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# CALCULATION OF SPECTRAL AND ANGULAR DISTRIBUTIONS OF DIFFUSE REFLECTED AND TRANSMITTED SOLAR RADIATION FLUXES FROM ATMOSPHERIC LAYERS

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## ABSTRACT

*The article theoretically investigates the transfer of natural solar radiation in the layers of the atmosphere, taking into account Rayleigh scattering on air molecules. The calculation of the spectral and angular distribution of fluxes of diffusely reflected, transmitted and not scattered solar radiation emerging from the layers of the atmosphere has been carried out. Calculations of the intensity of diffuse radiation were carried out within the framework of the theory of* ***S,T*** *- Chandrasekhar matrices, developed by the factorization method.*

***Key words:*** *solar radiation, radiation transfer, optical depth, blackbody spectrum, atmosphere.*

## АННОТАЦИЯ

*В статье теоретически исследован перенос естественного солнечного излучения в слоях атмосферы с учётом рэлеевского рассеяния на молекулах воздуха. Проведён расчёт спектрального и углового распределения потоков диффузно отраженного, прошедшего и не рассеянного солнечного излучения выходящих из слоев атмосферы. Расчёты интенсивности диффузного излучения проводились в рамках теории* ***S,T-*** *матриц Чандрасекара, развитой методом факторизации.*

***Ключевые слова***: *солнечное излучение, перенос излучения, оптическая толщина, спектр чёрного тела, атмосфера.*

## INTRODUCTION

The flux of natural solar radiation incident on the atmosphere's surface, due to interaction with the atmosphere, is divided into three streams: the first is a part of the total flux, which, after multiple scattering, passes through the atmosphere and forms diffuse transmitted radiation; the second is a part of the scattered radiation reflected by the atmosphere in the opposite direction towards space, forming diffuse reflected radiation; the third is a part of the primary radiation that passes through the atmosphere without scattering. In addition, part of the primary radiation, depending on the state of the atmosphere, may be absorbed by aerosol particles and converted into other forms of energy. Depending on the reflective properties of the Earth's surface, some of the solar radiation that has passed through the atmospheric layers is reflected from the Earth's surface, forming an additional radiation flux in the atmosphere. The incident solar energy is distributed between these fluxes. With a change in the angle of illumination, the amount of energy corresponding to each flux is redistributed.

The above-mentioned problem of atmospheric physics is widely discussed in textbooks and monographs, but sequential theoretical calculations on this topic are absent in the literature. Mostly, observational results and estimated figures for transmitted radiation are provided. This is due to certain difficulties in calculating the angular distribution of the intensity of diffuse radiation for a broad solar spectrum.

In this article, the theoretical redistributions of solar radiation between diffuse and unscattered fluxes are investigated depending on the angle of illumination, taking into account the spectral distribution. Calculations of the intensity of diffusely scattered radiation were conducted within the framework of Chandrasekhar's theory of polarized radiation transfer for plane-parallel media[1,2], developed using the factorization method.[3,4] It has been established that the results of intensity calculation for secondary radiation exiting the medium, using the equation of polarized radiation transfer, are 10% more accurate than similar calculations conducted using the scalar equation. [1]

**Generalization of the radiation transfer equation for monochromatic radiation for calculating the intensity of radiation fields with a broad spectrum**

When illuminating a plane-parallel, scattering, and absorbing medium without internal sources, with plane monochromatic radiation, the field of diffuse radiation in the medium is determined by the transfer equation[1].

$$\mu \frac{d\mathbf{I}(\tau,\Omega)}{d\tau} = \mathbf{I}(\tau,\Omega) - \frac{\widetilde{\omega}_0}{4\pi}\int_0^1 d\mu' \int_0^{2\pi} d\varphi' \,\mathbf{P}(\Omega,\Omega')\mathbf{I}(\tau,\Omega') - \frac{\widetilde{\omega}_0}{4}\exp(-\tau/\mu_0)\mathbf{P}(\Omega,\Omega_0)0\mathbf{F}. \quad (1)$$

here, $\tau$ – is the optical thickness of medium, $\widetilde{\omega}_0 = a^{\text{рас}}/(\alpha^{\text{ист}} + a^{\text{рас}})$ – is the single scattering albedo, $\alpha = \alpha^{\text{погл}} + a^{\text{рас}}$ –is the attenuation coefficient (per unit volume), $\alpha^{\text{погл}}$- is the true absorption, $a^{\text{рас}}$-is the scattering coefficient, $z$ –is the axis directed normal to the surface of the medium, $\mathbf{P}(\Omega,\Omega_0)$ – is the Rayleigh angular matrix.this equation allows computing the intensity of polarized radiation propagating in the medium the direction $\mathbf{I}(\tau,\Omega)$ – over a layer $\Omega = \Omega\ (\theta,\varphi)$ and is described by the Stokes matrix $\mathbf{I} = \mathbf{I}(I_l, I_r, U, V)$ (in the Chandrasekhar basis).

For a plane-parallel medium, the optical thickness of the radiation $\tau$ is determined by the integral.

$$\tau(\lambda, z) = \int_0^{\infty} \alpha(\lambda, z) dz \quad (2)$$

where integration is performed from sea level (z=0) to the upper layers of the atmosphere, taking into account the variation of air concentration with altitude. From equation (2), it follows that the optical thickness of the medium varies depending on the wavelength. Such dependence has been calculated by various authors, and according to Coulson [2], the data presented in Elterman's tables [5] are more accurate than those of other authors.

Equation (1) is written for monochromatic radiation, but it can be generalized for radiation with a broad spectral distribution. The intensities of diffusely reflected and transmitted radiation from the medium with an optical thickness $\tau$ are determined using – **S,T** matrices

$$\mathbf{I}^{(\text{отр})}(z=0,\Omega)=\frac{\tilde{\omega}_0}{4\mu}\mathbf{S}(\tau,\bar{\Omega},\mathbf{\Omega_0})\mathbf{F}(z=0,\mathbf{\Omega_0}),\quad \mathbf{I}^{(\text{прол})}(z,\Omega)=\frac{\tilde{\omega}_0}{4\mu}\mathbf{T}(\tau,\Omega,\mathbf{\Omega_0})\mathbf{F}(z=0,\mathbf{\Omega_0})$$

. (3)

Here, $\pi\mathbf{F}(z=0,\Omega_0)$ represents the total flux of a plane monochromatic wave with a certain wavelength falling onto a unit surface area of the medium. According to Elterman's table, for a given wavelength $\lambda$ , this flux corresponds to a specific optical thickness $\tau$.

Solar radiation has a broad spectrum, where each wavelength $\lambda_1,\lambda_2,\lambda_3\cdots\lambda_n$ corresponds to different optical thicknesses of the atmosphere $\tau_1,\tau_2,\tau_3\cdots\tau_n$. In the case of Rayleigh scattering of light, there is no transition of radiation from one wavelength to another. To describe the transport of such radiation, we require $n$ independent equations in the form of equation (1) and an equal number of solutions.

$$\mathbf{I}^{(\text{отр})}(\tau(\lambda_i),\Omega)=\frac{\tilde{\omega}_0}{4\mu}\mathbf{S}(\tau(\lambda_i),\bar{\Omega},\mathbf{\Omega_0})\mathbf{F}(\lambda_i,\mathbf{\Omega_0}),\ \mathbf{I}^{(\text{прол})}(\tau(\lambda_i),\Omega)=\frac{\tilde{\omega}_0}{4\mu}\mathbf{T}(\tau(\lambda_i),\Omega,\mathbf{\Omega_0})\mathbf{F}(\lambda_i,\mathbf{\Omega_0})\quad (4)$$

To determine the total fluxes of diffuse radiation intensities in (4), we integrate over the azimuthal and polar angles (hereafter, we omit the index i:

$$\pi\Phi^{\text{отр}}(\lambda)=\int_0^1\mu d\mu\int_0^{2\pi}d\varphi I^{\text{отр}}(\tau(\lambda),\mu,\varphi),$$

$$\pi\Phi^{\text{прол}}(\lambda)=\int_0^1\mu d\mu\int_0^{2\pi}d\varphi I^{\text{прол}}(\tau(\lambda)-\mu,\varphi).\quad (5)$$

In addition to multiply scattered radiation, part of the incident radiation passes through the medium without scattering. The unscattered portion of the primary flux, without changing the direction of incidence, is attenuated by $\exp(-\tau(\lambda)/\mu_0)\pi\mathbf{F}(\lambda,\Omega_0)$, and exits the medium as a planewave[1].

Let's determine the ratios of these three fluxes to the incident flux and sum them up.

$$\eta_{\text{отр}}(\lambda) = \Phi_{\text{отр}}(\lambda)/\mu_0 F(\lambda,\mu_0,\varphi_0), \eta_{\text{проп}}(\lambda) = \Phi_{\text{проп}}(\lambda)/\mu_0 F(\lambda,\mu_0,\varphi_0).$$

$$\eta_{\text{полн}}(\lambda) = \eta_{\text{отр}}(\lambda) + \eta_{\text{проп}}(\lambda) + \exp(-\tau(\lambda)/\mu_0). \quad (6)$$

In the case of a conservative medium ($\widetilde{\omega}_0 = 1$), where the atmosphere is clean and there is no absorption, the sum of these three quantities, regardless of the angle of incidence and the wavelength of the incident light, should equal one:

$$\eta^{\text{отр}}(\lambda) + \eta^{\text{проп}}(\lambda) + \eta^{\text{нерас}}(\lambda) = 1.$$

The last formula serves as a criterion for assessing the accuracy of the conducted analytical and numerical calculations. The values of $\eta^{\text{отр}}, \eta^{\text{проп}}, \eta^{\text{нерас}}$ represent the coefficients of diffuse reflection, transmission, and unscattered radiation, characterizing the reflective and transmissive properties of the medium at a wavelength $\lambda$, and they are functions of the distribution of these quantities across the spectrum.

Solar energy is primarily concentrated in the spectral range of 0.20 - 4.00 μm. Calculations were performed in the solar spectrum range of 0.27 - 1.10 μm, with a step of 0.01 μm, since approximately 91% of all the energy incident on the Earth's atmosphere's surface from solar radiation is concentrated in this spectral range. On the other hand, significant redistribution of energy is observed in this spectral range.

## The results of numerical calculations

For the spectral distribution of $\eta^{\text{отр}}(\lambda), \eta^{\text{проп}}(\lambda), \eta^{\text{нерас}}(\lambda)$ values at various angles of illumination are presented in Fig. 1. From Fig. 1a, it can be seen that for normal incidence of radiation into the medium ($\theta_0 = 0^0$), short-wavelength radiation makes the main contribution to the diffuse radiation fluxes. As the angle of incidence deviates from normal, the proportion of diffuse radiation flux increases. This is because, with an increasing angle of incidence relative to the normal, the incident radiation traverses a greater geometric distance within the medium before exiting compared to normal illumination, resulting in more scattering events.

The figures also show that the proportion of unscattered radiation has its maximum value at normal incidence. As the angle of incidence deviates from normal, the proportion of unscattered flux decreases. At $\theta_0 \to 90^0$,the proportion of unscattered flux in the short-wavelength spectral range is almost zero, and unscattered flux is observed only in the long-wavelength spectral range (Fig. 1c, 1d).

It is known that the spectral distribution of the incident flat solar radiation flux is very close to the spectrum of a black body [6,7]. If the distribution function of the spectrum $f(\lambda)$ is determined by the spectrum of a black body and normalized to unity, then equation (4) can be rewritten in the following form:

$$\mathbf{F}(\lambda,\Omega_0)=f(\lambda)\,\mathbf{F}(z=0,\Omega_0), \qquad \int_0^{\infty} f(\lambda)\,d\lambda = 1. \quad (8)$$

Here, unlike in equations (1) and (3), $\pi\mathbf{F}(z=0,\Omega_0)$ includes the entire spectrum of incident radiation. For the full spectrum of solar radiation incident on the outer surface of the atmosphere, $\pi\mathbf{F}(z=0,\Omega_0)$ numerically equals the solar constant ($e_0=1371\ Vt/m^2$).

The results of our calculations correspond very well to the black body distribution function calculated at a temperature of T=5630$^0$K (curve 7, Fig. 1a) [6]. For comparison, the result of calculating the black body distribution function at a temperature of T=5800$^0$ K is also presented in Fig. 1a (curve 8, Fig. 1a).

Table 1 presents the results of numerical calculations of integrals for $\eta^{\text{отр}},\eta^{\text{проп}},\eta^{\text{нерас}}$ values in the spectral wavelength range under consideration

$$\beta^{\text{отр}}=\int_{\lambda_1}^{\lambda_2} d\lambda\,\eta^{\text{отр}}(\lambda),\quad \beta^{\text{проп}}=\int_{\lambda_1}^{\lambda_2} d\lambda\,\eta^{\text{проп}}(\lambda),$$

$$\beta^{\text{нерас}}=\int_{\lambda_1}^{\lambda_2} d\lambda\,\eta^{\text{нерас}}(\lambda)\ . \quad (9)$$

The quantities $\beta^{\text{отр}},\beta^{\text{проп}},\beta^{\text{нерас}}$ represent the integral fluxes of outgoing radiation from the medium, which determine the total flux of outgoing radiation across the spectrum. The numerical values of these integrals are equal to the area under the curves described by the functions $\eta^{\text{отр}}(\lambda),\eta^{\text{проп}}(\lambda),\eta^{\text{нерас}}(\lambda)$, shown in Fig. 1. From the table, it can be seen that with a change in the angle of illumination, there is a redistribution of outgoing fluxes from the medium, but according to the law of energy conservation, their sum remains constant. The error in the calculations remains below 1%, indicating high accuracy in the calculations.

The normalization condition for the distribution function (8) is satisfied in the wavelength range $[\lambda_1,\lambda_2]$, does not depend on the angle of illumination:

$$\int_{\lambda_1}^{\lambda_2} d\lambda\, f(\lambda) = 1. \quad (10)$$

Finally, it should be noted that similar calculations can be carried out for a non-conservative medium, where absorption occurs, as well as taking into account the influence of radiation reflection from the Earth's surface on the radiation field.

**CONCLUSIONS**

The study demonstrates that the equation of polarized radiation transfer in plane-parallel media can be generalized to investigate the transfer of polarized radiation with a broad spectral distribution. Calculations of the spectral distribution of total fluxes, as well as using equation (9) for the total integral flux exiting the medium, incorporating radiation across the entire spectrum, have been conducted. The results of the calculations show that at small angles of illumination relative to the zenith, unscattered radiation predominates over diffusely scattered radiation. As the angle of illumination increases, the proportion of unscattered radiation decreases, and the proportion of scattered radiation increases. Surprisingly, it is found that for all wavelengths and angles of illumination, the flux of diffusely reflected radiation predominates over diffusely transmitted radiation, especially in the short-wavelength spectral range.

The results of the calculations demonstrate that within the framework of the – **S,T** matrices theory, it is possible to estimate the proportion of thermal energy in solar radiation, in the infrared spectral range, which is mainly absorbed by the atmosphere.

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