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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT OF THE METHOD OF INCREASING THE ACCURACY AND INFORMATIVE INDICATORS OF SUN PHOTOMETERS

Specialty: 3337.01–Information-measurement and control systems

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GENERAL CHARACTERISTICS OF THE WORK

Relevance and development of the topic. Sun photometers are widely used to study the atmosphere and illuminated celestial bodies. When illuminated celestial bodies are used as external irradiators, it is possible to study low-concentration gases and atmospheric aerosol.

As an example of sun photometers, the currently widely used CimelCE 318 type device can be shown. This device is used in the international "AERONET" measuring network, which consists of more than 500 automatic measuring points scattered all over the world. Here, measurements are made at wavelengths of 380, 440, 500, 670, 778, 870, 1020nm and allow measuring the total amount of water vapor in the atmosphere and various optical indicators of aerosol.

The characteristic instability of the atmospheric aerosol creates a measurement error in all spectral atmospheric measurements, which shows the relevance of ground and space research of the physical-optical indicators of the aerosol. For this purpose, sun photometers placed in more than 500 ground measurement stations of the AERONET Worldwide automated measurement network and also other local measurement networks measure the optical thickness of the aerosol and other indicators at different values of the optical air mass at certain minute intervals.

In general, the uncertainty of the measurement results of the optical thickness of atmospheric gases arises due to the following reasons: (a) instrument error of the measuring device; (b) error caused by inaccurate calibration; (c) error due to the effect of atmospheric aerosol.

An instrument error is usually caused by the device's components not matching the passport specifications, wear or failure. The calibration error of sun photometers is due to the use of Langley charts. Thus, this calibration method has a specific error due to the instability of the optical thickness of the aerosol with respect to time.

Extensive studies have been conducted in the field of aerosol error elimination of sun photometers and significant results have been obtained. However, many issues in this field remain unsolved and some of them are included in the main research issues of the dissertation. Atmospheric aerosol measurement results using a sun photometer allow more accurate validation of satellite data. Optical radiation of the Sun plays the role of a fundamentally important source for many physical, chemical and biological processes occurring on the planet. On the other hand, the total radiation balance of the Earth affects its climate, and the disturbance of the radiation balance is manifested by climate change. The main greenhouse gases that cause climate change on Earth are water vapor, carbon dioxide and methane. Therefore, accurate assessment of the composition of the specified atmospheric components is of great importance. In this sense, the role of Sun photometers in the study of aerosol water vapors is invaluable. The concept of atmospheric opacity is used to estimate the attenuation of solar radiation by atmospheric aerosols and water vapors. Water vapor absorbs both the long-wave radiation emitted by the Earth and the flood of long-wave optical radiation entering from the upper boundary of the atmosphere. This suggests the need for a more careful study of the absorption spectrum of water vapor in a real atmosphere polluted with small dispersed aerosols. Such measurements are performed in international networks such as AERONET, GAW – PRF, ESR – SKYNET. The main feature of water vapor measurement by Sun photometer is the use of 940nm wavelength, where water vapor has a strong absorption band. It should be noted that lidar systems are also widely used for atmospheric research. The development of new efficiency criteria of lidar-photometric systems is considered to be an urgent issue in order to carry out initial verification and validation of the data obtained during terrestrial lidar measurements.

The object and subject of the research. The object and subject of the research. The object of the dissertation work is Sun photometers, which are considered one of the most universal and widespread measuring devices for atmospheric research. The subject of the dissertation work is to increase the accuracy and informative indicators of Sun photometers, to develop new measurement methods, and to determine new application areas..

Research goals and objectives. The main goal of the dissertation work is to develop new methods and methods for improving the accuracy and informativeness of sun photometers and, on this basis, to expand the field of functional application of sun photometers.

The main tasks of the dissertation work are the following:

1. Optimizing the measurement of low-concentration gases in the atmosphere by means of a sun photometer during the day, taking into account the influence of atmospheric aerosol, and determining the condition of the highest working efficiency of the measurement mode.

2. Development of a method to eliminate the effect of atmospheric aerosol on the results of three-wave solar-photometric measurement.

3. Development of a three-wave measurement method that ensures the elimination of the influence of the unstable hydrophilic component of the atmospheric aerosol for the measurement of water vapors in the atmosphere by means of a sun photometer.

4. Based on the known three-wave method of solar-photometric measurements of water vapor in the atmosphere, by taking measurements at fixed moments, having information about the Angstrom indicator at these moments, developing a method of measuring the amount of water vapor in the atmosphere by calculating and applying correction coefficients.

5. Mutual comparison and study of the errors of measuring the total amount of water vapors in the atmosphere by means of a sun photometer at 817nm and 940nm wavelength.

6. Development of validation methods of the measurement results of the total value of water vapor in the atmosphere, taking into account the statistical data characteristic of the studied region.

7. Determination of the optimal function showing the dependence of the power of the laser beam on the sensing distance in the remote sensing complex consisting of a lidar and a sun photometer.

8. In order to further increase the accuracy of tracking orbital satellites from the ground, optimization of the operation mode of laser calibration platforms used for calibration of photometric observation microtelescopes and development a method of checking calibration results.

Research methods. The methods and provisions of atmospheric physics, optics, measurement theory, remote sensing, system analysis, and error theory were mainly used to solve the issues raised in the dissertation work, the obtained results are substantiated by mathematical methods such as mathematical analysis, functional analysis, variation optimization method and optimization based on the analysis of derivatives.

Main issues for review. The following provisions are submitted for defense in the dissertation work:

1. Taking into account the negative effect of the atmospheric aerosol of low-concentration gases in the atmosphere, the measurements made by the sun photometer during the day can be considered optimal and effective if there is a directly proportional functional dependence between the used wavelength and the optical air mass. (note: the "optical air mass" is a special parameter of atmospheric physics).

2. A new measurement method that allows to completely eliminate the influence of atmospheric aerosol on the results of three-wave solar-photometric measurement.

3. A new measurement method for measuring water vapors in the atmosphere using a sun photometer, which allows to eliminate the influence of the unstable hydrophilic component of the atmospheric aerosol.

4. A new modification of the three-wave method of sun-photometric measurements allows to accurately determine the amount of water vapor in the atmosphere by performing three-wave measurements at fixed moments and using available statistical information about the Angstrom indicator.

5. The error of measuring water vapor in the atmosphere at a wavelength of 817 nm by a sun photometer can be smaller than the

error of measuring at a wavelength of 940 nm, and the relative error of measuring the content of water vapor in the atmosphere at a wavelength of 817 nm is directly proportional to twice the optical thickness of the atmospheric aerosol at that wavelength .

6. Proposed model methods based on surface temperature measurements for validation of atmospheric water vapor measurement results, taking into account relevant statistical data.

7. The method of detecting the optimal type of function that shows the criterion reflecting the effectiveness of the remote sensing complex, consisting of a lidar and a sun photometer, and the dependence of the power of the laser beam on the sensing distance.

8. The proposal to place the laser platforms used for the calibration of the microtelescopes used for ground tracking of orbital satellites at different heights and the provision about the possibility of using the extreme value of the calibration signal as a diagnostic sign of the correctness of the calibration procedure under the condition of the optimal type of the height dependence function of the beam divergence.

Scientific novelty of the research. The main scientific innovations of the study are as follows:

1. Taking into account the negative effect of atmospheric aerosols of small concentrations of gases in the atmosphere, as a result of optimizing the measurement of small concentrations of gases in the atmosphere by means of a sun photometer during the day, it was found that the highest work efficiency of sun photometers in this measurement mode is achieved when there is a directly proportional functional dependence between the wavelength of the measurements and the optical air mass.

2. In order to completely eliminate the effect of atmospheric aerosol on the results of three-wave solar-photometric measurement, the principle of geometric averaging was applied for the first time in the processing of measurement signals.

3. In order to increase the accuracy of measuring water vapors in the atmosphere by means of a sun photometer, a new three-wave measurement method was proposed, which involves the application of

correction coefficients that compensate for the destabilizing effect of the more unstable hydrophilic component of the atmospheric aerosol.

4. Based on the known three-wave method of solar-photometric measurements of water vapor in the atmosphere, a newly improved three-wave method was proposed, it is shown the possibility of determining the current amount of water vapor in the atmosphere by performing three-wave measurements at fixed moments and having statistical information about the Angstrom index at these moments by calculating the correction coefficients.

5. If interference filters are applied in sun photometers, the error of measuring water vapors in the atmosphere at a wavelength of 817 nm by a sun photometer can be smaller than the error of measuring at a wavelength of 940 nm. It was determined that the relative error of measuring the total amount of water vapor in the atmosphere at a wavelength of 817 nm is directly proportional to twice the optical thickness of the atmospheric aerosol at that wavelength.

6. Taking into account the statistical data typical for the studied region, an experimental model method was proposed, which involves the measurement of the surface temperature of the earth's surface, the validation of the measurement results of the total value of water vapor in the atmosphere.

7. A new efficiency criterion of the remote sensing complex consisting of a lidar and a sun photometer was proposed, the optimal type (that is, bringing the efficiency criterion to the extreme) of the function showing the dependence of the laser beam power on the sensing distance was found.

8. In order to increase the calibration accuracy of photometer-type microtelescopes used for tracking orbital satellites from the ground, lasers of the same type were installed, calibration platforms were proposed to be placed at different heights, the type of height dependence function of laser beam divergence that brings the total calibration signal to an extreme value is defined.

The theoretical and practical significance of the research. The obtained main results have important theoretical and applied significance.

1. To evaluate the identity of theoretically and experimentally determined values of solar radiation on the Earth, not the current values of solar radiation, but the detected extrema of average integral values over a certain time interval within the accepted model conditions are used; In order to predict the number of sunny days and hours during the year in practice, for the application of the known statistical models used, with the inclusion of correction coefficients, the propositions put forward about the application of the precisely determined value of atmospheric external solar radiation by performing measurements at three values of the optical air mass and at three wavelengths are undoubtedly they have theoretical and practical importance.

2. In order to achieve the highest work efficiency of sun photometers in the measurement of small gases of the atmosphere, the provision of the necessity for the wavelength of measurements to have a functional dependence directly proportional to the optical air mass; A proposed new method based on the principle of geometric averaging for the complete elimination of the influence of atmospheric aerosol on the results of three-wave solar-photometric measurements; The results of the optimization of the daily operation mode of the sun photometer working in ozonometer mode are of theoretical and practical importance for expanding the functional measurement capabilities of sun photometers.

3. A new three-wave measurement method proposed to eliminate the influence of the unstable hydrophilic component of the atmospheric aerosol for the measurement of water vapors in the atmosphere by means of a sun photometer; New improved three-wave method proposed for water vapor measurement based on the known three-wave method; if interference filters with temperature-dependent optical indicators are applied in sun photometers, the provision that the error of measuring water vapor in the atmosphere at a wavelength of 817 nm by a sun photometer can be smaller than the error of measurement at a wavelength of 940 nm; The model method, which involves the measurement of the surface temperature of the earth, the validation of the measurement results of the indicator of the total price

of water vapors in the atmosphere, taking into account the statistical data characteristic of the studied region, when the measurements are related to the wavelengths of 0.82 μm and 0.94 μm, the share of the measurement results of water vapor in the total instability of the atmospheric aerosol opacity coefficient (β) above a certain limit is higher than at the wavelength of 0.94 μm, 0.82 μm, etc. scientific results are undoubtedly of theoretical and practical importance in such an important field as water vapor measurement.

4. The proposition that the proposed selection method for the selection of moments of measurement in the proposed generalized Langley method for the practical calibration of sun photometers will increase the accuracy of the calibration of photometers with the Langley method has a certain importance for the theory and practice of the calibration of sun photometers.

5. In order to use the well-known analytical model to determine the Linke opacity coefficient of the night image, to determine the value of the deposited water vapor, to perform simultaneous calibration of the channels in the two-wave measurement method performed at λ_1=0.82 and λ_2=0.94μm wavelengths, the total noise signal the provision to allow reduction has certain scientific and practical importance in the relevant field of atmospheric measurements.

6. According to the proposed efficiency criterion of the remote sensing complex consisting of a lidar and a sun photometer, the detection of the optimal function showing the dependence of the initial power of the laser beam on the sensing distance is of certain theoretical and practical importance in the field of atmospheric research using lidar.

7. Placement of calibration platforms at different heights with lasers installed to increase the calibration accuracy of photometer-based microtelescopes used for tracking orbital satellites from the ground, the proposition that the total calibration signal takes an extreme value under the condition of a certain optimal type of the function of the divergence of the laser beam depending on the height has a certain theoretical and practical significance in the technique of satellite observation from the ground.

Approbation and application. Our main research and practical results were discussed at the meetings and seminars of the "Instrumentation Engineering" department of the Azerbaijan State Oil and Industry University and at the following scientific-technical conferences and forums.

"Müasir İnformasiya, Ölçmə və İdarəetmə Sistemləri: Problemlər və perspektivlər. 2019" (MIMCS 2019). ADNSU – da keçirilmiş Birinci Beynəlxalq Elmi – Praktiki Konfransı, iyul 01-02, 2019, Bakı, Azərbaycan;

"Müasir İnformasiya, Ölçmə və İdarəetmə Sistemləri: problemlər və perspektivlər, 2019" (MIMCS 2020)". ADNSU – da keçirilmiş İkinci Beynəlxalq Elmi – Praktiki Konfransı, Dekabr 07-08, 2020, Bakı, Azərbaycan.

"Dördüncü sənaye inqilabının texnoloji perspektivləri: sənaye interneti, kiberfiziki sistemlər və intellektual texnologiyalar", Azərbaycan Texniki Universitetində keçirilmiş elmi – praktiki Konfrans, 26-27 Noyabr, 2020, Bakı, Azərbaycan;

Сборник Статей XIV Международной научно-практической конференции. Актуальные проблемы экологии и охраны труда. 31 мая 2022 года. Курск.

20 scientific works, including 16 articles, 4 scientific-conference materials, 5 articles without co-authors, corresponding to the topic of the dissertation work, were published.

Of these, 4 are indexed in the "Web of Science" scientific databases (one of them is included in the European platform, and the other three are included in the RSCI platform.)

Name of the institution where the dissertation work was performed: The dissertation work was carried out at the "Instrumentation Engineering" department of the Azerbaijan State Oil and Industry University and partially at the Scientific-Research Aerospace Informatics Institute of the National Aerospace Agency based on the agreement on scientific-technical cooperation

The total volume of the dissertation with a sign indicating the volume of the structural sections of the dissertation separately: The dissertation consists of an introduction (16480), chapter I (24581), chapter II (25158), chapter III (35902), chapter IV (56369), conclusion (3572) and a reference list. The total volume is 194 pages, including a bibliography consisting of 52 figures, 2 tables and 183 sources. The total volume of the dissertation (excluding pictures, tables, graphs, and reference list) consists of 165341 characters..

BRIEF CONTENT OF THE CASE

In the introduction, the relevance of the topic is substantiated, the main propositions, scientific innovation, the theoretical and practical importance of the work, the approval and application of the work are explained by defining the goals and objectives of the research.

The first chapter is devoted to new measurement and evaluation methods of optical solar radiation, which is the input signal of sun photometers.

At the beginning of the chapter**,** the issues of realizing solar photometric measurements in the optical radiation range were considered. The analysis of theoretical and experimentally determined values of solar radiation on Earth shows that these compared values differ significantly. It was suggested that for this purpose, not randomly taken values of solar radiation, but extremum values integrated over a certain time interval within the accepted model conditions should be used. In the first chapter, the issues of the study of the instability of the emission coefficient of the atmosphere in the absorption lines of water vapors were considered. Within the equation of the relative instability coefficients of atmospheric aerosol and water vapor optical thicknesses with respect to time, the limit value of the atmospheric aerosol opacity coefficient (β) related to the wavelengths of 0.82 μm and 0.94 μm was found such that the share of water vapor in the total instability is 0.94 μm wavelength is higher than that at 0.82 μm wavelength. The threshold value of (β) increases as the Angstrom index α increases, and the share of water vapor in the total instability continues to be higher at a wavelength of 0.94 μm than at a wavelength of 0.82 μm.

The dependence graph of the boundary condition β=f(α) is given

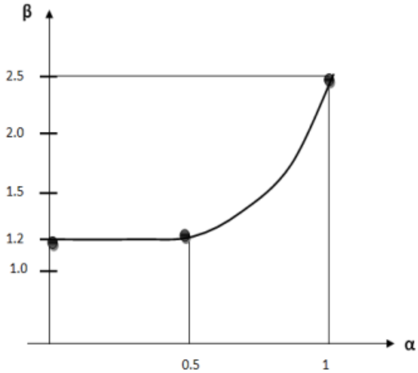

Figure 1. β=f(α) boundary condition dependence graph

The function β=f(α) increases as α increases, and the share of water vapor in the total instability at a wavelength of 0.94 μm continues to be higher than at a wavelength of 0.82 μm. In conclusion, such a rule can be formulated that water vapors should be measured at a wavelength of 0.82 μm in the half-plane above the graph of the β=f(α) function, and at a wavelength of 0.94 μm in the lower half-plane.

At the end of the first chapter, the issues of using Sun photometers for the formation of predictions on the optical radiation of the Sun were considered. In order to apply the well-known statistical models used to determine the number of sunny days and hours during the year, the use of Langley diagrams for the determination of external atmospheric solar radiation was shown to be a shortcoming of aerosol error, and a new method was proposed to overcome this shortcoming. This method includes correction factors. According to this method, external solar radiation is determined by measuring at three values of the optical air mass and at three wavelengths by including correction coefficients, and as a result, predictions are made more accurately based on known models.

The second chapter is devoted to the development of new methods for high-precision measurement of atmospheric components using a sun photometer. At the beginning of the second chapter, the issues of optimizing the measurement of small concentration gases in the atmosphere by means of a sun photometer during the day, taking into account the influence of the atmospheric aerosol, were considered.

According to the well-known Buger-Behr law, the signal at the input of the sun photometer is defined as follows.

$$I(\lambda) = I_0(\lambda)e^{-[\tau_{atm}(\lambda)\cdot m]} \qquad (1)$$

here I(λ) - is the optical signal at the input of the sun photometer; $I_0(\lambda)$ - is the value of optical radiation at the upper boundary of the atmosphere

The research question is formulated as follows:

A functional dependence λ=λ(m) should be found, so that the value of the integral of the relative indicator $I(\lambda)/I_0(\lambda)$ (1 – mmax) in the optical air mass variation range has reached its maximum.

In the first approximation, let us approximate the value of the optical thickness of the atmosphere in the wavelength range of 0.3÷1.0 μm with a decreasing linear function of the wavelength, that is:

$$\tau_{atm}(\lambda) = \tau_{atm\cdot 0} - k_1 \cdot \lambda \qquad (2)$$

here k_1=const.

Next, consider the following function:

$$\lambda = \lambda(m) \qquad (3)$$

(1), (2) və (3) we can write based on expressions:

$$I(\lambda) = I_0(\lambda)e^{-[\tau_{atm\cdot 0} - k_1 \cdot \lambda(m)]m} \qquad (4)$$

Let's design the optimization functional as shown below:

$$F_1 = {I(\lambda)}/{I_0(\lambda)} = \int_1^{m_{max}} e^{-[\tau_{atm\cdot 0} - k_1 \cdot \lambda(m)]m}\, dm \tag{5}$$

(3) let's apply the following restriction condition in relation to the function

$$F_2 = \int_1^{m_{max}} \lambda(m) dm = C \tag{6}$$

Here C=const.

It has been shown that,

$$k = \frac{\lambda_{01} - \lambda_{02}}{m_{max}} \tag{7}$$

Taking into consideration,

$$F_{11} > F_{12} \tag{8}$$

inequality is always satisfied, that is, it is a correct solution if the function $\lambda = f(m)$ is a decreasing function. The second chapter proposes a new method for aerosol correction in three-wavelength sun photometers.

In the proposed new method, a special parameter γ is included, which is calculated as follows:

$$\gamma = \frac{I_0(\lambda_1)^{k_1} \cdot e^{-k_1 \tau_a(\lambda_1)} \cdot I_0(\lambda_3)^{k_2} \cdot e^{-k_2 \tau_a(\lambda_3)}}{I_0(\lambda_2) \cdot e^{-\tau_a(\lambda_2)}} = \\ = \frac{I_0(\lambda_1)^{k_1} \cdot I_0(\lambda_3)^{(1-k_1)}}{I_0(\lambda_2)} \cdot e^{-k_1 \tau_a(\lambda_1) - (1-k_1)\tau_a(\lambda_3) + \tau_a(\lambda_2)} \tag{9}$$

It is obvious that the condition for eliminating the effect of aerosol in expression (9) can be written as follows:

$$\tau_a(\lambda_2) = k_1 \tau_a(\lambda_1) - k_1 \tau_a(\lambda_3) + \tau_a(\lambda_3) \tag{10}$$

If

$$k_1 = k_2 \qquad (11)$$

the condition is satisfied, we can write based on expression (8):

Thus, when the values of the quantities α, a_1, a_2 are known, it is possible to calculate such a wavelength λ_2 that at this wavelength it is possible to fully compensate the effect of atmospheric aerosol on the results of solar-photometric measurements.

In the second chapter, the issues of optimization of the operation mode of the sun photometer working in ozonometer mode were considered. It has been shown that the analysis carried out on the issue of optimizing the daily operation of the sun photometer working in the ozonometer mode, if the predicted value of ozone in the atmosphere is known, allows to correctly determine the time of day when the measurements are made and to move away from the mode of minimal sensitivity to the concentration of ozone in the measurements.

At the end of the second chapter, the proposed generalized Langley method for the calibration of Sun photometers is described. The proposed method is based on the daily variation statistics of the aerosol. In order to carry out measurements, it is required to select such moments of time that the results of measuring the optical thickness of the aerosol with an uncalibrated photometer are the same at these moments. As a baseline, it is assumed that the time-stable quantity $\tau_{aer}(\lambda)$ does not affect the accuracy of the Langley calibration.

The third chapter of the thesis work is dedicated to improving the methods of measuring water vapors in the atmosphere using a sun photometer. At the beginning of the chapter, issues of increasing the accuracy of the multiwavelength measurement method of the total amount of water vapor in the atmosphere by means of a Sun photometer were considered.

The well-known mathematical optical thickness model of the optical thickness of water vapor is written as follows:

$$\tau_W = a(mW)^b \qquad (13)$$

The coefficients a, b of this model depend on the wavelength, that is:.

$$a=a(\lambda) \qquad (14)$$

$$b=b(\lambda) \qquad (15)$$

According to the three-wave method of measurements, the final Wp quantity is defined as the following linear scalar fold:

$$W_p = \frac{d_1 W(0.72) + d_2 W(0.82) + d_3 W(0.94)}{3} \qquad (16)$$

here; i=¯1,3- are weight coefficients.

Thus, according to expression (16), the quantities *W*(0.72), *W*(0.82) and *W*(0.94) should be determined separately. However, in this case, the influence of aerosol humidification on the measurement result is inevitable, which makes the measurement experiment extremely difficult.

To eliminate such complications, the method of applying intermediate parameters and correction coefficients is used in the present section.

$$\tau_R \ll \tau_a, \qquad (17)$$

assuming that and also considering the model (13), we can write expression (17) as:

$$\left(\frac{V}{V_0}\right)_{\lambda_i} = e^{-\left[m_0(c_1(\lambda_i)+c_3(\lambda_i)W)+a(\lambda_i)(mW)^{b(\lambda_i)}\right]}$$

here that; i=¯1,3

Let's enter the following relative parameter:

$$\gamma_1 = \frac{\left(\frac{V}{V_0}\right)_{\lambda_1}^{k_1} \left(\frac{V}{V_0}\right)_{\lambda_3}^{k_3}}{\left(\frac{V}{V_0}\right)_{\lambda_2}^{k_2}} \qquad (18)$$

here k_i; i=$\overline{1,3}$ – are correction coefficients.

The selection of coefficients k_i is determined based on the following condition:

$$K_1 C_3(\lambda_1) + K_3 C_3(\lambda_3) = K_2 C_3(\lambda_2) \qquad (19)$$

$C_3(\lambda_1)$, $C_3(\lambda_2)$, $C_3(\lambda_3)$ coefficients can be set in advance. Assuming that k_2=1, we can write:

$$K_1 \frac{C_3(\lambda_1)}{C_3(\lambda_2)} + \frac{K_3 C_3(\lambda_3)}{C_3(\lambda_2)} = 1 \qquad (20)$$

That is

$$K_1 = \frac{0.5\ C_3(\lambda_2)}{C_3(\lambda_1)}; K_3 = \frac{0.5\ C_3(\lambda_2)}{C_3(\lambda_3)} \qquad (21)$$

if accepted, we can neutralize the effect of W on γ_i by fulfilling the condition (19).

Taking into account expressions (17)÷(21), it can be written as a final result that

$$0.5a(\lambda_1)(mW)^{b(\lambda_1)} - a(\lambda_2)(mW)^{b(\lambda_2)} + 0.5a(\lambda_3)(mW)^{b(\lambda_3)} = \ln(\gamma_1^{-1}) - -0.5m_0 * [C_1(\lambda_1) + C_1(\lambda_3) + C_1(\lambda_2)] \qquad (22)$$

Thus, the solution of the obtained algebraic equation (22) allows the value of W- to be determined without the influence of the unstable factor $C_3(\lambda_i) \cdot W$ -. The following model study was conducted to estimate the relative gain resulting from the removal of the $C_3(\lambda_i) \cdot W$ component.

It is obvious that $C_3(\lambda_i)$ determines the hydrophilic component of the atmospheric aerosol. This component is as volatile as the hydrophobic component.

Let us introduce the quantities $C_3(\lambda_i)$ and W as follows:

$$C_3(\lambda_i) = m_{c_3}(\lambda_i) + \sigma_{c_3}(\lambda_i) \quad (23)$$

$$W = m_w + \sigma_w \quad (24)$$

here $m_{C3}(\lambda_i)$ və m_W – are the mean values of $C_3(\lambda_i)$ and W_i respectively, $\sigma_{C3}(\lambda_i)$, σ_W are their mean squared tendencies.

Let's take the following values:

$$m_{c_3}(\lambda_i) = m_w = 0.5 \quad (25)$$

$$\sigma_{c_3}(\lambda_i) = \sigma_w = 0.1 \quad (26)$$

If the values (25) and (26) are taken into account, the instability coefficients of the quantities $C_3(\lambda_i)$ and W can be estimated as follows:

$$\beta_1 = \frac{\sigma_{c_3}}{m_{c_3}(\lambda_i)} = \frac{\sigma_w}{m_w} = 0.2 \quad (27)$$

If the values (25) and (26) are taken into account, let's calculate the value of $C_3(\lambda_i) \cdot W$

As a result, we get:

$$C_3(\lambda_i)W = m_{c_3}(\lambda_i)m_w + m_{c_3}(\lambda_i)\sigma_w + m_w\sigma_{c_3}(\lambda_i) + \sigma_w\sigma_{c_3}(\lambda_i) \quad (28)$$

Taking into account that,

$$\sigma_w\sigma_{c_3}(\lambda_i) \approx 0 , \quad (29)$$

We get the following result:

$$m_{c_3}(\lambda_i)W = 0.25 \quad (30)$$

$$\sigma_{c_3}(\lambda_i)W = 0.1 \quad (31)$$

Thus, the instability coefficient of the excluded $C_3(\lambda_i) \cdot W$ component can be calculated as follows:

$$\beta_1 = \frac{G_{c_3}(\lambda_i)W}{m_{c_3}(\lambda_i)W} = \frac{0.1}{0.25} = 0.4 \tag{32}$$

Thus, the conducted study showed that the instability of the excluded hydrophilic component of the aerosol is twice as much as the instability of the non-excluded hydrophobic component. It explains the possibility of doubling the accuracy of the three-wave measurement method of water vapor using a sun photometer.

The third chapter then proposes a new method of measuring the total amount of water vapor in the atmosphere using a Sun photometer.

In the new modification of the well-known three-wave measurement method created by us, the main issue when measuring small gas components is to eliminate the effect of aerosols on the measurement results.

In the proposed version of the well-known three-wave measurement method, where correction coefficients are applied, the central wavelength λ_5 is chosen equal to 940 nm.

In this case, similarly to (25), we can write:

$$\gamma_1 = \frac{T_1(\lambda_4)^{k_3} \cdot T_1(\lambda_6)^{k_4}}{T_1(\lambda_5)} \tag{33}$$

here $T_1(\lambda_4)$–λ_5 – atmospheric optical emission at wavelength $\Delta\lambda$;

$T_1(\lambda_6)$ – atmospheric optical emission at wavelength at $\lambda_5 + \Delta\lambda$; here $\lambda_4 = \lambda_5 - \Delta\lambda$; $\lambda_6 = \lambda_5 + \Delta\lambda$.

The value of $\Delta\lambda$ is chosen in such a way that the absorption band of water vapor at the central wavelength of 940 nm does not occupy the wavelengths λ_4 and λ_6.

The optical emission of the atmosphere at wavelengths λ_4, λ_5, λ_6 is defined as:

$$\mathrm{T}(\lambda_4) = exp\left[-\left(m_1 \tau_\mathrm{a}(\lambda_4)\right)\right] \tag{34}$$

$$\mathrm{T}(\lambda_6) = exp\left[-\left(m_1 \tau_\mathrm{a}(\lambda_6)\right)\right] \tag{35}$$

$$T(\lambda_5) = exp\left[-\left(m_1\tau_a(\lambda_5) + \tau_w(\lambda_5)\right)\right] \quad (36)$$

here τ_w (λ_5) – is the optical thickness of water vapor at wavelength λ_5

If we replace expressions (34)÷(36) in expression (33), we obtain the following next condition for eliminating the effect of aerosol on the quantity γ_1:

$$k_3\tau_a(\lambda_4) + k_4\tau_a(\lambda_6) = \tau_a(\lambda_5) \quad (37)$$

Assume that the values of τ_w (λ_5, t_1) and τ_w (λ_5, t_2)-are known at time instants , t_1 and t_2, where τ_w (λ_5, t_2) >τ_w (λ_5, t_1). Taking into account expression (37) and also expressions (28)÷(32), we can express the conditions for compensating the aerosol effect in determining the quantity γ at time t_1 as follows:

$$k_3{\lambda_4}^{-\alpha(t_1)} + k_4{\lambda_6}^{-\alpha(t_1)} = {\lambda_5}^{-\alpha(t_1)} \quad (38)$$

Analogously, we can write the following condition for the moment t_2 :

$$k_3{\lambda_4}^{-\alpha(t_2)} + k_4{\lambda_6}^{-\alpha(t_2)} = {\lambda_5}^{-\alpha(t_2)} \quad (39)$$

At the known values of $\alpha(t_1)$ və $\alpha(t_2)$ expressions and selected values of wavelengths, correction coefficients k_3 and k_4 can be found by solving system equations (38), (39).

If we substitute the obtained values of k_3 and k_4 for time instants t_1 and t_2 in expression (33), we get:

$$\gamma_1(t_1) = \frac{1}{exp\left[-\left(\tau_w(\lambda_5,t_1)\right)\right]} \quad (40)$$

$$\gamma_1(t_2) = \frac{1}{exp\left[-\left(\tau_w(\lambda_5,t_2)\right)\right]} \quad (41)$$

$\gamma_1(t_1)$, $\gamma_2(t_2)$ - is the value of quantity γ_1 at moments t_1 and t_2

Then, taking into account the Moskalenko model of the optical thickness of water vapor in the atmosphere, we can write for the moments t_1 and t_2

$$W_1 = \frac{1}{m} \cdot \sqrt[b]{\frac{ln\,\gamma_1(t_1)}{a}} \tag{42}$$

$$W_2 = \frac{1}{m} \cdot \sqrt[b]{\frac{ln\,\gamma_1(t_2)}{a}} \tag{43}$$

Thus, by performing three-wave measurements at time points t_1 and t_2, if the values of $\alpha(t_1)$ və $\alpha(t_2)$ are known, it is possible to determine the total amount of water vapor W_1və W_2 in the atmosphere by pre-calculating the applied correction coefficients.

Then, in the third chapter, the problems of the measurement error of the amount of water vapor in the atmosphere in the wavelength interval of 810÷826 nm were considered.

The method of measuring the content of water vapors in the atmosphere at the wavelength of 900÷960 has a serious drawback. This disadvantage is that the reading of this photometer can vary considerably due to the temperature drift of the passband of the interference filters used in the Sun photometer.

For example, at wavelengths 940 and 945, the photometer reading will differ by at least 20%. However, as can be seen from the curves shown in Figure 1, no such differentiation of indications is observed in the wavelength range of 817 – 825nm. Therefore, in the absence of thermostabilized interference filters, it may be more appropriate to measure the content of water vapors in the atmosphere in the 817÷825 nm wavelength interval.

It was shown that in the considered scenarios of mutual changes of their quantities β and τ, the relative error of measuring the content of water vapor in the atmosphere at a wavelength of 817 nm does not depend on the optical thickness of ozone in the atmosphere and is determined by the double value of the optical thickness of the atmospheric aerosol at a wavelength of λ=817 nm.

At the end of the third chapter, the issues of developing model validation methods of the results of measuring the value of the total amount of water vapor in the atmosphere by means of a Sun photometer were considered.

Based on the well-known Butler method, it can be written that

$$\mathrm{IWV} \approx \frac{P_0}{3\mathrm{T}_0} \tag{44}$$

here, *IWV* is measured in mm; P_0 – measured in mkBar; T_0 – measured in K.

A well-known expression for calculating the partial pressure of water vapor on the surface of the Earth

Given the strong correlation between *RH* and air temperature and the strong negative correlation between Earth's surface temperature and air temperature, we can write

$$P_0 = 2.409 \cdot 10^{12} \left(\frac{A - C_2 \cdot T_0}{C_1}\right) \cdot \left(\frac{300}{\mathrm{T}_0}\right)^4 \cdot e^{\frac{-22.64 \cdot 300}{T_0}} \tag{45}$$

Taking into account statements (44) and (45), we can write in conclusion:

$$\mathrm{IWP} = \frac{2.409 \cdot 10^{12} \left(\frac{A - C_2 \cdot T_0}{C_1}\right) \cdot \left(\frac{300}{\mathrm{T}_0}\right)^4 \cdot e^{\frac{-22.64 \cdot 300}{T_0}}}{3T_0} \tag{46}$$

Thus, by measuring the temperature T_0 of the surface, and also, if there is information about the value of the constants A, C_1, C_2, it is possible to estimate the quantity of IWV, and thus it is possible to conclude whether the obtained measurement result is correct or incorrect.

The fourth chapter is dedicated to the improvement of measurement and calibration methods of measurement complexes using sun photometers.

At the beginning of the chapter, a method for determining the Linke opacity coefficient of the atmosphere through solar-photometric measurements is proposed. The well-known analytical model showing the interaction between the Angstrom opacity coefficient and the

Linke opacity coefficient was used to determine the Linke opacity coefficient of the atmosphere by conducting sun-photometric measurements. For this purpose, a two-wave measurement method at λ_1=0.82 and λ_2=0.94μm wavelengths was proposed to determine the deposited value of water vapors in the two-wave method it is envisaged to carry out joint - synchronous calibration of the channels. It has been shown that this type of calibration allows to eliminate the error that may occur due to the change in the state of the atmosphere and to reduce the total noise signal of the channels in the case of separate calibration of the channels.

In the fourth chapter, the issues of increasing the effectiveness of Lidar - Sun - photometric systems were discussed. When calibrating lidars, the small value of the signal-to-noise ratio, the effect of clouds, and also the potential inaccuracy of the initial values of the ratio of the attenuation coefficient to the scattering coefficient can ultimately lead to wrong results. For this reason, sun photometers are used to estimate the measurement error of lidars.

The general scheme of the lidar-photometric complex is given in figure 2.

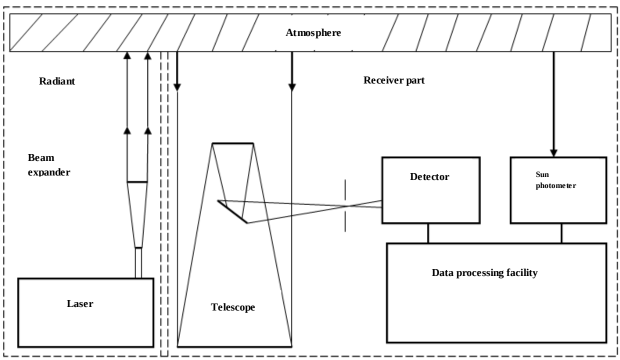

Figure 2. General scheme of the complex of lidar - solar - photometric atmospheric measurements

Based on the well-known simplification of the lidar equation and replacing the optical thickness of the aerosol measured by the lidar with the index τ_λ, the equation of the lidar-sun photometer complex can be written as follows**:**

$$P(r)\cdot C(r)=\frac{C^2(r)\phi(\beta_m,\tau_\lambda)}{r^2} \tag{47}$$

here *C=C(r)* is a newly proposed function showing the dependence of the lidar constant (this constant includes the power of the lidar beam) on the required current distance.

The operational efficiency of the lidar-solar photometer complex can be estimated using the following integral indicator, which consists of the integral of the scalar product of the functions *P(r)* and *C(r)*

$$\gamma=\int_0^{r_{\max}} P(r)\cdot C(r)dr' \tag{48}$$

(47) and (48) we get from their expressions

$$\gamma=\frac{\int_0^{r_{\max}} C^2(r)\phi(\beta_m,\tau_\lambda)dr'}{r'^2} \tag{49}$$

Let's define the condition that the energy resource of the mobile laser complex is limited as follows:

$$\int_0^{r_{\max}} C(r)dr=C_1;\quad C_1=const \tag{50}$$

Condition (50) can be physically interpreted as the limited energy resource of the mobile laser complex.

To find the optimal *C(r)* function, a variational optimization problem was formulated and the solution of this problem by Euler's method gave the following result.

$$C(r)_{opt} = \frac{C_1 \cdot r^2}{2\left[\int_0^{r_{\max}} \frac{r^2 dr}{2\psi B_m, \tau_\lambda}\right] \cdot \psi(B_m, \tau_\lambda)}$$

It is shown that the objective functional (50) within the solution of (49) takes the minimal value.

Since our proposed criterion is essentially the integral or covariance of the scalar product of the functions *P(r)* and *C(r)* with zero average values, the proposed efficiency criterion of the lidar-photometric system should reach a minimum in the optimal operating mode. This is explained by the fact that the signal received from the atmosphere will be significantly different from the sounding signal if it has maximum informativeness, that is, there will be a strong negative correlation between the initial sounding signal and the received informative signal.

In the fourth chapter, the issues of application of optical radiation sources of different altitudes for the calibration of the surface photometer-type microtelescope network designed for the tracking of orbital satellites were considered.

The main drawback of the well-known balloon method of ground-based microtelescopes calibration is that the calibration results have low accuracy due to measurements at the same flight height, and also due to the use of different types of light sources, which are not harmonized according to their spectral characteristics.

The following changes are proposed in the construction of the platform where the balloons are placed:

1. Replacement of all sources with laser emitters of the same type;
2. Conducting calibration procedures at different heights.

The first innovation shown above can provide radiation with a certain isotropy due to the divergence of laser beams of the same type.

The ground-level magnitude of an orbital laser is defined by the following expression:

$$m \approx -2.5\log_{10}\left(\frac{P}{h^2 d^2}\right) - 20.1 \qquad (51)$$

If we take into account that in the proposed method, the measurements are carried out according to the laser beam located at different heights ($0 \div h_{max}$), we can consider the following function, conditionally switching to the continuous model of the analysis:

$$d = \varphi(h) \qquad (52)$$

It can be assumed that as the divergence index *d* increases, the number of microtelescopes covered by the optical track of the laser beams from the lasers on the platform will also increase. Taking the above into account, we can calculate the total magnitude of the emitters on platforms of different heights *h* as follows.

$$m_{инт} = -\int_0^{h_{\max}} 2.5 \cdot k \cdot h \cdot \log_{10}\frac{P}{h^2\varphi^2(h)}dh + \int_0^{h_{\max}} C \cdot (h) dh \qquad (53)$$

To solve the problem of finding the optimal form of the function *φ(h),* let's accept the following restriction condition:

$$\int_0^{h_{\max}} \varphi(h) dh = C_1; \qquad (54)$$

here C_1=const.

Considering statements (53) and (54), the non-conditional variation optimization functional was designed and the solution of the optimization problem was obtained as follows:

$$\varphi(h) = \frac{2 \cdot C_1 \cdot h}{h^2{}_{\max}} \qquad (55)$$

It has been suggested that this maximum be used as a final indication of the correct calibration of microtelescopes. Let's conduct a model study to verify the accuracy of the obtained result.

The methodology of the inspection consists of the following:

1. A pair of functions meeting condition (48) is defined. Let's choose one of these functions according to expression (55). We define the second function from the following condition.

$$\int_0^{h_{max}} \varphi_2(h)dh = C_1 \tag{56}$$

here

$$C_1 = \frac{A \cdot h_m}{2} \tag{57}$$

here

$$A = \frac{2C_1}{h_m} \tag{57}$$

It can be shown that if the function φ_2 is chosen as a linear function:

$$\varphi_2(h) = \frac{2C_1}{h_m} - \frac{A \cdot h}{h_m} \tag{58}$$

in this case condition (55) is fulfilled (Figure 3).

2. In the objective functional (48), the extremum of the first term is sought, i.e.:

$$F_1 = -\int_0^{h_m} h \cdot \log_{10} \frac{P}{h^2 \varphi^2(h)} dh \tag{59}$$

For this purpose, we insert the solution (54) into the expression (59):

$$F_1(\varphi_1) = -\int_0^{h_m} h \cdot \log_{10} \frac{P \cdot h_{max}^4}{4{C_1}^2 h^4} dh \tag{60}$$

(58) Taking (59) into account, we can write:

$$F_1(\varphi_2) = -\int_0^{h_m} h \cdot \log_{10} \frac{P}{h^2 \left(\frac{2C_1}{h_m} - \frac{A \cdot h}{h_m} \right)^2} dh \tag{61}$$

So, let's construct the graphs of the integrands in expressions (60) and (61) and visually evaluate the areas covered by them.

Assume the following model values:

$$A = 1;\ h_m = 1;\ C_1 = 1;\ P = 1. \tag{62}$$

Thus, the graphs of the following functions should be constructed:

$$S_1(h) = -h \cdot \log_{10} \frac{10}{4h^4} \tag{63}$$

$$S_2(h) = -h \cdot \log_{10} \frac{10}{h^2(2-h)^2} \tag{64}$$

Graphs are drawn in the interval h=(0÷1).

Graphs of expressions $S_1(h)$ and $S_2(h)$ are given in figure 4.

From the graphs shown in Figure 4, it can be seen that the area covered by curve 1 is about 15% larger than the area covered by curve 2. This shows a 15% increase in the proposed calibration method.

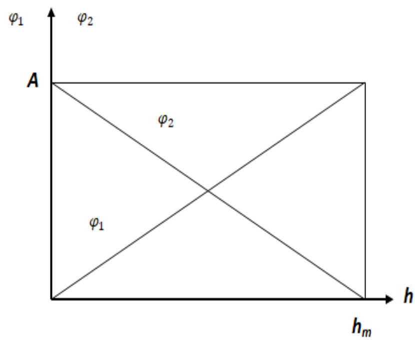

Figure 3. Selecting the φ_2 function

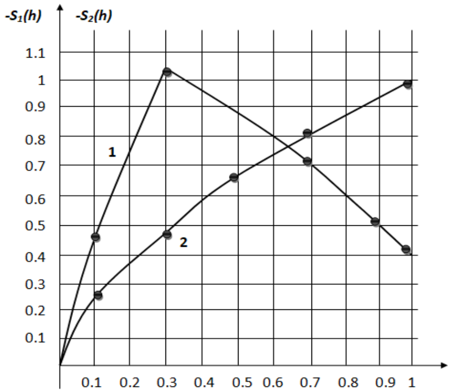

Figure 4. Graphs of functions *S_1*(*h*) and *S_2*(*h*)
Accepted Marks:
1- graph of *S_1*(*h*) function; 2 - Graph of function *S_2*(*h*)

At the end of the fourth chapter, the issues of measuring the amount of water vapor in the surface layer of the atmosphere with a photometer were considered using external irradiators and LED-type irradiators in photodetector mode.

In order to measure the total column amount of water vapors, a photodiode with a narrow wavelength band of optical radiation, working with a filter (940 nm) and a light-emitting LED diode with a wavelength of 825 nm were used in photodetector mode.

The signal spectrum of these photosensitive elements is given in figure 5.

We have installed a two-channel measuring device for the technical implementation of the surface-altitude method of water vapor measurement in the upper atmospheric layer, the optical-electronic scheme of this device is given in figure 6.

Experimentally, the above device operating at wavelengths λ_1= 940 nm and λ_2=870 nm was studied.

Figure. $7\ln\frac{V_1}{V_2} = f\left(\tau \cdot m - mPW^{\frac{1}{2}}\right)$ shows the experimentally derived curve of the suspension. Here, V_1 is the signal at the output of the 940 nm wavelength channel; V_2 is the signal at the output of the 870 nm wavelength channel.

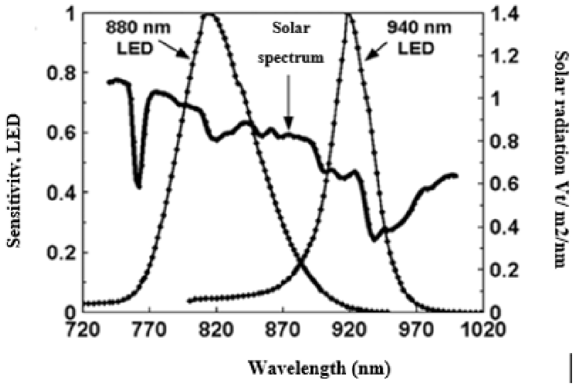

Figure 5. Emission bands of LED sensors used in a dual-band photometer operating at 815 nm and 920 nm wavelengths

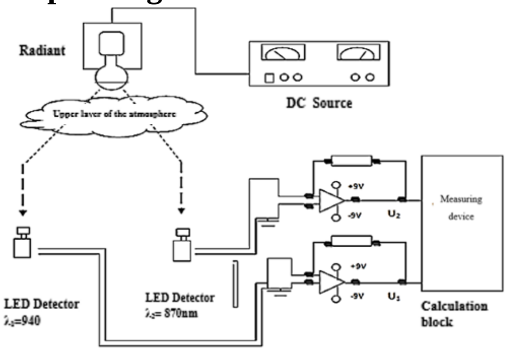

Figure 6. Optical-electronic scheme of the receiving-transmitting tract of the device for measuring the content of water vapors in the surface layer of the atmosphere

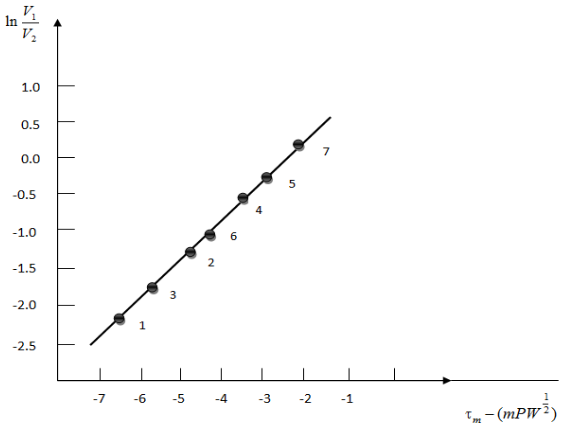

Figure 7. $\ln\frac{V_1}{V_2} = f\left(\tau \cdot m - mPW^{\frac{1}{2}}\right)$ **experimentally extracted curve of dependence**

The dates of the measurements are as follows:
1–10.04.2020; 2 – 12.04.2020; 3 – 14.04.2020; 4 – 16.04.2020; 5 – 18.04.2020; 6 – 20.04.2020; 7 – 22.04.2020.

To calculate the total amount of water vapor deposited, formula (65) is used, this formula is slightly modified by multiplying by the calibration coefficient

$$PW = \frac{k}{m}\left[17.627 - 30.719\left(\frac{I_{940}}{I_{815}}\right)\right] \tag{65}$$

here, m – the optical air mass; I_{940} – signals at the output of the photometer; k – the calibration coefficient.

The value of measurement results based on the Butler method was used as the standard value of the total amount of deposited water vapors.

The measurements showed that the value of the k coefficient can vary between 1.03÷1.08, which is partially explained by the fact that the Butler method used for comparison has a considerable methodological error.

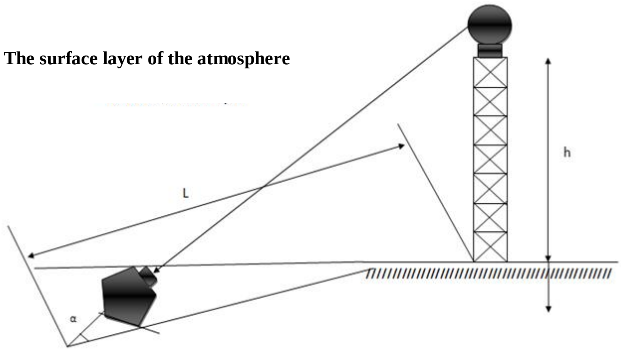

Figure 8. Technological scheme of the surface-altitude method used to measure the amount of water vapor in the surface layer of the atmosphere

THE MAIN RESULTS OF THE DISSERTATION WORK

1. The conditions for measuring small concentration gases in the atmosphere with the influence of atmospheric aerosol during the day with the highest efficiency by means of a sun photometer were investigated and it was shown that in order to achieve this goal, the measurements should be carried out in the optimal mode, i.e. ensuring a directly proportional functional dependence between the wavelength of the measurements and the optical air mass. should be done.

2. It is shown that the proposed new solar photometric measurement method, which uses a correction method based on the principle of geometric averaging, allows to completely eliminate the effect of atmospheric aerosol on the results of three-wave solar-photometric measurement, and can be applied for the accurate measurement of low-concentration gases and optical radiation indicators in the atmosphere.

3. A new three-wave measurement method was proposed for the measurement of water vapors in the atmosphere using a sun photometer, where the destabilizing effect of the most unstable hydrophilic component of the atmospheric aerosol is eliminated by the compensation method in order to increase the measurement accuracy.

4. It is shown that it is possible to accurately determine the amount of water vapor in the atmosphere at fixed moments by performing three-wave measurements at fixed moments using the proposed newly improved three-wave method, and by calculating the corresponding correction coefficients using the values of the Angstrom indicator related to these moments. . This result opens up new opportunities in the study of water vapor, which is the most important greenhouse gas.

5. It has been shown that if temperature-sensitive interference filters are applied in sun photometers, the accuracy of measuring water vapor in the atmosphere at a wavelength of 817 nm by a sun photometer can be higher than the accuracy of measurement at a wavelength of 940 nm and the relative error of measuring the total

amount of water vapor in the atmosphere at a wavelength of 817 nm is directly proportional to twice the optical thickness of the atmospheric aerosol at that wavelength.

6. For the validation of the preliminary measurement results of the total amount of water vapor in the atmosphere, experimental model methods have been proposed, which include the measurement of the air temperature on the surface of the earth and the consideration of the statistical data characteristic of the studied region, and these methods can be used in the preliminary processing of the measurement results.

7. The efficiency criterion for increasing the efficiency of the remote sensing complex consisting of a lidar and a sun photometer and the optimal type of the function showing the dependence of the proposed laser beam power on the sensing distance to the extreme were found, which can increase the efficiency of atmospheric research through the corresponding complex.

8. In order to increase the calibration accuracy of photometer-based microtelescopes used for tracking orbital satellites from the ground, it was proposed to place calibration platforms with lasers of the same type at different heights and the provision about the possibility of using the extreme value of the total calibration signal under the conditions of a certain optimal type of this function as a diagnostic sign of the correctness of the performed calibration procedure further expands the functional capabilities of photometer-based microtelescopes in the field of satellite observation.

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