UDC 535.2;538.3;550.33

Investigation of Possibility of Measuring the Albedo of Earth's Surface in Visible and Near Infrared Bands in Conditions of Aerosol Pollution of Atmosphere Using Unmanned Aerial Vehicles

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It is well-known that such processes as agricultural activities, urbanization processes, climatic changes leading to abnormal precipitation, etc. affect the magnitude of the Earth's albedo. At the same time, the results of remote albedo measurement in visible and near infrared bands also depend on the degree of aerosol pollution of the atmosphere. These factors leading to changes in the earth's albedo lead to the need for periodic measurements of regional values of the albedo of the earth's surface. There are a number of problems related to measuring the albedo of the earth, related to the spatial and temporal variability of this indicator. These include the dependence of albedo on the zenith angle of the Sun, the need to create albedo measurement networks in the form of numerous geographically distributed pyranometers, the dependence of satellite albedo measurements on the state of the atmosphere, leading to the need for inter-satellite calibration, or ground-based validation measurements. At the same time, the issue of fully accounting for the effect of atmospheric aerosol on the results of measuring the albedo of the Earth's surface is still open. The article is devoted to the measurement of the Earth's albedo visible and near infrared bands using UAVs in conditions of aerosol pollution of the atmosphere. The model of single scattering of the optical source signal of an atmospheric aerosol was adopted as the basis of the conducted research. The interrelation of such optical indicators as the optical thickness of the aerosol and the albedo of the Earth's surface is analyzed. A criterion for the effectiveness of atmospheric measurements using UAVs is proposed, in which efficiency is defined as the ratio of the total radiation entering the on-board spectroradiometer to the amount of extra-atmospheric radiation from the Sun. By switching from a discrete model to a continuous model created to calculate the proposed efficiency criterion, it is shown that with a synchronous change in the optical thickness of the aerosol and albedo, according to the calculated law, the minimum efficiency of measurements of the albedo of the earth's surface is achieved.

Keywords: albedo; aerosol; UAV; spectroradiometer; efficiency criterion

DOI: 10.20535/RADAP.2024.96.28-31

Introduction

It is well known that the reflectivity of the Earth's surface, or the albedo of the Earth, plays an important role in the Earth's climate system [1–5]. It is obvious that all processes occurring on the Earth's surface somehow affect the magnitude of the Earth's albedo. Such processes are agricultural activities, urbanization processes, climatic changes leading to abnormal precipitation, etc. At the same time, the results of remote albedo measurement in visible and near infrared bands also depend on the degree of aerosol pollution of the atmosphere [6, 7]. These factors leading to changes in the earth's albedo lead to the need for periodic measurements of regional values of the albedo of the earth's surface. There are a number of problems related to measuring the albedo of the earth, related to the spatial and temporal variability of this indicator. These include the dependence of albedo on the zenith angle of the Sun [8], the need to create albedo measurement networks in the form of numerous geographically distributed pyranometers, the dependence of satellite albedo measurements on the state of the atmosphere, leading to the need for inter-satellite calibration [4–6], or ground-based validation measurements [12–14]. The measures taken towards solving these problems usually lead to satisfactory results. At the same time, the issue of fully accounting for the effect of atmospheric aerosol on the results of measuring the albedo of the Earth's surface is still open [15].

As for the technical means used for albedometry, until recently small aircraft were used for this purpose

[16, 17]. However, there is currently a transition to the use of unmanned aerial vehicles [18, 19]. The main advantages of using unmanned aerial vehicles (UAVs) are high spatial resolution and accuracy of measurements due to flight at low altitudes, within troposphere excluding effect of stratospheric aerosol. At the same time, atmospheric aerosol, being a highly dynamic natural and/or anthropogenic factor, also affects the accuracy of the results carried out using UAVs. In particular, the results of the analysis of the influence of atmospheric aerosol on the accuracy of such measurements are presented in [20]. Here are some provisions of the analysis carried out in this work.

A model is considered where the aerosol is represented by a thin layer where the optical thickness of the aerosol and Rayleigh scattering are much smaller than the effects of single scattering.

The total optical signal reaching the UAV in visible and near infrared bands is defined as

$$I_{\Sigma} = I_1 + I_2, \tag{1}$$

where I_1 is a direct optical signal reflected from the Earth's surface; I_2 is diffusely scattered aerosol radiation.

According to [20], I_1 and I_2 are defined as

$$I_1 = I_0 A \cdot e^{-2\tau_A}, \tag{2}$$

where I_0 is extraspheric Solar radiation; A is the albedo of the Earth's surface; τ_A is aerosol optical depth,

$$I_2 = I_0 \tau_A \frac{\omega(1-g)}{2} + 2 I_0 A \tau_A \frac{\omega(1+g)}{2}, \tag{3}$$

where ω is the albedo of a single scattering; g is the parameter of asymmetry.

Further, the indicator was introduced in [20]

$$\gamma = \frac{I_{\Sigma}}{I_0} \tag{4}$$

and the expression was obtained for calculating τ_A

$$\tau_A = \frac{\gamma - A}{\frac{\varpi(1-g)}{2} + A(\varpi(1+g)-2)}. \tag{5}$$

Expression (5) allowed us to determine the sensitivity of τ_A with respect to A in the form

$$\frac{\partial \tau_A}{\partial A} = \frac{1}{2A\left(1 + \frac{\omega(1+g)}{2}\right) - \frac{\varpi(1-g)}{2}}. \tag{6}$$

Thus, expression (6) makes it possible to determine the sensitivity of the value τ_A when the albedo value changes.

However, it seems to us that the problem of the relationship between τ_A and A should be considered in a broader sense, because firstly, measurements of τ_A make it possible to determine A, and secondly, change of A prevents the exact definition of τ_A.

Thus, the task of determining the optimal relationship between τ_A and A is actualized, in which more effective measurements of these indicators can be carried out in visible and near infrared bands.

1 Materials and methods

Speaking about the overall effectiveness of measurements τ_A and A, it is obvious that a quantitative indicator of such efficiency should be determined. If we consider that, heuristically, the stronger the optical signal reaching the input of the measuring instrument, the greater the signal-to-noise ratio at the input of the meter, and therefore the more useful measuring information can be extracted. This reasoning allows us to consider the indicator β as the overall efficiency of the measurement of τ_A and A, defined as

$$\beta = \frac{I_{\Sigma 1}}{I_0}. \tag{7}$$

Taking into account (2) and (3) we write

$$I_{\Sigma 1} = I_0 A \cdot e^{-2\tau_A} + \tau_A \left[I_0 \frac{\omega(1-g)}{2} + I_0 A \omega(1+g) \right].$$

To determine the dynamics of the interrelated changes of τ_A and A, we introduce the communication function

$$\tau_A = \psi(A). \tag{8}$$

Next, consider the following model of the earth's surface, in which an ordered set A can be formed, where

$$A = \{A_i\}; \quad i = \overline{1, n}, \tag{9}$$

where $A_i = A_{i-1} + \Delta A$; $\Delta A = const$; $A_0 = 0$.

Taking into account (7)-(9), we will make up the sum

$$\sum_{i=1}^{n} \beta_i = I_0 \left[\sum_{i=1}^{n} \left[A_i e^{-2\psi(A)} + \right.\right.$$
$$\left.\left. + \ \psi(A_i) \left[\frac{\omega(1-g)}{2} + A_i \omega(1+g) \right] \right] \varphi(A_i) \right], \tag{10}$$

where $\psi(A_i)$ is a function of the frequency of occurrence of equal areas of the earth with albedo A_i.

We will replace the discrete model (10) with a continuous model

$$\int_0^{A_{max}} \beta \, dA = I_0 \int_0^{A_{max}} \left[A e^{-2\psi(A)} + \psi(A) \left[\frac{\omega(1-g)}{2} + A\omega(1+g) \right] \right] \varphi(A) \, dA. \tag{11}$$

Thus, the functional on the right in expression (11) is a criterion for the effectiveness of measurements τ_A and A.

We investigate the extremum of functional (11) depending on type of function $\psi(A)$. It is well known that in order to solve an optimization problem of type (11), one should calculate the derivative of the integrant in functional (11) on desired function, and equate it to zero. We have:

$$\frac{d\left\{\left[Ae^{-2\psi(A)} + \psi(A)\left[\frac{\omega(1-g)}{2} + A\omega(1+g)\right]\right]\varphi(A)\right\}}{d\psi(A)} = 0. \qquad (12)$$

From expression (12) we find

$$-2Ae^{-2\psi(A)} + \frac{\omega(1-g)}{2} + A\omega(1+g) = 0. \qquad (13)$$

From expression (13) we find

$$e^{-2\psi(A)} = \frac{\omega(1-g)}{4} + \frac{\omega(1+g)}{2}. \qquad (14)$$

Converting expression (14) by logarithm, we obtain.

$$\psi(A) = \frac{1}{2}\ \ln\frac{4A}{\omega(1-g) + 2\omega(1+g)} = \ln\sqrt{\frac{4A}{\omega(1-g) + 2\omega(1+g)}}. \qquad (15)$$

We investigate the type of extremum of the functional (11) in solving (15). To do this, calculate the derivative (13) of the desired function. We have:

$$\frac{d\left[-2Ae^{-2\psi(A)} + \frac{\omega(1-g)}{2} + A\omega(1+g)\right]}{d\psi(A)} = 4Ae^{-2\psi(A)}. \qquad (16)$$

As can be seen from expression (16), the result is always a positive number, i.e. the functional (11) reaches a minimum when solving (16). Taking into account the result obtained, the following recommendation can be made on the basis of the solution: effective measurement of the indicators τ_A and A in the sense of the introduced criterion β (7) can be carried out if the synchronous change of τ_A and A according to the law (15) is not allowed, i.e. the mutual change of τ_A and A according to expression (15) can lead to the worst possible outcome.

2 Discussion

Thus, using a single scattering model of the optical source signal of an atmospheric aerosol, the relationship of such optical parameters as the optical depth of the aerosol and the albedo of the Earth's surface is analyzed. The following circumstances are taken into account.

Atmospheric pollution prevents the accurate measurement of the albedo of the Earth's surface, however, in turn, spatiotemporal variability of albedo also prevents the accurate determination of the optical depth of the aerosol.

The analysis used a discrete model of the albedo of the Earth's surface, where it is assumed that there is an ordered set of albedos of equal-sized areas.

A criterion for the effectiveness of atmospheric measurements using UAVs is proposed, in which efficiency is defined as the ratio of the total radiation entering the on-board spectroradiometer to the amount of extra-atmospheric radiation from the Sun.

By switching from a discrete model to a continuous model created to calculate the proposed efficiency criterion, it is shown that with a synchronous change in τ_A and A, according to the calculated law, the minimum measurement efficiency of these indicators is achieved.

Conclusion

An efficiency criterion is proposed for measuring interrelated indicators: aerosol optical depth τ_A and the albedo of the Earth's surface A.

A technique is proposed for calculating the effectiveness of interrelated measurements of the values τ_A and A.

The condition under which the minimum efficiency of measuring τ_A and A would be achieved is determined.

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Дослідження можливості вимірювання альбедо земної поверхні у видимому та ближньому інфрачервоному діапазонах в умовах аерозольного забруднення атмосфери за допомогою безпілотних літальних апаратів

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Загальновідомо, що на величину альбедо Землі впливають такі процеси, як сільськогосподарська діяльність, урбанізація, зміни клімату, що призводять до аномальних опадів тощо. При цьому результати дистанційного вимірювання альбедо у видимому та ближньому інфрачервоному діапазонах також залежать від ступеня аерозольного забруднення атмосфери. Ці фактори, що спричиняють зміну альбедо Землі, призводять до необхідності періодичних вимірювань регіональних значень альбедо земної поверхні.

При вимірюванні альбедо Землі існує ряд проблем, пов'язаних з просторовою і часовою мінливістю цього показника. До них відносяться: залежність альбедо від зенітного кута Сонця; необхідність створення мереж вимірювання альбедо у вигляді численних територіально-розподілених піранометрів; залежність супутникових вимірювань альбедо від стану атмосфери, що призводить до необхідності міжсупутникового калібрування або наземних перевірочних вимірювань. Водночас залишається відкритим питання повного врахування впливу атмосферного аерозолю на результати вимірювання альбедо земної поверхні.

Стаття присвячена питанням вимірювання альбедо Землі у видимому та ближньому інфрачервоному діапазонах за допомогою безпілотних літальних апаратів (БПЛА) в умовах аерозольного забруднення атмосфери. За основу проведених досліджень прийнято модель одноразового розсіювання сигналу оптичного джерела атмосферного аерозолю. Проаналізовано взаємозв'язок таких оптичних показників, як оптична товщина аерозолю та альбедо земної поверхні. Запропоновано критерій ефективності атмосферних вимірювань за допомогою БПЛА, в якому ефективність визначається як відношення сумарного випромінювання, що надходить на бортовий спектрорадіометр, до кількості позаатмосферного випромінювання Сонця. Шляхом переходу від дискретної моделі до безперервної моделі, створеної для розрахунку запропонованого критерію ефективності, показано, що при синхронній зміні оптичної товщини аерозолю та альбедо, згідно з розрахованою закономірністю, мінімальна ефективність вимірювань альбедо земної поверхні є досяжною.

Ключові слова: альбедо; аерозоль; БПЛА; спектрорадіометр; критерій ефективності