Hardware-software complex for acoustic monitoring of meteorological fields in the atmospheric boundary layer

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Abstract. In the present paper, a hardware-software complex (HSC) intended for monitoring of lower layers of the atmosphere and subsequent forecasting of meteorological situations in a limited territory is described. The measuring network comprises remote and local meteorological measuring instruments distributed over the limited territory. The remote means of sounding are acoustic radars (sodars) and temperature profilers providing measurements of atmospheric parameters in the atmospheric boundary layer. The local instruments for measuring meteorological parameters in the near-ground layer of the atmosphere are ultrasonic meteorological stations. The key feature of the hardware-software complex is the application of multirotor aeromobile platforms (MAP) to the verification of data of remote meteorological measurements (RMP) in the atmospheric boundary layer to improve data quality.

1. Introduction
At present the problem of monitoring, supershort-term forecasting, and spatial extrapolation of the parameters characterizing the state of the near-ground and boundary layers of the atmosphere in a limited territory is extremely urgent. This is caused by the fact that the low density and high inhomogeneity of the network of aerological and meteorological station in the territory of Russia seriously restricts objective analysis of mesometeorological fields. In addition, the lack of data on the vertical profiles of meteorological parameters with high spatial resolution hampers the solution of the problem of supershort-term forecasting (for a forecast period of up to several hours).

The solution of problems of extrapolation and supershort-term forecasting of meteorological fields on the mesoscale level with the required spatial resolution and accuracy is closely related to the development of hardware for aerological and meteorological measurements [1-4] and mathematical methods of data processing [5-12]. In this connection, modern methods of remote sounding of the atmosphere have been recently developed for monitoring and subsequent forecasting of meteorological parameters. The most adequate means for these purposes is Doppler acoustic sounding. In acoustic sounding, natural atmospheric scatterers – turbulent vortices carried by wind that allow one to measure the current structure of the temperature and wind fields in the atmospheric boundary layer (ABL) – are used as targets [1, 2].

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In the near-ground layer of the atmosphere, it is expedient to use ultrasonic meteorological stations that provide local reference measurements of meteorological parameters by contact methods [3, 13].

The ABL height monitored with an acoustic radar (sodar) is usually several hundred meters and depends mainly on the current meteorological conditions. The vertical profiles of the measurable meteorological parameters can be extrapolated to higher altitudes using algorithms based on the theory of Kalman filtration and stochastic dynamical models [9–11]. The verification of acoustic measurements, refinement of the model parameters, and execution of algorithms of vertical extrapolation are provided by the application of multirotor aeromobile platforms (MAPs) [4]. A MAP equipped with a set of meteorological sensors allow contact measurements in a vertical profile of the ABL parameters to be performed during accent and descent of the measuring equipment. Taking into account the data obtained, the profiles of meteorological parameters can be reconstructed at altitudes up to several kilometers.

Based on the above, a hardware-software complex has been proposed and algorithms have been developed for spatio-temporal extrapolation of fields of meteorological parameters.

2. **Description of the hardware-software complex**

This paper continues and develops further the material presented in [13]. The general structure of the hardware-software complex (HSC) is shown in Figure 1. The hardware-software complex includes two main components: a measuring network (hardware) and a program-algorithmic complex (PAC). The measuring network includes three spatially separated measuring stations (MSs). Each MS is equipped with devices (both stationary and mobile) for measuring the meteorological parameters in the surface and boundary layers of the atmosphere [13]. The measurement data through communication channels arrive at the central server where they are stored and subsequently processed using the PAC.

The program-algorithmic complex is a multipurpose professional computing system providing solution of the following functional problems:

- Spatial extrapolation (interpolation) of temperature, wind velocity components, mesoscale wind shears, and turbulence characteristics in the surface and boundary layers of the atmosphere based on the results of real-time remote acoustic sounding at a point with preset coordinates in the territory uncovered by observations;
- Supershort-term forecasting (for a 12-h forecast period) of the atmospheric parameters (temperature, wind velocity components, and turbulence characteristic) based on real-time data of remote acoustic sounding in a given region;
- Spatial extrapolation of the vertical profiles of meteorological parameters with reconstruction of the parameter values at altitudes where measurement data are distorted or lacking.

The PAC comprises the following subsystems:

- Subsystem of transformation and processing of input data,
- Subsystem of adaptation to the state of the measuring sodar network and synoptic situation,
- Subsystem of supershort-term forecasting of atmospheric parameters at a point with preset coordinates,
- Subsystem of representation and visualization of computational results,
- User interface.

The operation of all above-listed subsystems is controlled by the user interface used to adjust the system parameters, to display the computational results on the monitor, to print them, and to store them in the memory from which they can be transmitted as primary parameters to more complicated complexes based on hydrodynamic models or through the communication channels to consumers of prognostic data.

The structure of the main subsystems and the key algorithms included into them are illustrated below.
Figure 1. Block diagram of the software-hardware complex for acoustic monitoring of meteorological parameters of the atmosphere equipped with a system of verification of data obtained from measuring devices placed on multirotor aeromobile platforms.

2.1. Subsystem of transformation and processing of input data
This subsystem is intended for testing of the integrity and reliability of data of the measuring network, rejection of distorted data, and their formatting for further storage in a database and use in extrapolation and forecasting algorithms [6, 9, 12].

Errors in the observation data arising during data recording, storage, and transmission through communication channels, and encoding and decoding lead to subsequent distortions of the results of spatial extrapolation and temporal forecasting. To reveal erroneous observations, the difference between
the actual measurement and its climatic (arithmetic average) values is used with subsequent comparison of the absolute value of the difference with $N \sigma$, where $\sigma$ is the standard deviation (SD) of the meteorological parameter being examined. Proceeding from the classical theory of hypothesis testing, it is assumed that $N = 3$.

The data of anomalous measurements are identified, rejected, or processed using adaptive algorithms [9, 16]. In this case the degree of reliability of the data is defined by a posteriori probability of anomalous overshoot calculated by the algorithm itself.

2.2. Base algorithm for subsystems of objective analysis and spatial extrapolation in the horizontal plane

The algorithm of spatial extrapolation (interpolation) of the meteorological parameter field at a point with preset coordinates provides the basis for all subsystems using spatial extrapolation in the horizontal plane. The algorithm is synthesized based on the theory of Kalman filtration [17] and is considered in detail in [9–10].

To synthesize the algorithm, the second-order spatial polynomial

$$
\xi_i(t) = a_0(t) + a_1(t)x_i + a_2(t)y_i + a_3(t)x_i^2 + a_4(t)y_i^2
$$

is used as the initial mathematical model, where $\xi_i(t)$ is the value of the meteorological parameter at the $i$th point at time $t$; $x_i$ and $y_i$ are the MS coordinates, or coordinates of the point on the plane chosen for forecasting.

The coefficients $a_0(t)$, $a_1(t)$, $a_2(t)$, $a_3(t)$, $a_4(t)$, and $a_5(t)$ determine the value of the meteorological parameter at each time at any point on the plane within a mesoscale experimental site. Therefore, within the limits of the theory of Kalman filtration, it is obviously possible to set the vector-column of the dynamic system states as follows:

$$
X(t) = [a_0(t), a_1(t), a_2(t), a_3(t), a_4(t), a_5(t)]^T.
$$

For convenience of technical realization of the synthesized algorithm, it is desirable to go over from continuous to discrete time with step $k$:

$$
X(k) = [X_1(k), X_2(k), X_3(k), X_4(k), X_5(k), X_6(k)]^T.
$$

The dynamics of changes of the state vector components of a dynamic system can be described by a system of six difference equations:

$$
\begin{align*}
X_1(k+1) &= X_1(k) + \omega_1(k) \\
X_2(k+1) &= X_2(k) + \omega_2(k) \\
&\ldots \\
X_6(k+1) &= X_6(k) + \omega_6(k)
\end{align*}
$$

or in the vector form, respectively,

$$
X(k+1) = \Phi(k)X(k) + \Omega(k),
$$

where $\Omega(k) = [\omega_1(k), \omega_2(k), \omega_3(k), \omega_4(k), \omega_5(k), \omega_6(k)]^T$ is the vector of generating noise (random system perturbations or state noise).
In this variant Equation (4) describes the elementary case assuming that the coefficients $a_i$ change randomly at each step $k$. Moreover, when $\sigma_0 \to 0$ Equations (4) describe constancy of the polynomial coefficients with time, that is, $a_i = \text{const}$. If necessary, a functional dependence of $a_i$ on time can be taken into account by using the corresponding mathematical expression in Equation (4).

According to the Kalman filter synthesis technique, the model of measurements takes the form

$$Z_i(k) = \hat{\xi}(k) + \varepsilon_i(k),$$

(6)

that is, measurements represent an additive mixture of the true value of the meteorological parameter $\hat{\xi}(k)$ given by Eq. (1) and of the measurement error $\varepsilon_i(k)$. For three measurement points ($i = 1, 2, 3$), the system of equations for observations takes the form:

$$Z_1(k) = \xi_1(k) + \varepsilon_1(k),$$

$$Z_2(k) = \xi_2(k) + \varepsilon_2(k),$$

$$Z_3(k) = \xi_3(k) + \varepsilon_3(k),$$

(7)

or in the matrix form:

$$Z(k) = H(k) X(k) + E(k),$$

(8)

where $H(k) = H(k, x, y) =

\begin{bmatrix}
1 & x_1 & y_1 & x_1^2 & y_1^2 \\
1 & x_2 & y_2 & x_2^2 & y_2^2 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
1 & x_n & y_n & x_n^2 & y_n^2
\end{bmatrix}

$$

is the transition matrix of measurements,

$$E^T(k) = \begin{bmatrix}
\varepsilon_1(k) \\
\varepsilon_2(k) \\
\vdots \\
\varepsilon_n(k)
\end{bmatrix}

$$

is the vector of measurement noise with the properties

$$M \{E(k)E^T(l)\} = R_l(k-l).$$

The dimensions of the vectors $Z(k)$ and $E(k)$ are determined by the number of measuring points $n$ (in this case, $n = 3$).

Matrix equations (5) and (8) unambiguously determine the structure of the algorithm for estimation of coefficients of the polynomial (1). According to the theory of Kalman filtration, the algorithm represents the following recurrent procedure:

$$\hat{X}(k+1) = \hat{X}(k+1 \mid k) + G(k+1) \cdot [Z(k+1) - H(k+1) \cdot \hat{X}(k+1 \mid k)],$$

(9)

where $\hat{X}(k+1)$ is the estimate of the state vector at the $(k+1)$th moment of time, $\hat{X}(k+1 \mid k) = \Phi(k) \cdot \hat{X}(k)$ is the calculated state vector at the $(k+1)$th moment of time being forecasted based on the data obtained at the $k$th step. The matrix $G(k+1)$ of weight coefficients is recurrently calculated from the known expressions [17].

The final value of the forecasted meteorological parameter $\hat{\xi}_0(k+1)$ at any point $i = 0$ with coordinates $(x_0, y_0)$ at the $(k+1)$th moment of time is calculated from the formula

$$\Phi(k) = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}

$$

is the $(6 \times 6)$ transition state matrix.
The order of choice of initial conditions to start execution of the filtration algorithm (9) at \( k = 0 \) (the initialization moment) was described in detail in [10]. It should be noted that the examined algorithm provides calculation of values of the field of meteorological parameters at one point. By changing the coordinates of the extrapolation point with a certain step and repeating the computation procedure many times, values of the meteorological parameters can be obtained for the entire preset local territory [9–11]. In this way the procedure of objective analysis was realized in the corresponding subsystem (Figure 1). Here values of the meteorological parameters were calculated at nodes of a regular grid with a step chosen by the PAC operator. In the subsystem of spatial extrapolation in the horizontal plane, the algorithm allows one to solve problems of calculating values of meteorological parameters along a preset rectilinear route.

2.3. Subsystem of adaptation to the state of measuring sodar network and synoptic situation

In actual practice, situations are possible when the number of measuring stations in the network changes. The stations can fail for technical reasons, scheduled switching off, moving to a new position, etc. In addition, during passage of an atmospheric front or a sharp change of the synoptic situation at a mesometeorological site, the conditions of uniformity and stationarity of meteorological fields may be violated. Accordingly, this may lead to failures in the operation of the extrapolation and forecasting algorithms and requires application of special adaptive data processing in a non-standard situation. The examined subsystem realizes a simplified adaptive algorithm of spatial extrapolation under conditions of a dynamically changing configuration of the measuring network and of sharp changes of the synoptic situation.

Synthesis of the adaptive algorithm of spatial extrapolation suggests updating of the classical expression (9) [6, 9]:

\[
\hat{\mathbf{X}}(k | k) = \hat{\mathbf{X}}(k | k-1) + \mathbf{p}(1 | k) \cdot \mathbf{G}(k) \cdot \mathbf{J}(k) \cdot [\mathbf{Z}(k) - \mathbf{H}(k) \cdot \hat{\mathbf{X}}(k | k-1)],
\]

where \( \mathbf{J}(k) \) is the diagonal matrix taking into account the presence of an atmospheric front at the points of location of measuring stations. Here \( \mathbf{p}(1|k) \) is an auxiliary diagonal matrix whose diagonal consists of a posteriori probabilities of correct operation of the measurement channels [16]:

\[
p_n(1 | k) = \frac{f_1^{(i)}(k) \cdot q^{(i)}(k)}{f_1^{(i)}(k) \cdot q^{(i)}(k) + f_0^{(i)}(k) \cdot [1 - q^{(i)}(k)]},
\]

where \( f_1^{(i)}(k) \) is the probability density distribution of measurements in the \( i \)th channel provided that \( \gamma(k) = 1 \), \( f_0^{(i)}(k) \) is the probability density distribution of measurements in the \( i \)th channel provided that \( \gamma(k) = 0 \), and \( q^{(i)} \) is the a priori probability of correct operation of the \( i \)th measurement channel. The distributions \( f_1^{(i)}(k) \) and \( f_0^{(i)}(k) \) are considered to be normal ones. For \( f_0^{(i)}(k) \), values \( \sigma_0^2 >> \sigma_1^2 \) are set (where \( \sigma_1^2 \) and \( \sigma_0^2 \) are the variances of noise in the measurement channel in the case of correct operation and failure, respectively).

As an obvious indication of passage of an atmospheric front, the attendant effect of sharp change in the wind direction by 90° [6, 9] was chosen. In this case, to reveal this effect in real time for each MS, the difference between (the increment of) the wind directions at two subsequent \((k)\)th and \((k + 1)\)th time moments is used [6, 9]:

\[
| \Delta Z(k + 1) | = Z(k + 1) - Z(k) \leq \Delta Z_{\text{thresh}},
\]

where \( \Delta Z_{\text{thresh}} \) is the threshold value of the wind direction change.
where $\Delta Z(k+1)$ is the change of the wind direction between two subsequent measurements; $Z(k+1)$ and $Z(k)$ are the wind directions measured, respectively, at the $(k+1)$th and $k$th time moments; $\Delta Z_{\text{thresh}}$ is its threshold value whose excess means passage of an atmospheric front and change in the synoptic situation at the measurement point. This technique is realized in Equation (11) in terms of the diagonal matrix $J(k)$. The elements of $J(k)$ are used to decide whether to use ($J_s=1$) or not use ($J_s=0$) of measurements at the $i$th station for estimating $\hat{X}(k|k)$. In the absence of atmospheric fronts within the mesoscale site $J(k) = I$.

Thus, performing the mathematical operations (11), the elements of the measurement vector $Z(k)$ for anomalous or lacking measurements or measurements performed during passage of the atmospheric front are excluded from the estimate $\hat{X}(k|k)$ or used with a lower weight. The final computation of the extrapolated value of the meteorological parameter at the point $(x_j, y_j)$ at the $k$th time moment is performed using formula (10).

2.4. Subsystem of supershort-term forecasting of atmospheric parameters

The problem of temporal extrapolation of a meteorological parameter at the point of MS location is solved by using the algorithm based on the second-order polynomial mathematical model [10] with an additional term taking into account periodic fluctuations characterizing natural variations of the examined process with time [9, 10]:

$$
Z(t) = a_0(t) + a_1(t) t + a_2(t) t^2 + A(t) \cos \left( \frac{2\pi}{24} t - \varphi(t) \right) + \varepsilon(t),
$$

where $Z(t)$ is the value of the meteorological parameter field at the observation point; $\varepsilon(t)$ is the observation error; $A(t) \cos \left( \frac{2\pi}{24} t - \varphi(t) \right)$ is the term considering periodic changes of the meteorological parameter during the observation period; $a_0(t)$, $a_1(t)$, and $a_2(t)$ are the unknown coefficients of the polynomial to be estimated; and $A(t)$ and $\varphi(t)$ are unknown values of the amplitude and phase of the diurnal variation of the meteorological parameter.

To solve the problem of temporal forecasting of the mesometeorological fields based on the model (14), the nonlinear algorithm of the Kalman filtration theory [9, 10, 17] was used. The algorithm was synthesized similarly to that considered in Subsection 2.2.

It should be noted that the spatio-temporal forecasting is based on the spatial extrapolation algorithms rather than on current measurements of the parameters being forecasted. This allowed us to calculate the value of the meteorological parameter at a preset point of space with the required term of forecast.

2.5. Subsystem of spatial extrapolation of meteorological parameters in the vertical plane

As noted above, the ABL height observed by the acoustic radar (sodar) is conventionally limited by several hundred meters. The verification of acoustic measurements and periodic refinement of the model parameters based on the contact methods are necessary for qualitative extrapolation of the vertical profile up to the altitude of the upper ABL boundary. For this purpose, the MS must be equipped with unmanned aerial vehicles [4]. The required set of meteorological sensors placed on a multirotor aeromobile platform (MAP) can be used to measure the vertical profiles of the wind speed and direction, temperature, humidity, and air pressure in the ABL during the sensor accent and descent. We now consider the algorithm of reconstruction of vertical profiles of the meteorological parameters measured with the sodar using data periodically arriving from the MAP.

During the MS operation, the vertical profiles of meteorological parameters are measured. The sodar yields 3 profiles per 1 h (the measurement period is 20 min). The contact sensors (placed on a
quadrocopter) yield 2 profiles every 3 h (20 min ascent and descent to an altitude of 2.0 km and 2.5 h preparation for the next launching). During the ascent and descent the quadrocopter hangs immobile (creates platforms) to fix the measurements of meteorological parameters at preset altitude levels. The altitude of the upper measurement level is 2 km. For the vertical grid step $\Delta h = 10$ m, the number of altitude levels is $N = 200$. For the step $\Delta h = 50$ m, the number of levels $N = 40$.

The profile measured by the MAP is considered to be the reference one, since it contains the most reliable measurements, and is used during the subsequent 3 h before the next refinement. Between refinements values of the meteorological parameters in the vertical profile are estimated using sodar measurements. Thus, the profile is reconstructed by extrapolation of the data from the last actually measured level to the altitude of the upper ABL boundary (2 km).

Let us consider the algorithm of reconstruction of the vertical profiles of meteorological parameters measured with the sodar using periodically arriving data from the MAP. We designate the reference ABL profile $\mathbf{Z}(k) = \{\mathbf{Z}(k), \mathbf{Z}_1(k), \mathbf{Z}_2(k), ..., \mathbf{Z}_N(k)\}$, where $h = (1,2,3, ..., N)$ are the numbers of the altitude levels in the vertical profile, and $N = 200$ (or 40) is the number of the upper boundary level of the ABL depending on the regular grid step $\Delta h$. The vertical profile with sodar measurements is $\mathbf{Z}_s(k) = \{\mathbf{Z}_s(k), \mathbf{Z}_s(k), \mathbf{Z}_s(k), ..., \mathbf{Z}_n(k), ..., \mathbf{Z}_n(k)\}$, where $n$ is the number of the upper level of sodar measurements. Here $n$ changes from measurement to measurement depending on a concrete meteorological situation. In this case, the existence of a stable linear dependence between the values of the meteorological parameters for two neighboring altitude levels is assumed. The dependence is given by the mathematical expression $\mathbf{Z}_n(k) = \mathbf{Z}_{n-1}(k) + \gamma_n \cdot \Delta h_{n-1,n}$, where $\gamma_n$ is the proportionality coefficient between the values of the meteorological parameters at the $n$th and $(n-1)$th altitude levels. The extrapolation procedure is as follows:

- At the moment of arrival of measurements of the next reference ABL profile ($k = 0$), the proportionality coefficients $\gamma_n = [\mathbf{Z}_n(0) - \mathbf{Z}_{n-1}(0)] / \Delta h_{n-1,n}$ are calculated for all altitude levels. The $\gamma_n$ values form the vector $\Gamma = [\gamma_1, \gamma_2, \gamma_3, ..., \gamma_N]$.

- When the next sodar profile arrives, the difference between the measurements is calculated (they are centered) [7, 10] from the formula $\mathbf{Z}_n(k) = [\mathbf{Z}_n(k) - Z_n(k)]$. The centered values are then processed using the Kalman filter which allows the smoothed estimate $\hat{Z}_n(k)$ of the current deviation from the regular behavior $\mathbf{Z}_n(k)$ to be obtained for each altitude level.

- The estimated deviation for the upper level measured with the sodar is used to reconstruct (extrapolate) the values of the meteorological parameters in the vertical profile up to the upper ABL boundary. The calculations are performed using the recurrent relations

$$\hat{Z}_n(k) = \hat{Z}_{n-1}(k) + \gamma_n \cdot \Delta h_{n-1,n};$$

$$Z_n(k) = \hat{Z}_n(0) + \hat{Z}_n(k).$$

Thus, the algorithm of spatial extrapolation in the vertical plane provides reconstruction of the vertical profile from the sodar data starting from the upper actually measured altitude level to the upper ABL boundary. It should be noted that the algorithm is not limited by the application of sodar measurements and the upper measurement layer altitude. It is possible to complete measurements with the data of a ground-based ($h = 0$) meteorological station and to perform extrapolation already from the altitude level $h = 10$ m. This is of interest for the case when the vertical profile must be forecasted more often than every 20 min.
3. Conclusions
The structure of a hardware-software complex was considered to provide spatial extrapolation of fields of meteorological parameters including temperature, wind velocity components, mesoscale wind shears, and turbulence characteristics in the surface and boundary layers of the atmosphere. The meteorological fields and the extrapolation are based on remote acoustic sounding and measurements using a multirotor aeromobile platform.

A new original algorithm was proposed for spatial extrapolation of vertical profiles of meteorological parameters with reconstruction of the parameters at altitude levels where the measurement data are distorted or not found at all.

A model test of the PAC was performed to demonstrate the feasibility of forecasting of vertical profiles of the temperature and wind velocities for distances up to 100 km.

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