Development of an information and analytical system for presenting data on the refractive properties of the environment

V N Bobrov\textsuperscript{1}, A V Dushkin\textsuperscript{2}, A I Sitnikov\textsuperscript{3} and E A Sushko\textsuperscript{4}

\textsuperscript{1}IT Department, Voronezh Institute Federal Penitentiary Service of Russia, Irkutskaya Street 1a, Voronezh, RU
\textsuperscript{2}Department of Information Security, National Research University of Electronic Technology, Shokin square, 1, Zelenograd, Moscow, RU
\textsuperscript{3}Voronezh Institute of Interiors of Russia, Patriotov, 53
\textsuperscript{4}Voronezh State Technical University, Voronezh, 20 – letya Oktyabrya, 84

E-mail: a_dushkin@mail.ru

Abstract. The article proposes a variant of constructing an information and analytical system that makes it possible to control the refractive properties of the environment (atmosphere) based on the actual values of its parameters, as well as to determine the numerical values of the refractive index of the atmosphere. Its operation is based on a method that makes it possible to detect errors during measurements by optical systems in a real atmosphere. The main feature of the method under consideration is the comparison of the refractive indices in a real and ideal atmosphere. The difference in the corresponding values of the refractive index of the atmosphere makes it possible to correct the results obtained during measurements by optical systems. This article describes the operation of the software algorithm, which allows not only measuring and evaluating based on information on hydrometeorological parameters and refractive properties of the surface layer of the atmosphere, but also visualizing the results of measurements carried out by optical systems. Experimental studies carried out confirm the high adequacy of the models underlying the described complex.

1. Introduction

One of the main reasons for the low reliability of measurement results by optical systems in the environment is the incomplete accounting of information that determines the state of the atmosphere, namely, its refractive properties.

The existing means of control of the refractive properties of the atmosphere are usually based on refractometry. This method is widely used not only as a method for studying the structure of a substance, but also as a method for quality control of various products [1-5]. However, the use of instruments that implement this method allows its use only in laboratory conditions. Stationary (point) posts for observing the state of the atmosphere are not equipped with devices and measuring systems capable of determining the refractive properties of the atmosphere.

The purpose of this work is to develop a variant of constructing an information and analytical system that allows monitoring the refractive properties of the environment (atmosphere) based on the...
actual values of its parameters, as well as determining the numerical values of the atmospheric refractive index.

2. Taking into account the peculiarities of the refractive properties of the atmosphere

When developing and designing electronic systems for monitoring the refractive properties of the atmosphere, we took into account and taken as the main information resources on the spatial distribution of quantities characterizing the state of the atmosphere [6]. With the help of these quantities, which undergo significant changes in space [7], it is possible to indirectly determine the value of the gradient of the atmospheric refractive index [8], the values of which affect the trajectory of the optical signal when it passes the investigated layer of the atmosphere.

The trajectory of the probing optical signal on an inclined path at angles close to total reflection in an ideal atmosphere has a specific projection value onto a horizontal surface with a fixed measurement base. It is known that when the values of the quantities that determine the state of the atmosphere change in space, the refractive index changes in space, the value of which can be calculated using the well-known relation [9-10]:

\[
n = 1 + 10^{-6} N = 1 + 10^{-6} \left[ \frac{77.6}{p} \left( p + 4810 \frac{e}{T} \right) \right]
\]

where \( n \) – refractive index of the atmosphere in the surface layer; \( T \) – absolute air temperature, \( p \) – atmospheric pressure; \( e \) – partial pressure of water vapor.

The atmosphere can be considered both in the form of an ideal (the observation trajectory is rectilinear) and a real environment (the observation trajectory differs from the rectilinear one).

It is obvious that the trajectory of the probing optical signal passing along an inclined path in the real atmosphere has a certain projection onto the horizontal surface and differs from the projection onto the corresponding surface in an ideal atmosphere.

Thus, by the difference between the projections of trajectories in ideal and real atmospheres, one can judge its refractive properties and organize monitoring by electronic systems [11].

In an ideal atmosphere, we will consider its refractive properties to be constant throughout the entire layer. In this case, the projection of the observation trajectory 1 onto the horizontal surface shown in Fig. 1 will be equal to \( L_0 \) if the observation is carried out at a height \( h_0 \) at an angle \( \alpha_0 \) [12].

![Figure 1. Trajectory of the signal of the optical system in the surface layer of the atmosphere.](image-url)
In a real atmosphere, the observation trajectory 2 determines $L_{\text{meas}}$ provided that the parameters of the partial pressure of water vapor ($e$), atmospheric pressure ($P$), air temperature in the ambient layer ($T$), height ($h_0$) and angle ($\alpha_0$) of observation did not change and were constant for the current state of the environment.

Using information resources about the numerical values of the quantities characterizing the state of the atmosphere, the projection onto the horizontal surface of the aiming trajectory along the inclined path is calculated. In this case, the following functional dependence is valid:

$$L_0 = f(n_{\text{ideal}}) = f(e, P, T, h_0, \alpha_0)$$  \hspace{1cm} (2)

where $n_{\text{ideal}} = \text{const}$ – refractive index in an ideal atmosphere.

Using the mathematical model of the ideal atmosphere [13-15], the numerical value of the projection onto the earth's surface of the observation trajectory 1 is calculated. Further, at the second stage, the $L_{\text{meas}}$ value is experimentally measured on the same inclined path. Obviously, in this case, a functional dependence of the form will be valid:

$$L_{\text{meas}} = f(n_{\text{real}}) = f(e_{\text{meas}}, P_{\text{meas}}, T_{\text{meas}}, h_0, \alpha_0)$$  \hspace{1cm} (3)

where $n_{\text{real}} \neq \text{const}$ – the refractive index of the real atmosphere.

By the difference between the projections on the horizontal surface of the observation trajectory in the ideal and real atmosphere, one can judge the magnitude of the observation error $\Delta L$:

$$\Delta L = |L_0 - L_{\text{meas}}| = f(n_{\text{real}})$$  \hspace{1cm} (4)

The design of an electronic complex with the use of optical sensing is carried out using standard remote means for measuring the state of the atmosphere – devices that allow you to quickly receive information about the current values of quantities and determine the state of the atmosphere both at an altitude of $h_0$ and at the earth's surface.

The difference between the ideal and the real state of the atmosphere makes it possible to implement monitoring in different physical and geographical regions to eliminate refraction errors when carrying out measurements by optical measuring systems.

3. Description of the experimental device

When organizing monitoring of the atmosphere by the optical method, its sounding can be used. The method is based on the refraction of an optical signal when it passes through a gradient atmosphere [16]. A common drawback for all known technical optical-measuring systems that implement optical methods is the creation of a pseudo-objective reference channel in the measuring circuit.

When creating a measuring circuit with a truly objective reference channel, the gradients of quantities determining the state of the atmosphere were taken into account. This made it possible to optimize the measurement procedure as much as possible and increase the objectivity of the calibration of the measuring system.

When organizing monitoring of the atmosphere by the optical method, its sounding can be used. The method is based on the refraction of an optical signal when it passes through a gradient atmosphere [17].

The method of information processing of the current state of the atmosphere determines the technical system for monitoring the atmosphere [18], which consists of four main elements: a radiation source; diaphragm; an optical focusing system at the first measuring base; a signal processing unit based on an amplifier and an observation error indicator on the second measuring base.

The elements of the system on the first measuring base are jointly placed on a single platform (on the first tripod at a fixed height). Using a tripod, you can change the angle of the probing optical signal within 90° with respect to the second measuring base.

On the second measuring base, located on the second tripod, at a lower fixed height relative to the first base, the following elements are located vertically: CCD-matrix; two calculators; source of
threshold voltage; sounding angle voltage source; four voltage amplifiers; temperature sensors at the lower and upper boundaries of the studied atmospheric layer; atmospheric pressure sensor.

The output of the CCD matrix is connected to the first input of the first calculator, and the output of the threshold voltage source is connected to its second input. The output of the first calculator through the first voltage amplifier is connected to the first input of the second calculator, to the second input of which the voltage source of the sensing angle is connected. The temperature sensors of the lower and upper boundaries of the studied layer of the atmosphere and the atmospheric pressure sensor are connected to the third, fourth and fifth inputs, respectively, through their voltage amplifiers. The output of the second calculator is connected to the signal processing unit.

The functional diagram of the proposed optical-measuring system is shown in Figure 2 [19].

The first measuring base of system 1 contains a radiation source 2, a diaphragm 3, an optical focusing system 4. On the second measuring base 5, a line of photodetectors 6, two calculators 7 and 10, a threshold voltage source 8 and a voltage source of a sensing angle 11, four voltage amplifiers 9, 13, 15 and 17, temperature sensors of the lower and upper boundaries of the investigated surface layer of the atmosphere 14 and 12, respectively, an atmospheric pressure sensor 16, a signal processing unit based on a voltage amplifier 18 and an indicator of anthropogenic pollution 19.

**Figure 2.** Functional diagram of an optical-measuring system for monitoring the refractive properties of the atmosphere.

The essence of the operation of the optical-measuring system for monitoring the refractive properties of the atmosphere is illustrated in Figure 3.

The system is located on two bases: A and B. The system elements on the first measuring base $A$ are jointly located at a fixed height $H_{\text{meas}}$ in the atmosphere on a single platform (on the first tripod), with which it is possible to change the sounding angle $\alpha$ within $90^\circ$ with respect to the second measuring base. In the ideal state of the atmosphere, the optical signal 1 passes without deflection, creating a projection in the form of a line of the measuring base $L_{\text{meas}}$.

On the second measuring base $B$, the rest of the system elements (on the second tripod) are placed at a fixed height $h_{\text{meas}}$, so that $H_{\text{meas}} > h_{\text{meas}}$. The CCD is located vertically relative to the $AB$ basis. The signal processing circuit is set up so that in the case of optical signal 1 passing, a calibration illumination is created on the CCD matrix and the indicator shows the presence of deviations of the observation path equal to zero at values in the atmosphere corresponding to the ideal state of the atmosphere and a fixed sensing angle $\alpha$. 
Refraction in the atmospheric layer deflects the optical signal 1, and the latter takes the form of trajectory 2. This leads to a corresponding change in the position of the illumination in the section of the CCD matrix 6 and the appearance of a certain voltage $\Delta U$ at the output of calculator 7 at a given threshold voltage (block 8) at the time of calibration, which is amplified in block 9. With the measured values of the quantities that determine the state of the atmosphere (blocks 12-17) and a given sounding angle $\alpha$ (block 11), the calculator 10 is converted into the corresponding readings of the indicator of the measurement error 19 (Figure 2) [20].

![Figure 3. Optical measuring system for monitoring the refractive properties of the atmosphere.](image)

4. Program implementation of the method
A block diagram of the observation trajectory calculation algorithm [21] is shown in Figure 4 and consists of the following program blocks:

1. Block of data entry and correction.
2. Block for calculating the characteristics of air humidity at the upper and lower boundaries of the investigated layer of the atmosphere.
3. Block for calculating the refractive index at the upper and lower boundaries of the studied atmospheric layer.
4. Block for calculating the geometric parameters of the measuring device before and after sounding the investigated layer of the atmosphere.
5. Block for calculating the value of the angle of refraction.
6. Block for calculating the refractive index at the lower boundary of the investigated surface layer of the atmosphere according to the results of sounding.
7. Block for checking the presence of deviations in the investigated layer of the atmosphere.
8. Block for calculating the magnitude of deviations along the vertical and horizontal in the investigated layer of the atmosphere according to the results of sounding.
9. Block for outputting results.

The data input and correction unit is intended for input and correction of initial data, which include the following parameters at the upper and lower boundaries of the studied atmospheric layer, respectively: $t_a$ – air temperature, °C; $t_a'$ – temperature of the wetted thermometer, °C; $e_a$ – partial pressure of water vapor, mb; $p_w$ – atmospheric pressure, mb; $t_n$ – air temperature, °C; $t_n'$ – temperature of the wetted thermometer, °C; $e_n$ – partial pressure of water vapor, mb; $p_H$ – atmospheric pressure, mb; $S_0$ – measuring base, m; $S_{flow}$ – measured base, m; $\Delta h$ – thickness of the studied layer of the atmosphere, m.
The block for calculating the moisture characteristics is designed to calculate the partial pressure of water vapor at the upper and lower boundaries of the investigated layer of the atmosphere, taking into account the current parameters.

The block for calculating the refractive index at the upper and lower boundaries of the investigated surface layer of the atmosphere is designed to calculate the refractive index at the upper and lower boundaries of the investigated layer.

Figure 4. Block diagram of the "Air" program.

The block for calculating the geometric parameters of the measuring device before and after sounding the investigated layer of the atmosphere is intended for calculating the hypotenuse of the measuring circuit \(dS\) and the real hypotenuse \(dS_{flow}\) obtained during sounding of the investigated layer of the atmosphere.
The unit for calculating the value of the angle of refraction is designed to calculate the value of the angle of refraction from experimental data.

The block for calculating the refractive index at the lower boundary of the investigated layer of the atmosphere according to the results of sounding is intended to calculate the value of the refractive index at the lower boundary of the investigated layer of the atmosphere according to experimental data.

The unit for checking the presence of deviations in the investigated layer of the environment is intended to compare the experimental and calculated values of the refractive index at the lower boundary of the investigated layer of the atmosphere.

If the values of the refractive indices of the atmosphere are equal, there is no deviation. If the values of the refractive index differ, readdressing follows to calculate the deviations in the investigated layer of the atmosphere according to the results of the experiment.

The block for calculating deviations in the investigated layer of the atmosphere along the vertical and horizontal is intended for calculating the deviations in the investigated layer of the atmosphere.

The block for outputting the results is intended for presenting the results of the program's work in the form of graphic files and printing the results of the calculation in a given form.

The operation of the "Air" program is as follows: after the start of the program, the initial data necessary for the calculations are entered in the dialogue mode, and, if necessary, their correction.

Further, the program converts information about the temperature of dry and wetted thermometers to the temperature on an absolute scale, atmospheric pressure in millibars for each level, and also initiates the investigated layer of the atmosphere according to the geometric parameters of the measurement base.

After converting the initial parameters, the partial pressure of water vapor is calculated based on the current state of the layer for the upper and lower layers of the atmosphere.

Next, the refractive index of the atmosphere is calculated at the appropriate levels.

After calculating the refractive index taking into account the state of the atmosphere layer, the hypotenuse of the measuring device triangle and the hypotenuse are calculated taking into account the influence of the atmosphere layer. Further, based on the results obtained, the value of the refraction angle is calculated from the changes in the geometric parameters of the measuring circuit.

After that, the refractive index of the atmosphere is calculated taking into account the value of the angle of refraction. The calculated result is compared with a similar parameter calculated taking into account the parameters of the atmosphere. If the calculated and experimental parameters are equal, the program transmits the result about the absence of deviations in the atmospheric layer to the results output unit.

When the calculated and experimental parameters differ, the deviations of the observation trajectory in the atmosphere are calculated. Further, the results obtained are transferred to the results output unit.

The program provides the ability to save the calculated data in the form of spreadsheets.

5. Experimental results

The operability of the optoelectronic information and analytical system was tested on a model, which included the following elements: an optical signal source with a radiation wavelength $\lambda = 0.5893 \mu m$ with its own optical system; optical signal receiver – CCD-matrix located in a protective hood; a personal computer, on the basis of which the calculation was made using mathematical models [3, 22].

Experimental studies were carried out in the following sequence:

1. The quantities determining the state of the atmosphere at the upper and lower boundaries of the layer and the horizontal projection of the trajectory of the probing optical signal passing through this layer were measured simultaneously.

2. With an interval of 20 minutes, synchronous measurements of the quantities determining the state of the atmosphere were made according to claim 1, the horizontal projection of the observation
trajectory of the probing optical signal passed through the studied layer of the atmosphere, and visual readout was carried out through the optical system along a vertical ruler located parallel to the CCD matrix.

3. Using mathematical models, the deviations of the observation trajectory were calculated and compared with the data obtained during visual readout.

The results obtained during the experiment confirmed the performance of the proposed system for its intended purpose. The error of the calculated and results obtained by visual readout is within 10-15%, which makes it possible to obtain information about the presence of observation errors in the atmosphere layer for the corresponding monitoring of the refractive properties of the atmosphere. Thus, the developed optoelectronic information-analytical system makes it possible to evaluate the observation errors in the atmosphere in an automated mode. The proposed technical measuring system also makes it possible to visualize the observation trajectory in space at the current time.

6. Conclusion
The results of experimental studies confirm the high adequacy of the theoretical calculation models. The discrepancy between theoretical and experimental data does not exceed 5%.

The possibility of using the proposed approach to control the refractive properties of the surface layer of the atmosphere has been experimentally confirmed. The discrepancy between the data of the measuring device and control measurements using standard measuring instruments of hydrometeorological values does not exceed 15-20%, and when an estimate of the monitored parameter is obtained by the method of sequential observation based on the least squares method, the error of the results decreases to 5% or less practically starting from 5-6th dimension.

An algorithm and a program [10] have been developed to control the refractive index in the surface layer of the atmosphere, using information on the hydrometeorological parameters and refractive properties of the surface layer of the atmosphere.

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