Study of the small-scale turbulence structure of the atmospheric surface layer

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***Abstract*—This paper presents the results of mathematical and software development for experimental study of turbulence structure of atmosphere surface layer. The data was obtained via ultrasonic thermo anemometer. The data processing and atmosphere turbulence parameter calculations were executed by using discretization and scaling schemes for studied meteorological parameters. The calculated parameters are sufficient to estimate the dynamic turbulence in surface layer of the atmosphere, including determining the stability class of atmospheric stratification.**

Keywords*— *atmospheric turbulence, ultrasonic thermo-anemometer, meteorological parameters, discretization, scaling

I. INTRODUCTION

The study of processes in the surface layer of atmosphere is necessary to solve a number of fundamental and applied tasks in the field of atmosphere physics, propagation of radiation in atmosphere, intellectual decision making in the problems of environmental protection and estimation of transformation of urban ecosystems. Atmosphere surface layer is characterized by its constant temporal and spatial variability. The structure of atmosphere surface layer and turbulence parameters of atmospheric air depend on various external and internal causes. External causes include wind speed, radiation regime, heterogeneity of underlying surface. Internal causes are connected with stratification of atmospheric air (distribution of air temperature over altitude). The surface layer of atmosphere is responsible for heat exchange and amount of movement between regional air masses. Therefore, turbulence plays an important role in the formation of vertical thermodynamic, aerodynamic and hydrodynamic structure of surface layer of atmosphere. In a region covered by a turbulent movement the temperature equalization occurs rapidly, which, in turn, affects the movement of air masses.

The goal of this study is to reproduce the internal structure of the surface layer of atmosphere by using small-scale observation data of meteorological value fields obtained by ultrasonic thermal anemometer AMK-03. The device measures instant values of wind speed and air temperature every 12.5 ms.

II. APPLICATION AND TOOLS

A. Overview

A large number of scientific works is dedicated to mathematical modeling of structure of atmosphere surface layer and to using said models to study the influence of turbulence on processes occurring in these layers. The theory that supports the results of observations of turbulence processes in the boundary layer between atmosphere and ocean is described in works [1-6]. The basics of geophysical turbulence theory are systematized in works [7-12]. The distribution of impurity in a turbulent medium is studied in [13-15]. An empirical study of the characteristics of small-scale turbulence based on the results of expeditionary studies in the ocean is given in [16–18]. The basic statistical processing of measurements of meteorological parameters obtained by ultrasonic meteorological complexes is presented in [19-20].

The review of available literature has shown that averaged properties of geophysical fields (such as medium velocity, temperature and density) are comprehensively studied. However, this is not the case for the properties of small-scale turbulence, such as turbulence energy and scale, viscous dissipation rate, vertical turbulent flows of momentum, heat and thermodynamically active impurity. It should also be added that atmosphere surface layer differs from other layers of atmosphere by its significant daily variability of every meteorological parameter. Using common means of measurement (such as atmospheric radio sounding) is not suitable for temporal and spatial scales of said variability. It's not possible to fully describe the ongoing processes and properly characterize the vertical structure of surface layers without necessary volume of experimental data. It only becomes possible through use of dedicated hardware designed to register various kinds of data.

B. AMK-03

The ultrasonic thermo-anemometer of the sensor of meteorological parameters is used to measure three orthogonal components of the wind velocity and air temperature vector using ultrasound (ultrasonic waves). The method is based on the dependence of the group sound velocity in the atmosphere on temperature and wind speed. More precisely, the technique is based on measuring the speed of sound depending on the orientation of the air motion vector (wind direction) relative to the sound propagation path. The speed of sound is measured by the time of passage of ultrasonic pulses between a fixed distance from the emitter to the ultrasonic microphone, and then the measured times are recalculated into three components of air velocity (wind speed). The use of an ultrasonic method for measuring temperature and wind speed ensures low inertia of measurements, high sensitivity to turbulent changes in specified meteorological parameters, and the absence of solar radiation on measurement results.

III. CONCEPT

Following the generally established practices and requirements for the hydrometeorological posts of World Meteorological Organization and Roshydromet, we conducted statistical processing for a set of measurements. The registration time for the set of measurements was limited by two parameters – meteorological observation time tobs and interval of data statistical analysis (averaging) – t_s. The first

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observation data was registered at the point of time which can be calculated as t_s-t_{avg}. The objective of the processing is to create an informative set of time series for various atmospheric parameters that reflect the statistically stable trends for periods of time longer than t_{avg} (day, month, year etc.).

At the first stage of mathematical processing we are calculating the parameters that describe the average state of atmosphere in the period from t_s-t_{avg} to t_s (air characteristics, wind characteristics, standard parameters required to be measured by Roshydromet for interval between measurement times).

For the second stage of calculating the parameters of atmospheric turbulence we created new data bulks to process – to be precise, time series that describe temperature pulses and wind speed components, particularly significant in the atmospheric turbulence theory. For temperature: $T' = T - \langle T \rangle$, for vertical component of wind speed: $w' = w - \langle w \rangle$, for longitudinal component of wind speed: $u' = (\langle v_s \rangle \times (v_s - \langle v_s \rangle) + \langle v_e \rangle \times (v_e - \langle v_e \rangle)) / V_h$, for transverse component of wind speed: $v' = (-\langle v_s \rangle \times (v_e - \langle v_e \rangle) + \langle v_e \rangle \times (v_s - \langle v_s \rangle)) / V_h$, where V_h is the direction of average vector of horizontal wind. Then, parameters of atmospheric turbulence were calculated by using standard mathematical correlations.

Basing upon Monin-Obukhov similarity theory we made predictive estimates of wind speed and temperature local gradients for a specific altitude. Additionally, we calculated coefficients of turbulent exchange of momentum and heat, energy dissipation rate of temperature and wind fluctuations, and gradient Richardson number.

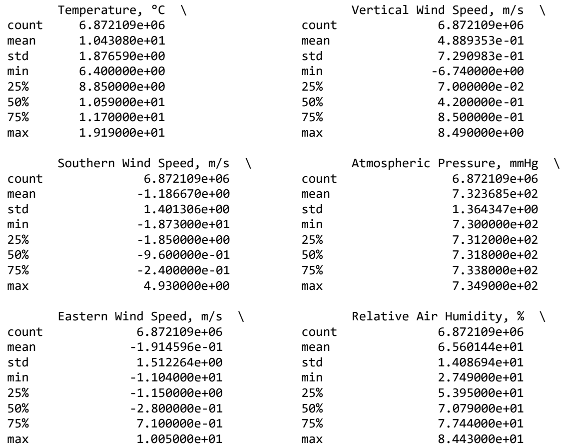
IV. ANALYSIS

This study has used the data obtained by automatic ultrasonic meteorological complex AMK-03, which measures primary meteorological values, such as wind speed and direction, temperature, air humidity and atmospheric pressure. The instantaneous values of wind speed and air temperature were measured on 80 Hz frequency with corresponding sensitivity of 0.05 m/sec and 0.05 °C. A single meteorological complex set to measure a single parameter will output 6 912 000 values daily. Given that even a small region (such as city) requires tens of automated meteorological complexes for adequate quality of mathematical analytical predictions, we end up with considerably large volumes of data to process. The results of the processing of daily measurements are listed below. Launching projects that include processing large volumes of data on a single PC can be troublesome even if data is stored on a web server.

TABLE I. INFORMATION AFTER STATISTICAL DATA PROCESSING DESCRIBING THE AVERAGE METEOROLOGICAL STATE OF THE ATMOSPHERE (FOR THE PERIOD FROM T_N - T_{USR} TO T_N)

Air characteristics	**Wind characteristics**
T – average air temperature, ^oC; σ[T] – standard deviation of temperature, ^oC; P – atmospheric pressure, hPa (or in mm Hg); r – relative humidity of air, %; e – elasticity (pressure) of water vapor, hPa; E_d – lack of moisture, hPa; T_d – dew point temperature, ^oC; q – absolute air humidity, g/m^3; m – mass concentration of moisture, kg/m^3; ρ – air density, g/m^3; c – speed of sound in air, m/s.	V – average horizontal wind speed, m/s; V_{min} – minimum speed of an instant horizontal wind, m/s; V_{max} – maximum speed of instantaneous horizontal wind, m/s; σ[V] – standard deviation of the horizontal wind speed, m/s; D – average direction of the horizontal wind, degrees; σ[D] – standard deviation of wind direction, degrees; w – average vertical wind speed, m/s; σ[w] – standard deviation of the vertical wind speed, m/s; W – modulus of the average wind velocity vector, m/s; α – angle of inclination to the horizon of the average wind velocity vector, degrees; v_s – average value of the southern component of the wind speed, m/s; v_e – average value of the eastern component of wind speed, m/s.

Fig. 1 shows some statistical parameters for a studied series of observations.



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        Temperature, °C  \                   Vertical Wind Speed, m/s  \
count      6.872109e+06              count                6.872109e+06
mean       1.043080e+01              mean                 4.889353e-01
std        1.876590e+00              std                  7.290983e-01
min        6.400000e+00              min                 -6.740000e+00
25%        8.850000e+00              25%                  7.000000e-02
50%        1.059000e+01              50%                  4.200000e-01
75%        1.170000e+01              75%                  8.500000e-01
max        1.919000e+01              max                  8.490000e+00

        Southern Wind Speed, m/s  \          Atmospheric Pressure, mmHg  \
count                6.872109e+06    count                  6.872109e+06
mean                -1.186670e+00    mean                   7.323685e+02
std                  1.401306e+00    std                    1.364347e+00
min                 -1.873000e+01    min                    7.300000e+02
25%                 -1.850000e+00    25%                    7.312000e+02
50%                 -9.600000e-01    50%                    7.318000e+02
75%                 -2.400000e-01    75%                    7.338000e+02
max                  4.930000e+00    max                    7.349000e+02

        Eastern Wind Speed, m/s  \           Relative Air Humidity, %  \
count               6.872109e+06     count                6.872109e+06
mean               -1.914596e-01     mean                 6.560144e+01
std                 1.512264e+00     std                  1.408694e+01
min                -1.104000e+01     min                  2.749000e+01
25%                -1.150000e+00     25%                  5.395000e+01
50%                -2.800000e-01     50%                  7.079000e+01
75%                 7.100000e-01     75%                  7.744000e+01
max                 1.005000e+01     max                  8.443000e+01
```

Fig. 1. Some statistical parameters

Experimental researches for determining parameteres of atmosphere turbulence by ultrasonic thermal anemometer were conducted according to the following schemes.

Scheme 1 – discretization. We study a given series of observations with different intervals between data values. The length of a studied series remains unchanged in time, while we varied the discretization stop of instantaneous value acquisition (fig. 2 - fig. 7). The figures show the results of calculation some of atmospheric turbulence parameters with the following discretization intervals: 12.5 ms (0), 30 sec (2), 10 min (4), 1 hour (6), 3 hours (8), 12 hours (10).

Fig. 2. Pulse flow moment

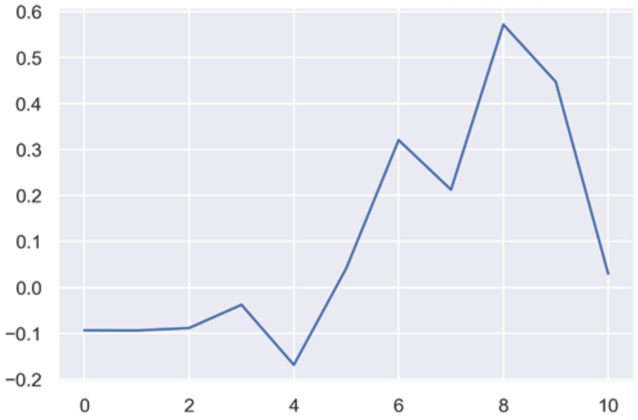


Fig. 3. Heat flow moment

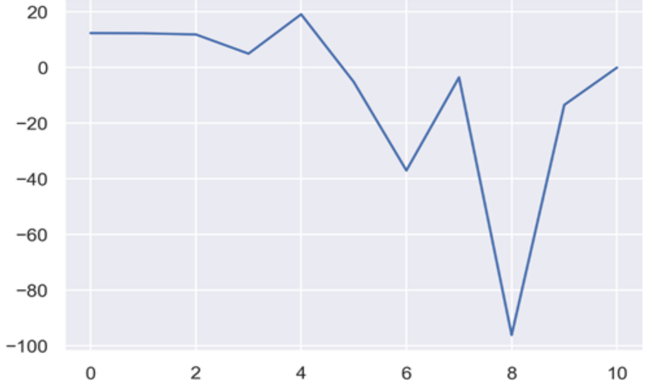


Fig. 4. Monin-Obukhov scale

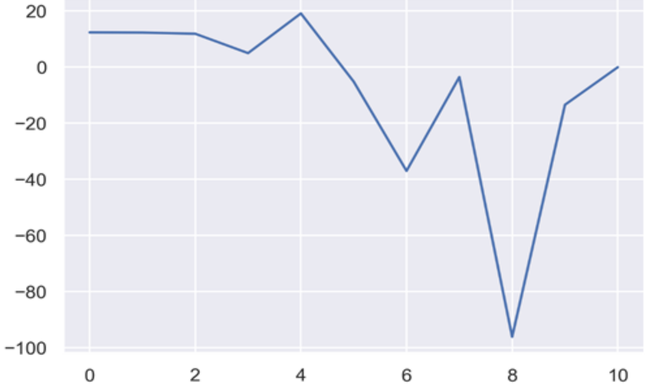


Fig. 5. Structural constant of fluctuations of the acoustic refractive index

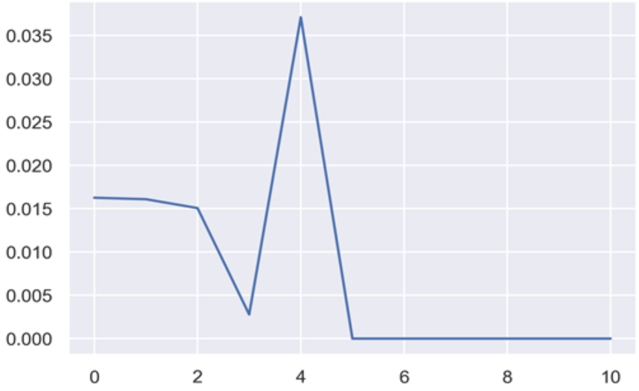


Fig. 6. External turbulence scale

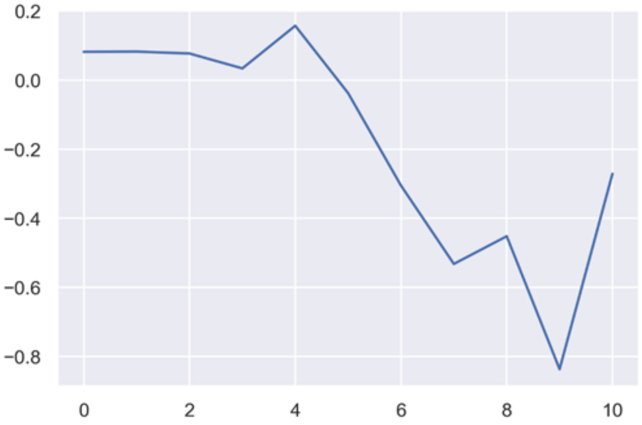


Fig. 7. Richardson Gradient

Scheme 2 is scaling. It includes program experiments for a same given series of observations, but each step of experiments is conducted by using data with size increasing in temporal scale by a fixed amount (fig. 3 - fig. 8). The figures show the results of calculation of some atmospheric turbulence parameters with discretization interval of 12.5 ms, and for following observation periods: 15 min (0), 1 hour (2), 3 hours (4), 9 hours (6), 18 hours (8), 24 hours (10).

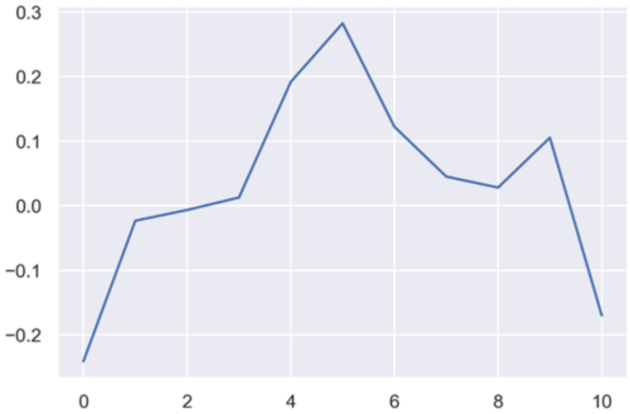


Fig. 8. Pulse flow moment

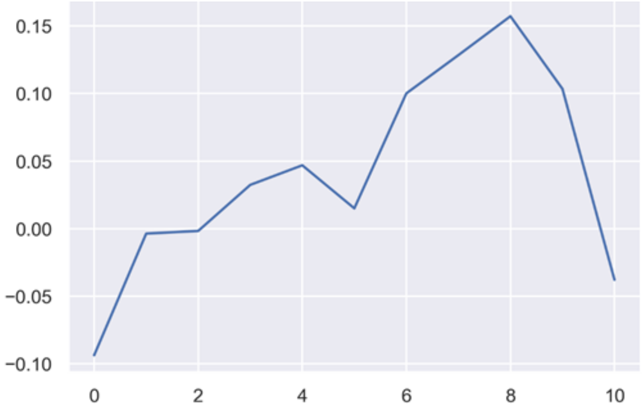


Fig. 9. Heat flow moment

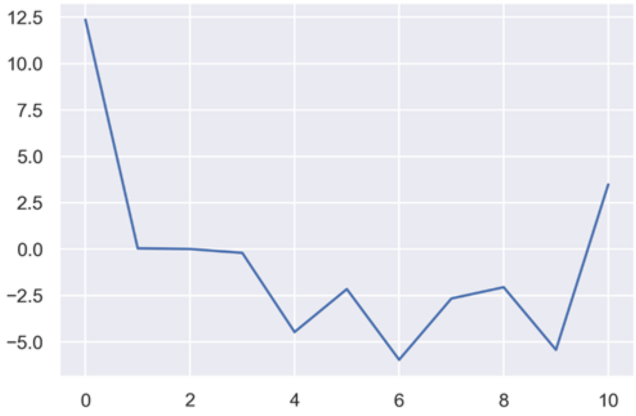


Fig. 10. Monin-Obukhov scale

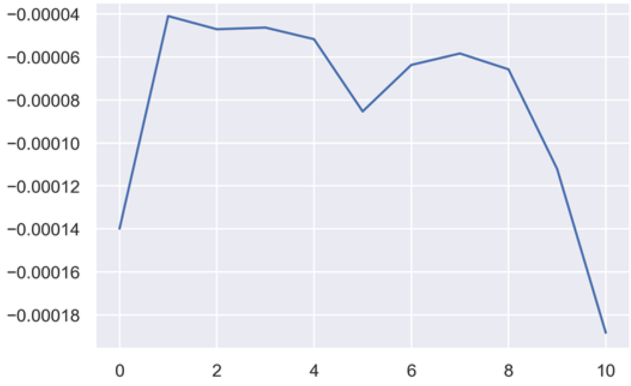


Fig. 11. Structural constant of fluctuations of the acoustic refractive index

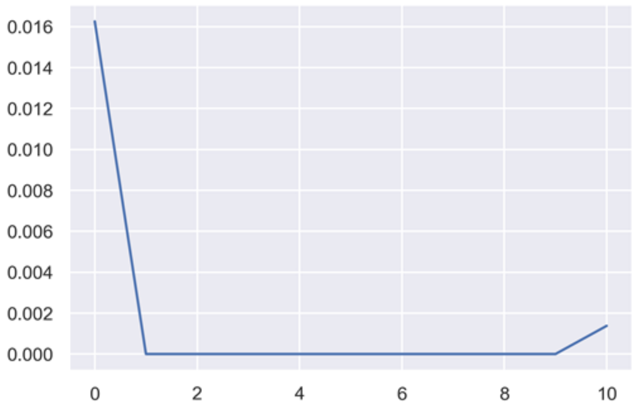


Fig. 12. External turbulence scale

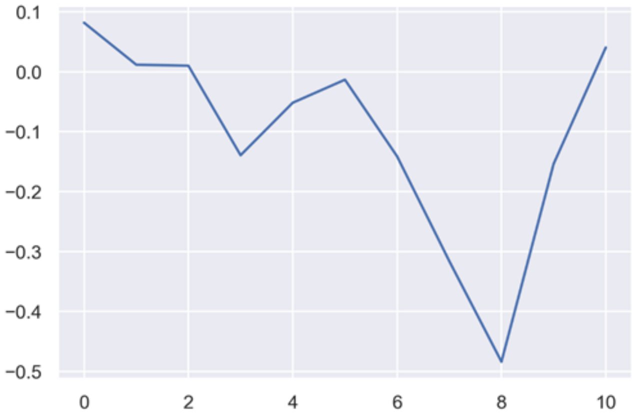
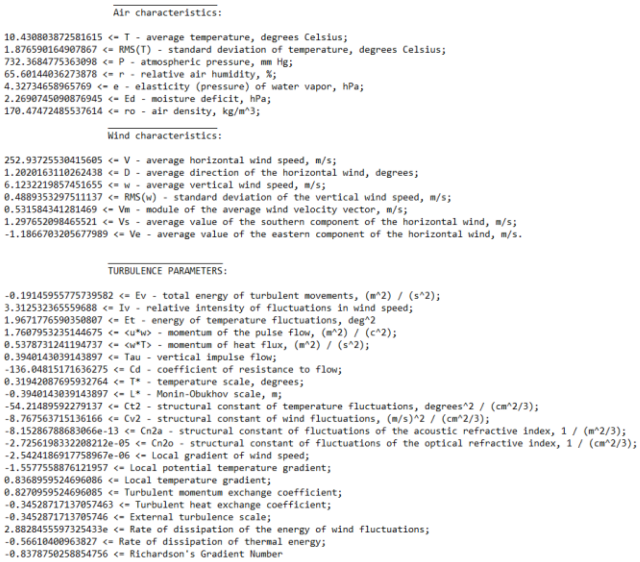


Fig. 13. Richardson Gradient

Fig. 14 shows a summary table of results. Turbulence parameters are added to air and wind characteristics: total energy of turbulent motions, relative intensity of wind speed fluctuations, temperature of temperature fluctuations, moment of flow of impulses, moment of heat flow, vertical flow of impulses, coefficient of resistance to flow, temperature scale, Monin-Obukhov scale, structural. temperature fluctuation constant, structural wind fluctuation constant, structural constant for acoustic refractive index, structural constant for optical refractive index, local wind speed gradient, local potential temperature gradient, local temperature gradient, coefficient of turbulent exchange of momentum, turbulent heat exchange coefficient, external scale turbulence, the energy dissipation rate of wind fluctuations, the energy dissipation rate of temperatures s fluctuations, gradient Richardson number.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                    Air characteristics:

10.430803872581615 <= T - average temperature, degrees Celsius;
1.876590164907867 <= RMS(T) - standard deviation of temperature, degrees Celsius;
732.3684775363098 <= P - atmospheric pressure, mm Hg;
65.60144036273878 <= r - relative air humidity, %;
4.32734658965769 <= e - elasticity (pressure) of water vapor, hPa;
2.2690745090876945 <= Ed - moisture deficit, hPa;
170.47472485537614 <= ro - air density, kg/m^3;

                   Wind characteristics:

252.93725530415605 <= V - average horizontal wind speed, m/s;
1.2020163110262438 <= D - average direction of the horizontal wind, degrees;
6.1232219857451655 <= w - average vertical wind speed, m/s;
0.4889353297511137 <= RMS(w) - standard deviation of the vertical wind speed, m/s;
0.531584341281469 <= Vm - module of the average wind velocity vector, m/s;
1.297652098465521 <= Vs - average value of the southern component of the horizontal wind, m/s;
-1.1866703205677989 <= Ve - average value of the eastern component of the horizontal wind, m/s.


                   TURBULENCE PARAMETERS:

-0.19145955775739582 <= Ev - total energy of turbulent movements, (m^2) / (s^2);
3.312532365559688 <= Iv - relative intensity of fluctuations in wind speed;
1.9671776590350807 <= Et - energy of temperature fluctuations, deg^2
1.7607953235144675 <= <u*w> - momentum of the pulse flow, (m^2) / (c^2);
0.5378731241194737 <= <w*T> - momentum of heat flux, (m^2) / (s^2);
0.3940143039143897 <= Tau - vertical impulse flow;
-136.04815171636275 <= Cd - coefficient of resistance to flow;
0.31942087695932764 <= T* - temperature scale, degrees;
-0.3940143039143897 <= L* - Monin-Obukhov scale, m;
-54.21489592279137 <= Ct2 - structural constant of temperature fluctuations, degrees^2 / (cm^2/3);
-8.767563715136166 <= Cv2 - structural constant of wind fluctuations, (m/s)^2 / (cm^2/3);
-8.15286788683066e-13 <= Cn2a - structural constant of fluctuations of the acoustic refractive index, 1 / (m^2/3);
-2.725619833220821 2e-05 <= Cn2o - structural constant of fluctuations of the optical refractive index, 1 / (cm^2/3);
-2.5424186917758967e-06 <= Local gradient of wind speed;
-1.5577558876121957 <= Local potential temperature gradient;
0.8368959524696086 <= Local temperature gradient;
0.8270959524696085 <= Turbulent momentum exchange coefficient;
-0.34528717137057463 <= Turbulent heat exchange coefficient;
-0.3452871713705746 <= External turbulence scale;
2.8828455597325433e <= Rate of dissipation of the energy of wind fluctuations;
-0.56610400963827 <= Rate of dissipation of thermal energy;
-0.8378750258854756 <= Richardson's Gradient Number
```

Fig. 14. Summary table of results

V. CONCLUSION

We would like to apologize for a small scale of results presented in the figures above. The analysis of the results is not included in the current work. Here we demonstrate the research tool for computing parameters of atmospheric turbulence. In other words, we are presenting a mathematical and software development for experimental research of the low-scale turbulence structure of the atmospheric surface layer. It allows clarifying and detailing the atmospheric processes, the degree of variability, to identify the signs of changes in weather and prerequisites for hazards by using data obtained via ultrasonic thermal anemometer.

The conducted research is the natured qualitative, since turbulence characteristics were calculated through standard experiments and analytical formulas. It allows obtaining formal ideas of turbulence phenomena. However, it has not necessarily to assess the dynamic turbulence regimes on the atmospheric surface layer, including the determination of the class stability of atmospheric stratification. For better understanding of atmospheric turbulence phenomenon of ground layer can be understandable by implementing of statistical analysis tools with the help of measured meteorological parameters.

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