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DEVELOPMENT OF A METHOD FOR ADAPTATION OF RADIOACOUSTIC SOUNDING SYSTEMS OF THE ATMOSPHERE TO THE METEOROLOGICAL CONDITIONS

The object of research is the process of ensuring the Bragg condition between the lengths of acoustic and electromagnetic waves when measuring the altitude profiles of the atmosphere using the radioacoustic sounding (RAS) method.

The problem solved in the work is the lack of a generalized theoretical basis for developing methods for adapting RAS systems to maintain the Bragg condition during the movement of the acoustic wave packet (AWP) in the atmosphere.

In the work, using the theory of stochastic optimal control, a method for frequency adaptation of RAS systems was developed to ensure the Bragg condition along the sounding path. The method includes the operations of estimating the speed of sound, stochastic linear filtering of the AWP state parameter vector and controlling the frequency of the radio signal based on the obtained data. A method for estimating the information parameters of the signal was proposed, and an algorithm for sequential filtering of AWP parameters was developed.

The developed frequency adaptation method will significantly improve the quality indicators of RAS systems – the accuracy of measuring atmospheric temperature profiles and the efficiency of sounding. The use of the method in practice will also allow to increase the range of sounding systems by more effectively adjusting to the Bragg conditions at small values of the signal-to-noise ratio, characteristic of long ranges.

The improvement of the main characteristics of the systems is achieved by more accurately ensuring the Bragg condition in the process of measuring the sound speed values, as a result of which the measurement results do not have systematic errors, and the random component of errors is significantly reduced. Therefore, the averaging time of individual measurement results to achieve the required integral accuracy of estimating the atmospheric temperature profile is significantly reduced, from tens to units of minutes.

The proposed method can be implemented in practice by improving the existing RAS atmospheric systems manufactured by industry.

Keywords: *radioacoustic sounding of the atmosphere, Bragg condition, frequency adaptation, stochastic control, sounding signal.*

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1. Introduction

The method of radioacoustic sounding (RAS) of the atmosphere allows obtaining the necessary information about the state of the lower layers of the atmosphere in the form of vertical profiles of temperature, wind speed and direction [1]. The principle of operation of RAS systems is based on the scattering of radio waves on the inhomogeneities of the environment created by acoustic waves [2].

The method has been developed for several decades [3] and is currently used in practice in solving a number of urgent applied problems – meteorological support for take-off and landing of aircraft [4], weather forecasting [5], detection of weather conditions that can lead to the creation of a dangerous environmental situation [6]. Radioacoustic sounding stations are produced by a number of manufacturing companies in small batches.

A feature of the method is that obtaining a sufficient level of the reflected radio signal for processing and recording in RAS systems of the atmosphere is possible only when the Bragg relation between the lengths of the sound λ_s and electromagnetic λ_e waves is fulfilled. The physical reason for the violation of the Bragg condition in the atmosphere is the change in the spatial length of acoustic waves under the influence of changing weather conditions, primarily temperature [7].

Thus, an essential feature of RAS systems is the need to maintain the Bragg condition in space – the correspondence between the lengths of the acoustic and electromagnetic waves, which ensures the "resonant" nature of the scattering of radio waves on sound. It is possible to achieve the fulfillment of the Bragg condition in the process of measuring the profiles of meteorological parameters by changing the frequency of either the acoustic or electromagnetic signals.

A number of methods for adapting RAS systems to changing conditions are known in the literature in order to compensate for the impact of the violation of the Bragg condition on the quality of radioacoustic sounding [8]. However, the known adaptation methods and algorithms are not sufficiently perfect, since they are developed heuristically without using the main achievements of control theory, and do not take into account the peculiarities of scattering of electromagnetic waves on inhomogeneities created by sound.

Due to the inefficiency of the current adaptation algorithms, the results of temperature measurements have significant non-random errors, and the time for measuring temperature profiles is too long and is about one hour [9].

Therefore, there is a need to develop a more effective method for adapting RAS systems to variable external atmospheric conditions using the basic principles of the theory of stochastic optimal control.

Currently, RAS systems are produced by a number of research and production companies: METEK, REMTEC, BIRAL, SCINTEC. The RAS system of the METEK company [10] is built on the basis of the PCS.2000 Doppler sodar by supplementing it with radar components. The system is fully integrated into the structure and algorithms of the sodar operation: its sounding acoustic radiation, a scattered signal processing system, a personal computer with the Windows operating system, which is part of the sodar structure, are used. Radar transmitters and receivers that supplement the acoustic system to the RAS system operate at frequencies of 915 and 1290 MHz, and for measurements at longer distances, a version of the system is available at a frequency of 482 MHz. Continuous unmodulated radio radiation is used at all operating frequencies and, accordingly, two antennas – transmitting and receiving.

The PCS.2000-24 sodar [10] operates at audio frequencies of 1500–2900 Hz, emits a pulsed acoustic signal with the possibility of changing the pulse duration and provides a maximum sounding height of 1000 m.

To ensure that the Bragg condition is met in the entire possible range of ambient temperatures expected in the vertical profile, the acoustic emitter sequentially scans the frequency in an interval wide enough to ensure the presence of all the necessary spatial wavelengths in the atmosphere.

The RAS system from Biral [11] is also built on the basis of the PCS.2000 sodar from METEC, only using a different set of radio equipment. The radio channel operates in the mode of continuous unmodulated radiation, and the acoustic radiation is pulsed. When performing the sounding process, the frequency of the sounding acoustic signal changes for each height range depending on the changing metrological conditions, primarily temperature. In this case, the average frequency of the acoustic signal remains 2900 Hz ($\lambda_s = 0.115$ m), and the frequency of the electromagnetic wave is 1274 MHz ($\lambda_e = 0.23$ m).

The RAS system from Remtech [12] is built on the basis of PA-0 or PA-5 acoustic locators developed by the same company, and also includes a CW radar, which is added to the specified brands of sodars used. The sounding acoustic signal is emitted using the acoustic locator used, and a digital sodar signal processing system is used to process and extract useful information from the radio signal scattered on the sound. The RAS system operates at frequencies of 915 MHz or 1290 MHz, the PA-0 sodar [13] at a frequency of 3.6 kHz, and the PA-5 sodar [14] at a frequency of 1 kHz.

Thus, satisfying the Bragg condition requires that different values of acoustic frequencies be used for different radar frequencies. The range of acoustic frequencies used extends from approximately 100 Hz for radars with a radio frequency of 50 MHz to 4 kHz for radars operating at around 2 GHz.

The characteristics of the methods of adaptation to the meteorological situation, which are implemented in industrial RAS systems, largely determine the potential capabilities of the methods of measuring meteorological parameter profiles. The fulfillment of the Bragg condition in the process of obtaining atmospheric temperature profiles must be ensured with a sufficiently high accuracy, since deviation from this condition leads to a decrease in the amplitude of the scattered signal. In addition, a systematic error is formed in the results of measuring the speed of sound, and therefore, the temperature. The value of the systematic error in temperature can reach 1–2°C and even more.

Currently, there are no effective methods of controlling the frequencies of sounding acoustic and radio signals that ensure the necessary accuracy of fulfilling the Bragg condition in the sounding process. Methods of adaptation by changing the frequency of acoustic radiation have been developed in more detail and it is they that are used in modern systems produced by industry due to their simplicity and relative efficiency. Methods based on changing the frequency of the radio signal are imperfect, and their implementation in practice is still unknown.

Therefore, in the above-mentioned industrial RAS systems, when obtaining altitude profiles of atmospheric temperature, sounding techniques based on changing the frequency of the acoustic signal are used. A "cloud" of measurement results is formed, which is characterized by significant redundancy. Processing of the redundant "cloud" of data allows eliminating systematic errors in the results of temperature measurements.

Significant redundancy is achieved in the obtained measurement results at each sensing height in the following way. As a rule, several acoustic wave packets are emitted with a small time delay and at different acoustic frequencies. Each of the packets ensures the receipt of a reflected radio signal from several altitude points of the profile, while the value and sign of the parameter $q = \lambda_e - 2\lambda_s$ of violation of the Bragg condition at different points of the profile will be different. Then, the atmosphere is sounded at other values of the frequencies of the sounding acoustic signal, which leads to a change in the conditions of radio wave scattering at the considered points of the profile. As a result, the value and sign of the parameter q at these points change, and therefore the modulus and sign of the systematic error in the results of measurements of the speed of sound and temperature. Thus, over a certain period of time, about several tens of minutes, a significant number of measurement results accumulate at each altitude point of the data "cloud" profile. Given that the scattered radio signals were formed at each point of the profile under different conditions and at different values of the parameter q, the obtained measurement results have different values of the systematic error – in modulus and in sign. As a result, the obtained systematic errors are compensated for in the averaging process. Thus, in the used method of sounding and obtaining profiles of meteorological parameters, the formation of a significant in volume, characterized by redundancy, array of measurement results allows significantly reducing the impact of systematic errors of single measurement results on the averaged temperature profile. As a result, the averaged temperature profile [15] obtained by the RAS system and the profile obtained using traditional contact sensors are in agreement within approximately 0.2°C.

This approach allows obtaining meteorological parameter profiles only with a significant averaging time of about one hour, which significantly limits the efficiency – one of the potential advantages of the method. The time spent on obtaining altitude profiles of meteorological parameters can be compared with the time of quasi-stationary processes in the atmosphere, during which, in principle, it is possible to average meteorological parameter values without a significant increase in the resulting measurement error caused by a non-stationary trend. Obtaining profiles within a shorter time, which is required when solving a number of applied problems, cannot be achieved with acceptable accuracy in principle.

The method of measuring atmospheric temperature profiles, implemented in most of the currently known RAS systems produced by the industry, was proposed by development engineers, since science could not offer effective methods for adapting systems to changes in weather conditions. In these conditions, the development engineers proposed a heuristic procedure based on the concept of forming a data array that has significant redundancy and is formed over a long period of time [16]. In the process of processing the data array, due to its redundancy, it is possible to reduce the impact of systematic errors of single measurement results performed when the Bragg condition is violated on the averaged profile.

A cardinal solution to the issue of increasing the efficiency of radioacoustic sounding of the atmosphere and the accuracy of measuring meteorological parameters would be to adjust the frequency of electromagnetic radiation to the Bragg condition as the acoustic pulse advances in the atmosphere.

A significant drawback of all currently known adaptation algorithms is that they are deterministic, i. e. they do not take into account random errors that arise when measuring the Doppler frequency of a radio signal. These errors are caused, first of all, by the action of internal noise of the equipment, the instability of the frequency of the radio transmitter, as well as the influence of external interference coming to the input of the radio receiving device. In addition, the known algorithms are characterized by the fundamental existence of a dynamic error caused by not taking into account the regularities of the process change observed in the time and space intervals between measurements. Due to the above shortcomings, there are no known cases in the literature of successful implementation of the method of adapting RAS systems with radio signal frequency tuning in practice. Thus, currently known algorithms for frequency adaptation of RAS systems were obtained by a heuristic method and do not meet the requirements imposed by the practice of meteorological observations in terms of accuracy and efficiency of obtaining the necessary profiles of meteorological parameters.

The object of research is the process of ensuring the Bragg condition between the lengths of acoustic and electromagnetic waves in the process of measuring atmospheric temperature profiles by radioacoustic sounding.

The aim of research is to develop a method for frequency adaptation of RAS systems to a changing meteorological situation by controlling the frequency of the sounding radio signal using the main achievements of the theory of stochastic optimal control and the theory of measuring radio systems.

Research objectives:

1. To develop a method for controlling the frequency of the sounding radio signal to fulfill the Bragg condition in RAS systems.
2. To propose a method for estimating signal parameters to determine the speed of sound.
3. To develop an algorithm for filtering and extrapolating the vector of state parameters of an acoustic wave packet.

As a result of more accurate provision of the Bragg condition using the developed method in the process of measuring sound speed values, the measurement results will not have systematic errors, and the random component of errors is significantly reduced. Therefore, it is expected that the time for averaging individual measurement results to achieve the required integral accuracy of estimating the atmospheric temperature profile will also be significantly reduced (from tens to units of minutes).

2. Materials and Methods

The conducted studies used the methodology of systems research and design of information radio-electronic systems [17], methods of theoretical analytical synthesis of signal processing devices, adequate mathematical models of useful radio signals carrying information about the state of the atmosphere. Methods of mathematical computer modeling of devices and algorithms of radio system functioning are also used to verify their operability and evaluate the values of quality indicators of synthesized devices.

According to the principle of decomposition, the tasks of adaptation to a changing meteorological situation and the tasks of controlling the parameters of vector sounding signals of sounding systems in order to fulfill the Bragg condition as the acoustic wave packet passes through the atmosphere are distinguished from the complex algorithm of RAS systems. When developing a method for controlling the frequency of the sounding radio signal, the methods and results of the theory of stochastic optimal control [18] are used, and when developing an algorithm for filtering and extrapolating the state vector of the acoustic wave packet, the theory of optimal linear Kalman filtering of random processes [19] is used.

It is proposed to measure the speed of sound in the atmosphere in the sounding signal frequency control loop based on the results of estimating the parameter q. The methods of measuring the speed of objects based on the results of Doppler frequency measurements, which are common in technology, cannot be used in this case, since the measurement results will have a significant systematic error. Using measurement results with a systematic error in a closed control loop will lead to a breakdown of the auto-tracking process.

The work also uses and investigates models, methods, and techniques [20] developed in the theory of radio-acoustic sounding of the atmosphere, which relate to the issues of studying the impact of violation of the Bragg condition on the operation of RAS systems. Currently, there is a significant number of scientific results that have made it possible to clarify the essence of physical processes that affect the violation of this condition in the process of radioacoustic sounding in order to obtain vertical profiles of meteorological parameters. At the same time, the state of current technical means of sounding does not allow to ensure the fulfillment of this condition in the process of functioning of RAS systems. And the current state of the theory of RAS systems does not allow to eliminate this drawback and ensure the synthesis of sufficiently advanced devices and algorithms for controlling the frequencies of sounding signals.

The current situation has deep reasons. In the field of radioacoustic sounding, a powerful scientific school has been formed that studies the propagation and scattering of waves in a turbulent atmosphere. The research of scientists from this school has made it possible to clarify issues related to the violation of the Bragg condition.

At the same time, the issue of studying the features of the functioning of RAS systems has not been developed sufficiently. This is primarily due to the fact that most of the technical solutions used in such stations were borrowed from the field of radar. However, the sound package used as a radar target in RAS systems has a number of significant features, which is due to the significant influence of the characteristics of the atmosphere on the sound packet. One of these features is the change in the acoustic wavelength under the influence of the atmosphere, which leads to a change in the Bragg condition. A full-fledged methodology for research and design of RAS systems, which takes into account the features of the observation object used, has not yet been formed in science.

In the process of designing modern industrial RAS systems, development engineers, based on a heuristic approach and engineering acumen, developed methods for adapting to a changing situation and based on them, methods for measuring meteorological parameter profiles. However, the application of systems analysis methods to study technical solutions for RAS systems manufactured by industry showed that these solutions are imperfect and do not meet the requirements of practice.

Thus, to solve current scientific and applied problems – problems of developing methods for tuning to the Bragg condition in RAS systems, heuristic, engineering methods were previously used. In the conducted studies, the problem is posed, formulated and solved using methods and approaches that are currently developed in the relevant scientific disciplines – the theory of stochastic optimal control and the theory of measuring radio-electronic systems. The research methods used in the indicated fields are proven in practice and ensure reliable scientific results.

To verify the developed methods, the MATLAB R2018b software environment was used, in which simulation of signal processing methods and control of sounding station parameters using m-files was performed.

3. Results and Discussion

3.1. Method of controlling the frequency of the sounding radio signal to fulfill the Bragg condition in RAS systems

Processes that lead to violations of the Bragg condition during the propagation of an acoustic packet in turbulent atmosphere conditions, as well as processes that cause errors in measuring the speed of sound, are random. Therefore, the task of developing a method of controlling the frequency of the sounding radio signal should be considered as a task of stochastic optimal control.

This task is formulated as follows: based on the sequential observation of the propagation speed of the acoustic wave packet (AWP) using radar measurements, it is necessary to perform optimal, in the sense of the selected quality criterion, adjustment of the frequency of the sounding radio signal to fulfill the Bragg condition.

As a criterion of optimality of the functioning of the device for controlling the frequency of the sounding radio signal to fulfill the Bragg condition, it is possibel to choose an accuracy criterion. Depending on the choice of the appropriate physical parameters, two types of writing of the optimality criterion are possible:

$$J_M = \left\langle \left\{ \sum_{k=1}^{M} \left(\left[\lambda_{ek} - 2\lambda_{sk} \right]^2 \right) \right\} \right\rangle,$$
$$J_M = \left\langle \left\{ \sum_{k=1}^{M} \left(\left[c_{sk} - c_{s0k} \right]^2 \right) \right\} \right\rangle, \qquad (1)$$

where M – the number of points of the height profile; k – current point of the profile; λ_{sk} – the value of the wavelength of the acoustic signal at the k-th point; λ_{ek} – the wavelength of the sounding radio signal; c_{s0k}, c_{sk} – the true and determined (to achieve the Bragg condition) value of the sound speed; the sign <·> means the mathematical expectation operation.

The criterion of the form (1) provides the minimum of the integral dispersion of the tuning error for the Bragg condition, as well as the minimum of the tuning dispersion for each time point (each profile point).

The quadratic quality criterion chosen to solve this problem has an important feature that allows to significantly simplify the task of developing a method for optimal control of the radio signal frequency. This feature is associated with the existence of the so-called principle of stochastic equivalence (the principle or theorem of separation) [21]. This result occupies a very important place in the problems of synthesis of optimal controls in linear and nonlinear systems under random disturbances and is widely used in theory and practice.

For linear systems, the separation theorem is formulated as follows [21]. The optimal controller under random Gaussian processes and a quadratic quality criterion is a serial connection of the optimal linear filter for estimating the system state vector and the deterministic optimal controller. This important result allows to reduce the control problem to two sequentially solved separate problems of stochastic filtering and deterministic control (Fig. 1).

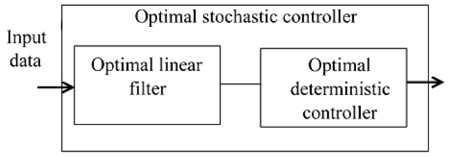

Fig. 1. Separation of the optimal stochastic control function into two sequentially performed operations – stochastic filtering and deterministic control

The optimal linear filter implements the stochastic averaging operation in this sequential scheme, and the optimal deterministic controller – the functional part of the control.

Thus, the method of controlling the frequency of the sounding radio signal of RAS systems includes the operations of estimating the speed of sound, stochastic linear filtering of the vector of parameters of the state of the acoustic wave packet and controlling the frequency of the radio signal based on the received data.

3.2. Method of estimating signal parameters

A significant drawback of the known algorithms for controlling the parameters of sounding signals for tuning to the Bragg condition is the use of the results of Doppler measurements for this. But the results of measuring the Doppler frequency in RAS systems carry a significant systematic, non-random error, which prevents sufficiently accurate tuning to the Bragg condition. As shown [22], it is advisable to estimate the speed of sound at each altitude point of the profile using the measurement of the informative parameter of the signal q. In this case, each value of the parameter q will correspond to its own form of the scattered radio signal, which is determined by the scattering function $F(t, q)$.

In this case, the value of the informative parameter q is determined using a multi-channel correlation estimation scheme by selecting the channel with the largest value of the output signal amplitude [23].

For different fixed values of the parameter, the shape of the curve of the function $F(t, q)$ is different and corresponds to the shape of the scattered radio signal in the atmosphere at a certain value of the sound speed. Forming reference signals using the scattering function, which determines the shape of the electromagnetic signal scattered by the AWP and, comparing them with the radio signal received from the atmosphere, it is possible to estimate the speed of sound at which the received radio signal was formed.

Since the parameter q is functionally related to the speed of sound and for all reference signals the values of the parameter q are known, in which they were formed, the processing result is determined by the value of the parameter q [24], and then the current value of the speed of sound at a given point of the profile is calculated

$$c_s = 2\pi f_s c_e / \left(4\pi f_e - q c_e\right), \qquad (2)$$

where f_e – the frequency of the radio signal; f_s – the frequency of the acoustic signal; c_e – the speed of propagation of radio waves.

The algorithm for processing the obtained sound velocity values is further considered using the procedure of sequential filtering and controlling the frequencies of the sounding oscillations based on the filtering results. According to the results of sequential filtering, it is possible to obtain $c_{s(k)}$ – the optimal estimated value of the sound velocity at the previous altitude level (at the previous profile point), $c_{s0(k+1)}$ – the value of the sound velocity extrapolated to the next profile point.

The extrapolated value $c_{s0(k+1)}$ is used to calculate the required value of the radio signal frequency and to adjust the frequency of the radio transmitter to the Bragg condition

$$f_{e(k+1)} = c_e f_s / \left(2 c_{s0(k+1)}\right). \qquad (3)$$

The optimal estimate of the sound velocity value $c_{s(k-1)}$, obtained according to the results of sequential filtering at the current profile point, is used to calculate the temperature value at this altitude level.

A more detailed description of the sequential filtering algorithm used in the frequency control loop of the RAS systems' probing signals is given below.

3.3. Algorithm for filtering and extrapolating the acoustic wave packet state parameter vector

The structure and parameters of the optimal linear Kalman filter largely depend on the mathematical model of the filtered process used, which also has a significant impact on the filtering efficiency.

The peculiarity of the filtered process in the considered problem is due to the complexity and spatio-temporal variability of atmospheric processes, the dynamics of changes in its main characteristics – temperature, wind speed and direction, air humidity, the presence of turbulence [25]. The parameter to be filtered in this problem – the speed of sound, is an integral characteristic of the environment and depends on all the above characteristics. Therefore, the AWP propagating in a real turbulent atmosphere is a rather complex object for observation. In connection with this issue of choosing an adequate mathematical model of the filtered process – the dependence of the speed of sound on height, the necessary attention should be paid when building a filtering algorithm in specific atmospheric conditions [5].

A similar task of constructing a filtering algorithm and selecting a mathematical model implemented in the filter is considered in observation systems for various objects – space, aerodynamic, maneuvering, non-maneuvering, etc. As is known from the literature, each of these objects uses its own mathematical model of motion and its own, special filtering algorithm.

Optimal linear filtering of sound velocity estimates in RAS systems in order to adapt sounding systems to a changing meteorological situation consists in sequentially obtaining estimates of the state vector of the acoustic wave packet at a specific point of the profile. In this case, the algorithm for sequential filtering and extrapolation of the values of the wave packet parameters is determined by the selected mathematical model that describes the nature of the change with height of the parameter being estimated – the sound velocity.

For example, at the *k*-th measurement step, as a result of the primary processing of the radio signal reflected from the sound packet, an estimate of the acoustic packet state vector $\widehat{\boldsymbol{c}}_{sy(k)} = c_{sy(k)}\dot{c}_{1sy(k)}^{\;T}$ was obtained, where $c_{sy(k)}$ – an estimate of the sound speed; $\dot{c}_{1sy(k)}$ – an estimate of the first derivative of the sound speed. Next, the state vector is predicted at the $(k + 1)$-th step, to the next profile point, at which an a priori estimate $\widehat{\boldsymbol{c}}_{s0(k+1)}$ will be formed.

At the $(k + 1)$-th measurement step, as a result of processing the input signal, a current estimate of the packet state vector $\widehat{\boldsymbol{c}}_{sy(k+1)}$ is formed. Then, based on the estimates $\widehat{\boldsymbol{c}}_{s0(k+1)}$ and $\widehat{\boldsymbol{c}}_{s0(k+1)}$, an optimal estimate $\widehat{\boldsymbol{c}}_{s(k+1)}$ is formed. The first component $c_{s0(k+1)}$ of the extrapolated value of the AWP state vector $\widehat{\boldsymbol{c}}_{s0(k+1)}$ is used to determine the frequency of the sounding radio signal at the $(k + 1)$ profile point. The first component $c_{s(k+1)}$ of the optimal estimate of the state vector $\widehat{\boldsymbol{c}}_{s(k+1)}$ is used to find the value of the atmospheric temperature at this point.

The set of equations according to which linear filtering of estimates of the state vector of the acoustic wave packet in RAS systems is performed has the form:

$$\begin{aligned}
&\widehat{\boldsymbol{c}}_{s(k+1)} = \boldsymbol{P}_k\widehat{\boldsymbol{c}}_{s(k)} + \boldsymbol{D}_{k+1}^{-1}\boldsymbol{H}_{k+1}^{T}\boldsymbol{D}_{y(k+1)}\left(\widehat{\boldsymbol{Y}}_{sy(k+1)} - \widehat{\boldsymbol{Y}}_{s0(k+1)}\right),\\
&\boldsymbol{D}_{k+1} = \boldsymbol{D}_{0(k+1)} + \boldsymbol{H}_{k+1}^{T}\boldsymbol{D}_{y(k+1)}\boldsymbol{H}_{k+1} = \left(\boldsymbol{P}_k\boldsymbol{D}_k^{-1}\boldsymbol{P}_k^{T} + \boldsymbol{Q}_k\right)^{-1} + \boldsymbol{D}'_{y(k+1)},
\end{aligned} \quad (4)$$

where $\widehat{\boldsymbol{c}}_{s(k+1)}$ – the optimal estimate of the state vector of the acoustic wave packet; $\boldsymbol{P}_k$ – the transition matrix, according to which the predicted estimate is determined, i. e. $\boldsymbol{P}_k\widehat{\boldsymbol{c}}_{s(k)} = \widehat{\boldsymbol{c}}_{s0(k+1)}$; $\widehat{\boldsymbol{Y}}_{sy(k+1)}$ – the estimate of the vector of observed parameters at the $(k + 1)$-th observation step; $\widehat{\boldsymbol{Y}}_{s0(k+1)} = \boldsymbol{H}_{k+1}\boldsymbol{P}_k\widehat{\boldsymbol{c}}_{s(k)}$ – the predicted value of the vector of observed parameters; $\boldsymbol{D}_{y(k+1)}$ – the accuracy matrix of the current measurement result; $\boldsymbol{H}$ – the recalculation matrix, which is determined from the expression

$$\boldsymbol{H}^{-1}\boldsymbol{Y}_s = \boldsymbol{c}_s,$$

where $\boldsymbol{Y}_s$ – the vector of observed parameters; $\boldsymbol{c}_s$ – the state vector of the acoustic wave packet; $\boldsymbol{D}_{k+1} = \boldsymbol{D}_{0(k+1)} + \boldsymbol{D}_{y(k+1)}$ – the resulting accuracy matrix; $\boldsymbol{Q}_k$ – the correlation matrix of the maneuver (disturbance) of the trajectory of the acoustic wave packet.

The application of the filtering equations (4) in RAS systems involves the selection of a model of the change of the information parameter with height depending on the state of the atmosphere [26]. The choice of a mathematical model of the sound velocity profile can be made on the basis of a priori data on the state of the atmosphere or by carrying out some trial, preliminary sounding cycles, which will be accompanied by refinement of the structure and parameters of the model.

The model of the trajectory of the observed object – AWP in general has the following form

$$\boldsymbol{\gamma}_{n+1} = \boldsymbol{P}_n\boldsymbol{\gamma}_n + \boldsymbol{F}_n\boldsymbol{\mu}_n, \quad (5)$$

where $\boldsymbol{\gamma}_n$ – the r-dimensional vector of the AWP trajectory parameters at the n-th step; $\boldsymbol{P}_n$ – the known transition matrix; $\boldsymbol{F}_n$ – the known matrix; $\boldsymbol{\mu}_n$ – the r-dimensional vector of perturbation of the object trajectory parameters.

The measurement equation that specifies the mathematical model of the formation of a random sequence of system measurement results

$$\boldsymbol{Y}_n = \boldsymbol{H}_n\gamma_n + \Delta\boldsymbol{Y}_n, \quad (6)$$

where $\boldsymbol{Y}_s$ – the vector of observed parameters; $\Delta\boldsymbol{Y}_n$ – the vector of measurement errors.

Mathematical models that describe the change in time and space of the filtered AWP information parameters are usually divided into deterministic and stochastic or random. Deterministic models are models which equations do not include random components.

Stochastic models include a model of the form

$$\gamma_{k+1} = c\gamma_k + \mu_k, \quad (7)$$

where μ_k – a random variable, which probability distribution determines the nature of the change in the values of the parameter γ. If the values of the parameter μ_k, characterizing the rate of change of the parameter in the intervals between the samples, are independent of each other, the model is called a model with independent first increments.

The following random model of parameter change is described by a system of equations

$$\left.\begin{aligned}
\gamma_{1(k+1)} &= c\gamma_{1(k)} + \gamma_{2(k)};\\
\gamma_{2(k+1)} &= \gamma_{2(k)} + \mu_k,
\end{aligned}\right\} \quad (8)$$

where $\boldsymbol{\gamma} = \gamma_1\gamma_2$ – a vector parameter that directly includes the information scalar parameter γ_{1k} and the rate of change of this parameter γ_{2k}; μ_k – a parameter of a random perturbation (maneuver) of the object's speed of movement. Model (8) is a model with independent second increments, with the independent second increments μ_k representing the values of the acceleration of change of the informative parameter.

The variability of the realizations of the sound speed profile obtained using stochastic models (7) and (8) is determined by the value of the variance of the parameter μ_k. By changing the variance of the specified random parameter, which acts as a perturbing factor, it is possible to achieve greater similarity between the real and simulated processes.

Processing of sound velocity profiles obtained experimentally and by the method of statistical mathematical modeling showed that the use of deterministic models does not provide the necessary efficiency of the filtering process. The average value of the mean square errors of filtering and extrapolation in this case turns out to be quite large, and in some cases the phenomenon of filter "divergence" occurs, when the values of the filtered process significantly deviate from the trajectory of the original random process. It can be concluded that such atmospheric states are quite rarely observed that can be adequately described by the model of deterministic change in sound velocity with height, especially a linear deterministic mathematical dependence.

Fig. 2 shows a comparison of the original sound velocity profile obtained by the modeling method using a model with independent first increments at a dispersion of the sound velocity disturbance $\sigma_\mu = 1.3\ \text{m}^2/\text{s}^2$, with the profile obtained after filtering. Measurements of the sound wave velocity, which varies along the sounding path, were performed at points in space, spaced apart in height by $\Delta H = 30$ m. As can be seen, the use of a stochastic mathematical model with independent first increments in the filtering algorithm ensures smoothing of the fluctuation component of the sound velocity profile and the resulting profile obtained after filtering becomes smoother (Fig. 2).

The use of a mathematical model with independent other (third and further) increments for modeling the filtered profiles in the filtering algorithm does not reduce the dispersion of the obtained profiles and as a result the obtained profiles become more variable. Therefore, this model does not adequately reflect the real observed process and cannot be recommended for use in RAS system adaptation algorithms.

The dispersion of the perturbation of random mathematical models of profiles should be selected from a priori data on the current state of the atmosphere. The more unstable the state of the atmosphere, the greater the maneuver dispersion of the real sound speed profile will have and the greater the value of the perturbation dispersion σ_μ must be included in the filtering algorithms.

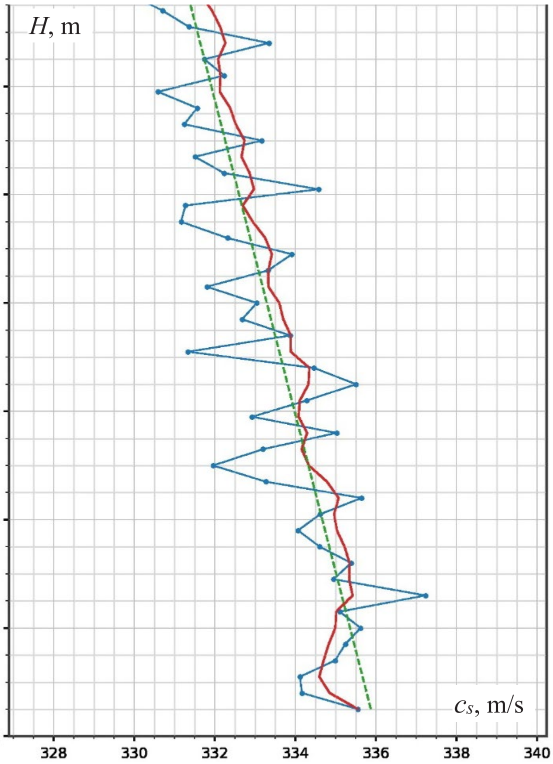

Fig. 2. Altitude profiles of sound speed, which: enter the input of the processing system (green color); obtained after performing the sequential filtering process (red color); true profile (dashed line)

Statistical data obtained from the simulation results show that the application of filtering algorithms to the sound velocity profile allows reducing the profile perturbation variance value by an average of 8.21 times for a posteriori estimates and 6.08 times for extrapolation estimates.

The quality of the tuning algorithm for the Bragg condition according to expression (1) is determined by the uncertainty, or error, with which the sound velocity value is known at the profile point at which the measurement is performed. The wave detuning indicator at the current profile point, due to insufficient information about the state of the environment in a given region of space, is determined by the expression

$$(\lambda_s + \Delta\lambda_s)/\lambda_e = (c_s + \Delta c_s)/2c_s, \tag{9}$$

where $\Delta\lambda_s$ – the change in the acoustic wavelength due to changes in meteorological parameters; Δc_s – the uncertainty value with which the sound velocity at the current profile point is known.

The a priori error value with which the value of the sound speed at a point of the height profile is known before measuring the information parameter of the signal is described by the formula [27]

$$\Delta c_s = 0.65\Delta T + \Delta v + \delta c_s, \tag{10}$$

where Δv – the difference in the values of the vertical wind speed between neighboring points of the profile; ΔT – the difference in the values of the temperature between the closest points of the profile in height; δc_s – the random component of the error in the measurement result of the sound speed at the previous point of the profile, caused by the influence of noise and external interference. The first two components in expression (10) are the dynamic error of tuning to the Bragg condition, and the third term is the fluctuation error.

The dependence of the intensity of the scattered radio signal on the ratio of wavelengths λ_s/λ_e at different lengths of the AWP (different number of wavelengths in the acoustic pulse N) is determined by the relation

$$I_n = N^2 exp\left[-4\pi^2 N^2 \left(\left(2\lambda_s/\lambda_e\right)-1\right)^2\right]. \tag{11}$$

The graphs of the dependences of the normalized intensity of the scattered radio signal on the ratio λ_s/λ_e for different values of the parameter N are shown in Fig. 3. It can be seen from Fig. 3 that the greater the number of wavelengths in the AWP, the steeper the intensity decreases with increasing detuning parameter λ_s/λ_e, and the more accurate the tuning to the Bragg condition must be to obtain the required amplitude of the reflected signal.

The level of possible energy losses due to failure to meet the Bragg condition was analyzed using expression (11). For the values of the quantities: $c_s = 335$ m/s, $\Delta T = 0.50$°C, $\delta_{cs} = 1$ m/s, the wave detuning index, determined by the ratio $(\lambda_s + \Delta\lambda_s)/\lambda_e$, is 0.50191. If the number of wavelengths in the sound packet $N = 100$, during scattering there is a decrease (relative to the maximum) of the radio signal intensity by approximately 402 times (–26.02 dB), and at $N = 60$ by approximately 8.6 times.

Fig. 2 shows that at a height of $H = 260$ m the error in measuring the speed of sound is $\delta c_s = 2.1$ m/s, as a result of which the intensity of the scattered signal decreases by $2.9 \cdot 10^{-7}$ times. If the optimal filter is not used in the control loop, then in fact, at a height of $H = 260$ m, the auto-tracking will fail due to the fulfillment of the Bragg condition. In the case of using the proposed adaptation method, such a decrease in the level of the scattered signal is not observed up to the maximum sounding height of $H = 1350$ m, and the intensity of the scattered radio signal on average along the sounding route (Fig. 2) increases by 26.35 times.

The use of the improved method of measuring the speed of sound in the developed adaptation method, which forms maximum likelihood estimates, eliminates systematic measurement errors that are suitable for known measurement methods, and also reduces the random component of the error.

The use of an optimal linear filtering algorithm in the frequency control loop of the sounding radio signal reduces the random error component, as well as the dynamic error – by forming a predicted estimate of the sound speed at the next profile point at which the measurement is performed.

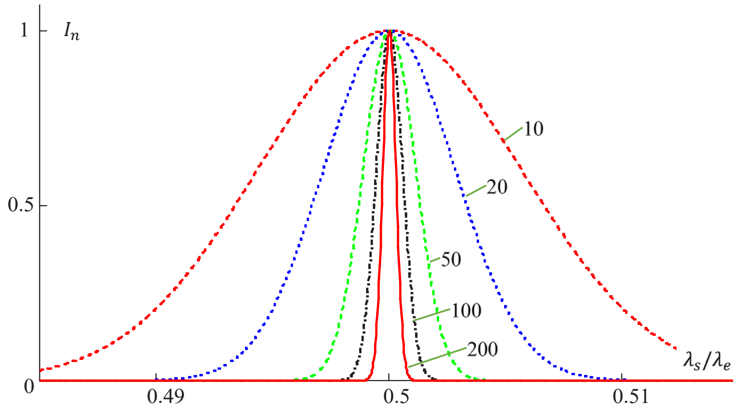

Fig. 3. Dependences of the normalized intensity I_n of the reflected radio signal on the ratio of the wavelengths of the signals λ_s/λ_e at theAWP lengths: N = 10, 20, 50, 100, 200

Ensuring the fulfillment of the Bragg condition in the entire range of possible values of acoustic wavelengths by changing the frequency of the sounding radio signal is impossible. Therefore, slow changes in meteorological parameters caused by daily and seasonal changes in the state of the atmosphere should be compensated by adjusting the frequency of the acoustic generator of the RAS system.

Such periodic adjustment of the sound frequency can be performed using direct measurements of the temperature and speed of sound near the earth's surface and can be implemented automatically. Compensation for rapid changes in the acoustic wavelength (during the propagation time of the acoustic packet along the sounding path) must be carried out by changing the radio frequency. To ensure the fulfillment of the Bragg condition when the atmospheric temperature changes with a height of 10 degrees, it is necessary to be able to adjust the radio signal frequency within 1.5% with an accuracy of about 0.05% and a speed of about 0.1% per 0.1 s.

The method of measuring atmospheric temperature profiles, implemented in RAS systems produced by industry, was proposed by system developers and is heuristic. It was created in conditions when science could not offer an effective method of adapting systems to changes in the meteorological situation. The method is based on the concept of accumulating a significant, excessive amount of data over a long time interval and their subsequent averaging.

The use of a scientifically substantiated method of frequency adaptation of systems, which was synthesized using the basic principles of the theory of stochastic optimal control, allows improving the method of measuring meteorological parameter profiles by RAS systems. Therefore, the time of averaging individual measurement results to achieve the required integral accuracy of estimating the atmospheric temperature profile is significantly reduced – from tens to units of minutes.

Existing RAS systems of industrial production by METEK, REMTEC, BIRAL, SCINTEC can be improved by implementing the proposed adaptation method and a more effective method of measuring atmospheric temperature profiles. This requires modification of the devices for generating sounding radio signals in the systems. Signals with adaptively changing emission frequency can be implemented using frequency synthesizers.

3.4. Limitations and directions for further development of research

The main limitations of the impact of the research results on the effectiveness of the RAS atmospheric systems are associated with the existence of a number of physical factors that significantly affect the functioning of RAS systems. This is primarily the AWP shift in the horizontal direction under the influence of horizontal wind, which leads to a shift of the focused radio signal from the aperture of the receiving radio antenna. This mechanism is currently the main one that limits the range of RAS systems. The range and other indicators of RAS systems are also negatively affected by atmospheric turbulence, which leads to a violation of the coherent structure of the AWP and reduces the positive effect of the effect of achieving the Bragg condition in the sounding process. The attenuation of sound waves in the atmosphere leads to a decrease in the amplitude of the scattered radio signal and also negatively affects the process of obtaining useful information about the state of the atmosphere by RAS systems.

Prospects for further development of the developed method are associated with the improvement of mathematical models of the height profile of the speed of sound. The speed of sound is an integral characteristic of a very dynamic environment – the atmosphere, and in order to achieve high quality filtration in specific atmospheric conditions, considerable attention must be paid to the selection of an adequate mathematical model of the profile.

4. Conclusions

1. Using the theory of stochastic optimal control based on the separation theorem, a method for controlling the frequency of the sounding radio signal to fulfill the Bragg condition of the sounding path of RAS systems has been developed. The control method includes the operations of estimating the speed of sound, stochastic linear filtering of the AWP state parameter vector, and deterministic control of the radio signal frequency based on the obtained data.

Previously known methods for controlling the frequencies of sounding signals of RAS systems were developed heuristically. The use of the fundamental results of the theory of stochastic optimal control to solve the current scientific problem made it possible to obtain a new, scientifically substantiated sequence of actions, in which the functions of optimal stochastic control are divided into two sequentially performed operations – stochastic filtering and deterministic control of the frequency of the sounding radio signal. The developed method allows to significantly increase the use of the energy potential of sounding stations and, accordingly, to improve the quality of the obtained atmospheric temperature profiles.

2. It is proposed to use in the frequency control loop of the sounding radio signal a method of estimating signal parameters to determine the speed of sound, which forms maximum likelihood estimates. The estimates have no bias, i. e. do not include a systematic error, unlike the known methods of estimating the speed of sound, which are based on measuring the value of the Doppler frequency of the signal. This allows to significantly improve the quality of the frequency control process.

3. An algorithm for filtering and extrapolating the vector of parameters of the state of the acoustic wave packet has been developed, which is performed in real time as the AWP moves along the sounding path. A feature of the algorithm is tracking the acoustic wave packet – an extremely variable and dynamic object that propagates in an atmospheric turbulent environment. The structure and parameters of the optimal linear filter are proposed. It is shown that in this problem it is necessary to use stochastic models that describe changes in the information parameter. Deterministic profile models do not provide the required results.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, that could influence the research and its results presented in this article.

Financing

The research was conducted without financial support.

Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Volodymyr Kartashov: Conceptualizatio, Project administration; ***Igor Kondrashov***: Writing – original draft; ***Olexander Kartashov***: Conceptualization, Methodology, Formal analysis, Investigation, Writing – review and editing; ***Roman Bobniev***: Writing – review and editing; ***Anton Shamrai***: Software.

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