples  $\xi_{i,k}$  (where  $k$  is the ordinal number registered from the  $t_{\text{per}} - t_{\text{avg}}$  point of time). Averages are calculated with equation  $\langle \xi_i \rangle = \frac{1}{N} \sum_{k=0}^{N-1} \xi_{i,k}$ , where  $N \approx F_d \cdot t_{\text{avg}}$  (whole number) – number of the existing  $\xi_{i,k}$  discrete samples in the analyzed time interval ranging from  $t_{\text{per}} - t_{\text{avg}}$  to  $t_{\text{H}}$ ,  $F_d = 80$  Hz – the weather station hardware measurement frequency (data sampling rate). The  $D_i$  dispersion of  $\xi_{i,k}$  value can be calculated as follows:  $D_i = \frac{1}{N-1} \sum_{k=0}^{N-1} (\xi_{i,k} - \langle \xi_i \rangle)^2$ .

### 3. Calculated parameters

The averages of orthogonal wind velocity components ( $\langle v_s \rangle$  – south component of wind velocity horizontal vector,  $\langle v_e \rangle$  – eastern component of horizontal wind velocity vector and  $\langle w \rangle$  – vertical component of full wind velocity vector) are used to evaluate the following parameters:

The absolute value of wind velocity mean vector –  $\langle V \rangle = \sqrt{\langle v_s \rangle^2 + \langle v_e \rangle^2 + \langle w \rangle^2}$ .

Horizontal wind average speed –  $\langle V_h \rangle = \sqrt{\langle v_s \rangle^2 + \langle v_e \rangle^2}$ .

The inclination angle to the horizontal of wind velocity mean vector –  $\psi = \arccos\left(\frac{\langle V_h \rangle}{\langle V \rangle}\right)$ .

The direction of horizontal wind average velocity  $\langle D \rangle$ :

$$\langle D \rangle = \begin{cases} \pi + f, \langle v_s \rangle > 0,01 \\ f, \langle v_s \rangle < -0,01; \langle v_e \rangle \geq 0 \\ 2\pi + f, \langle v_s \rangle < -0,01; \langle v_e \rangle < 0 \\ \frac{\pi}{2}, |\langle v_s \rangle| \leq 0,01; \langle v_e \rangle \geq 0 \\ \frac{3\pi}{2}, |\langle v_s \rangle| \leq 0,01; \langle v_e \rangle < 0 \end{cases},$$

where  $f = \arctg(-\frac{\langle v_e \rangle}{\langle v_s \rangle})$ .

Saturated vapor pressure –  $e_w = \left(6.112 * e^{\frac{17.62T}{243.12+T}}\right) * (1.0016 + 3.15 * 10^{-6}P - 0.074P^{-1})$ ,

where T stands for temperature, P stands for atmospheric pressure.

Average pressure of atmosphere water vapor (e, GPa) –  $e = \frac{e_w * r}{100\%}$ , where r is relative air humidity.

Moisture deficit (E<sub>d</sub>, GPa) –  $E_d = e_w - e$ .

Absolute air humidity (q, g/m<sup>3</sup>) –  $q = \frac{r * P * M}{R * T * 100\%}$ , where M is the molar mass of dry air, R is the universal gas constant.

Air density ( $\rho$ , g/m<sup>3</sup>) –  $\rho = \frac{P * M}{R * T}$ .

The preparation for atmospheric turbulence calculation includes creating new arrays of data to process and evaluating the statistical moments of second order (or higher). The first part of this stage is the computing process and use the immediate values of ultrasonic measurements T, v<sub>s</sub>, v<sub>e</sub> and w to form new time series that describe the turbulent fluctuations:

For temperature –  $T' = T - \langle T \rangle$ .

For vertical wind velocity component –  $w' = w - \langle w \rangle$ .

For longitudinal wind velocity component –  $u' = (\langle v_s \rangle * (v_s - \langle v_s \rangle) + \langle v_e \rangle * (v_e - \langle v_e \rangle)) / \langle V_h \rangle$ .

For transverse wind velocity component  $v' = (-\langle v_s \rangle * (v_e - \langle v_e \rangle) + \langle v_e \rangle * (v_s - \langle v_s \rangle)) / \langle V_h \rangle$ .

To analyze turbulence for the ground atmosphere layer, it is important to evaluate the second order correlational statistical moments:

Heat flux momentum –  $\langle T' * w' \rangle$ .

Moment-of-momentum flux –  $\langle u' * w' \rangle$ .

Atmospheric turbulence parameters (average from t<sub>h</sub> – t<sub>ycp</sub> to t<sub>h</sub>):

The total energy of turbulent motions –  $E_v = (\sigma_u^2 + \sigma_v^2 + \sigma_w^2) / 2$ , where  $\sigma_u^2, \sigma_v^2, \sigma_w^2$  are dispersions of turbulent fluctuations for three wind velocity components u', v', w'.

The relative intensity of wind velocity fluctuations –  $I_v = E_v / V_m^2$ .

The energy of temperature fluctuations –  $E_t = \sigma_t^2 / 2$ , where  $\sigma_t^2$  is the dispersion of turbulent fluctuations of T' temperature.

Vertical momentum flux –  $\tau = -\rho \langle u' * w' \rangle$ , where  $\rho$  – air density.

Vertical heat flux –  $H = c_p * \rho * \langle T' * w' \rangle$ , where  $c_p$  is air specific heat capacity at the constant pressure.

Wind friction velocity –  $v^* = \sqrt{-\langle u' * w' \rangle}$ .

Temperature scale –  $T^* = -\langle T' * w' \rangle / v^*$ .

Monin-Obukhov length –  $L^* = \langle T \rangle * (v^*)^2 / \chi * g * T^*$ , where  $\chi = 0,4$  and  $g = 9,81 \text{ m/s}^2$ .

Flow resistance coefficient –  $C_d = (\frac{v^*}{\langle V \rangle})^2$ .

The structure constant of temperature fluctuations  $C_T^2 = \langle [T'(t + \Delta t) - T'(t)]^2 \rangle * (\langle V \rangle \Delta t)^{-2/3}$ , where V is the absolute value of mean wind velocity vector;  $\Delta t$  – the time between immediate meteorological parameters measurements.

The structure constant of wind fluctuations  $C_V^2 = \langle [u'(t + \Delta t) - u'(t)]^2 \rangle * (\langle V \rangle \Delta t)^{-2/3}$ .

The structure constant of acoustic refraction index fluctuations  $C_{na}^2 = \frac{C_T^2}{4\langle T \rangle^2} + \frac{C_V^2}{\langle c \rangle^2}$ , where  $T_k$  is air temperature measured in kelvins,  $c$  is sound speed.

The structure constant of optical refractive index fluctuations  $C_{no}^2 = \{8 * 10^{-5} * \langle P \rangle / \langle T \rangle^2\}^2 * C_T^2$ , where  $P$  is atmospheric pressure measured in hPa.

The Monin-Obukhov similarity theory [13, 14] is used to predict values of a parameter group. The calculations use  $\varphi_V$  and  $\varphi_T$  – the universal similarity functions of the dimensionless height  $\xi = z/L^*$  for wind and thermal stratification, respectively. The universal similarity functions use  $\varphi_V$  and  $\varphi_T$  of the dimensionless height parameter  $\xi = z/L^*$ . Those parameters are semi-empirical, since their general form is determined by the theoretical analysis of a ground turbulent flux and can be found using the following formulas [15, 16]:

$$\varphi_V(\xi) = \begin{cases} 1 + 4,7\xi, \dots \xi > 0 \\ (1 - 15\xi)^{-1/4}, \dots \xi < 0 \end{cases}$$

$$\varphi_T(\xi) = \begin{cases} 0,74 + 4,7\xi, \dots \xi > 0 \\ 0,74 * (1 - 9\xi)^{-1/2}, \dots \xi < 0 \end{cases}$$

Local gradient of wind velocity at  $z_m$  height:

$$\frac{du}{dz} = \frac{v^*}{\chi} \varphi_V\left(\frac{z_m}{L^*}\right)$$

Local gradient of potential temperature at  $z_m$  height:

$$\frac{d\theta}{dz} = \frac{T^*}{\chi} \varphi_T\left(\frac{z_m}{L^*}\right)$$

Local gradient of temperature at  $z_m$  height:

$$\frac{dT}{dz} = \frac{d\theta}{dz} - 0,0098$$

The turbulent exchange coefficient for momentum:

$$K_m = v^{*2} / \frac{du}{dz}$$

The turbulent heat exchange coefficient:

$$K_h = v^* * T^* / \frac{d\theta}{dz}$$

Turbulence outer scale:

$$L_0 = \left( K_m / \left| \frac{du}{dz} \right| \right)^{1/2}$$

Energy dissipation rate for wind fluctuations:

$$\varepsilon = K_m \left( \frac{du}{dz} \right)^2 - \left( \frac{g}{\langle T \rangle} \right) K_h \frac{d\theta}{dz}$$

Energy dissipation rate for heat fluctuations:

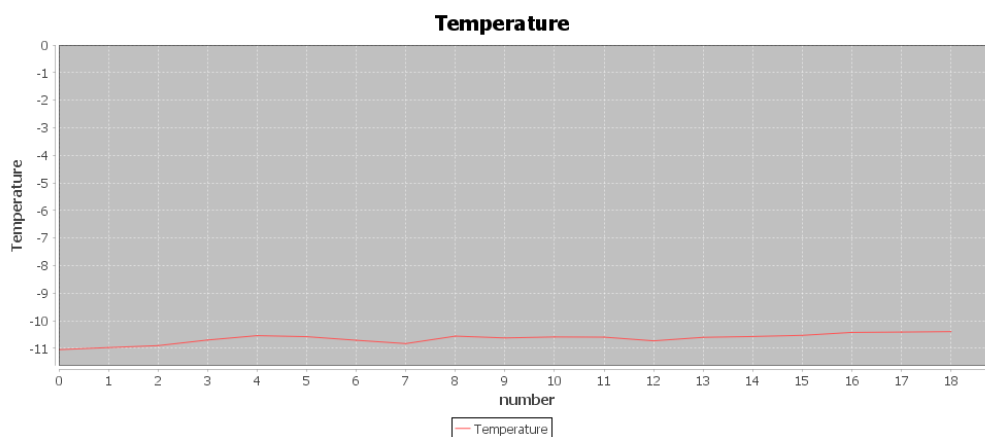
$$N = K_h \left( \frac{d\theta}{dz} \right)^2$$

Richardson gradient number:

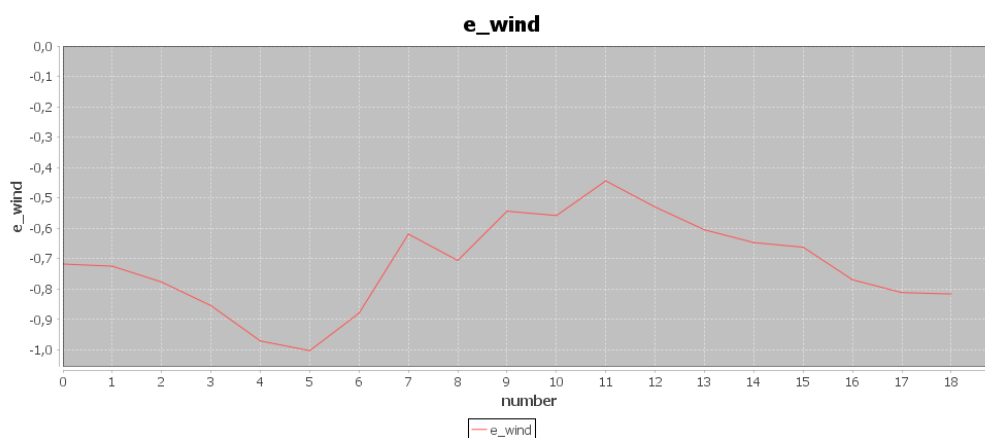
$$R_i = \left( \frac{g}{\langle T \rangle} \right) \left( \frac{d\theta}{dz} \right) / \left( \frac{du}{dz} \right)$$

#### 4. Screens interface

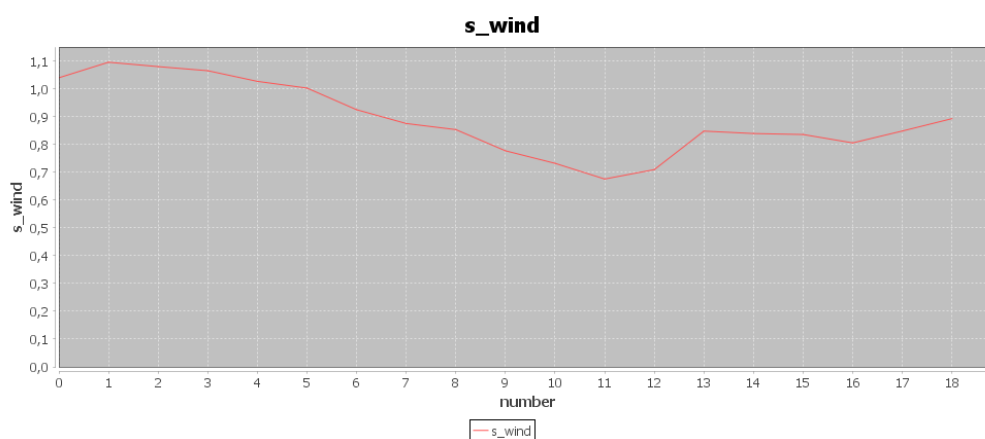
The developed means of visualization are shown in figures 3 – 8, displaying the meteorological data calculated means, describing the quasi-equilibrium state (for a given averaging interval) at the measurement location in a specific point of time (or for a given observation period).



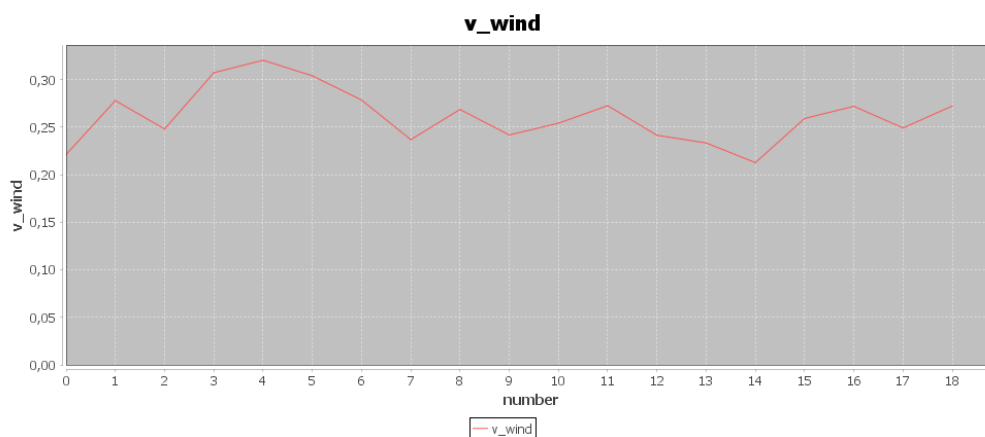
**Figure 3.** Average temperature chart.



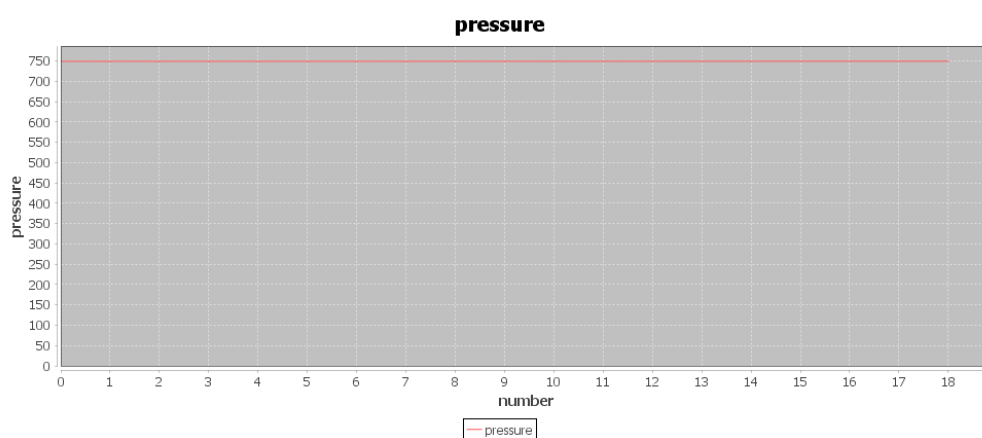
**Figure 4.** Eastern wind component mean vector chart.



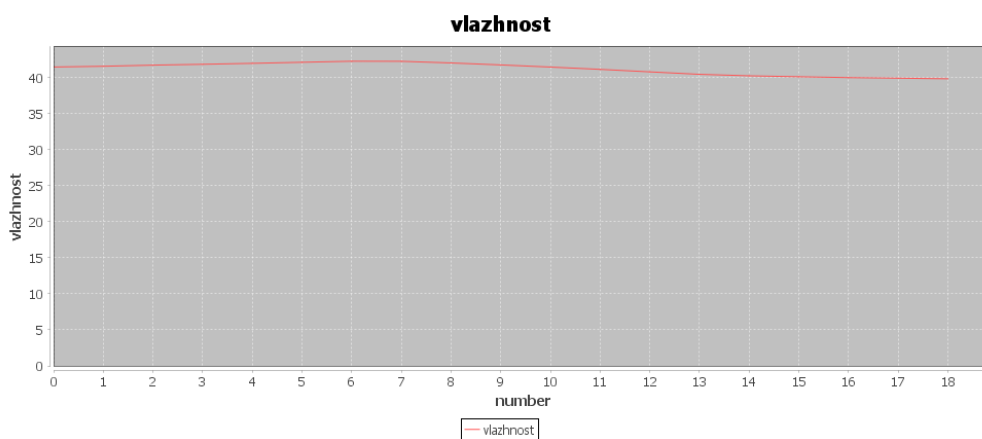
**Figure 5.** Southern wind component mean vector chart.



**Figure 6.** Vertical wind component mean vector chart.



**Figure 7.** Average pressure chart.



**Figure 8.** Average humidity chart.

A fragment of the web-interface window for the developed software is shown in Figure 9 below.



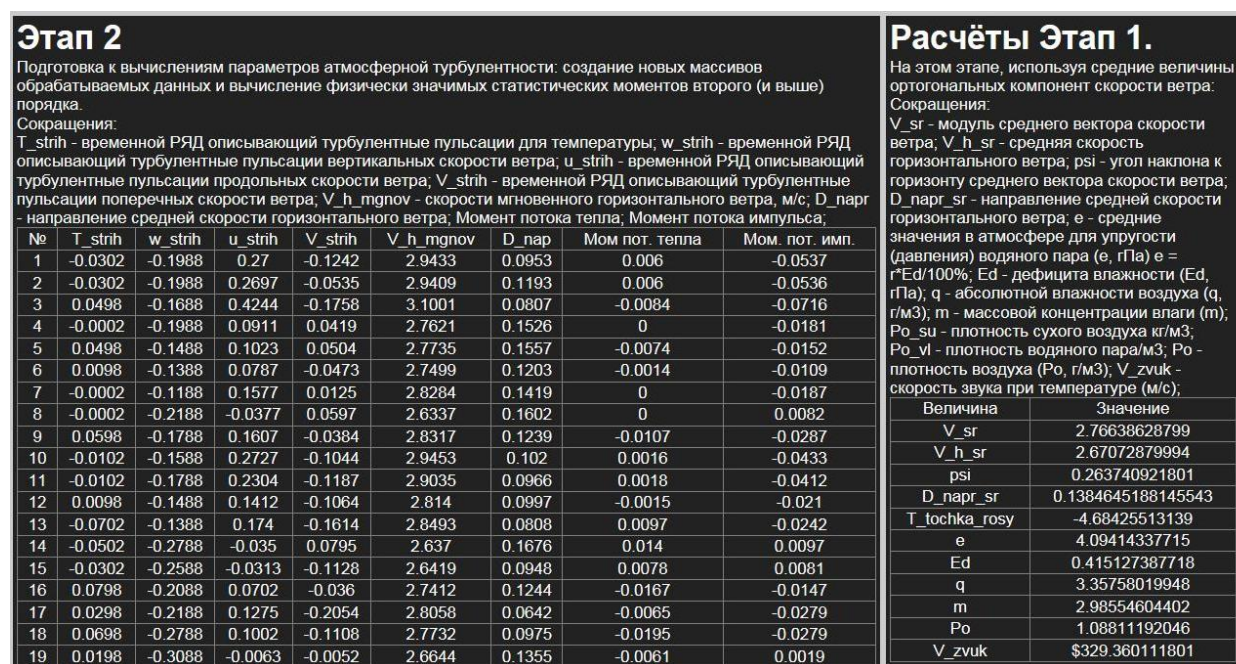


Figure 9. Fragment of data control panel window.

## 5. Conclusions

The developed software is capable of using ultrasonic thermo-anemometer measurements data to calculate averages of meteorological values, as well as parameters and statistical functions for temperature and wind atmospheric fields, traditionally used to conduct the atmosphere ground layer thermodynamic condition analysis and numerical evaluation of its turbulence properties.

The importance of this work lies in its high practicality – it suggests the hardware and software that allow to approach automated computation of meteorological fields' secondary parameters row. The final version of the hardware-software complex will be useful to the specialists in related fields as an "instrument" for gaining new knowledge.

The results are obtained in the framework of the project "Development and research of intelligent information-analytical system for analysis and prediction of climatic processes on the basis of high-performance clusters" of RAS 1.33P fundamental research program "Fundamental problems of mathematical modeling. Fundamental problems of factorization methods in different fields. Algorithms and software for ultra-high performance computing systems".

## References

- [1] Tikhomirov A A 2010 *Atmos. Ocean. Opt.* **23** 585–600
- [2] Tuton J and Pethica C 2010 *J. Atmos. Ocean. Technol.* **27** 2031–2038
- [3] Azbukin A A, Bogushevich A Ya, Illichivski V S, Korolkov V A and Tikhomirov A A 2006 *Russian Meteorology and Hydrology* 89–97
- [4] Azbukin A A, Bogyshevich A Ya, Kobzev A A, Korolkov V A, Tikhomirov A A and Schelevoy V D 2012 *Sensors and Systems* 47–52
- [5] Tikhomirov A A, Korolkov V A, Bogyshevich, Azbukin A A, A Ya and Schelevoy V D 2008 *Bulletin of the Academy of Military Sciences* 144–149
- [6] Kaimal J C and Gaynor J E 1991 *Bound-Lay. Meteorol.* **56** 410–418
- [7] Kabanov M V 1997 *Regional atmospheric monitoring. Part 1: Scientifically-methodical bases* (Tomsk: Publishing House of the SB RAS) p 211
- [8] Kabanov M V 1997 *Regional atmospheric monitoring. Part 2: New tools and measurement techniques* (Tomsk: Publishing House of the SB RAS) p 295
- [9] Sherstnev V S, Sherstneva A I, Botygin I A and Kustov D A 2016 *High Technology: Research*



- and Applications (Key Engineering Materials vol 685)* (Switzerland: Trans Tech Publications) pp 867–871
- [10] World Community Grid <http://www.worldcommunitygrid.org/> Accessed: January 2016
- [11] Botygin I A, Popov V N, Tartakovsky V A and Sherstnev V S 2015 *Proc. 21st Int. Symp. Atmospheric and Ocean Optics: Atmospheric Physics* (Tomsk: SPIE) vol. 9680 pp 96800J1–96800J4
- [12] Popov V N, Botygin I A and Koshelev N V. 2016 *High Technology: Research and Applications (Key Engineering Materials vol 685)* (Switzerland: Trans Tech Publications) pp 925–929
- [13] Monin A S, Obukhov A M 1954 *Proc. Geophysical Institute of the USSR Academy of Sciences* **24** 163–187
- [14] Zilitinkevich S S 1970 *The dynamics of the atmospheric boundary layer* (Leningrad: Hydrometeorological Publishing House) p 292
- [15] Businger J A, J.C. Wyngard J C, Isumi Y and Bradley E F 1971 *J. Atmos. Sci.* **28** 181–189
- [16] Dyer A J 1974 *Boundary-Layer Meteorol.* **7** 363–372