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A complex satellite experiment of investigating aerosolic optical properties in the atmosphere

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Aerosols substantially affect the thermal regime of the Earth-atmosphere system by scattering and absorbing large portion of the sun irradiation in all spectral ranges. Therefore, the investigation of the optical properties of the aerosols in the earth atmosphere via satellite systems is of significant importance for the solution of many problems of climatology, meteorology, geospace research, environmental pollution, etc.

This paper considers the possibilities of a satellite radiational experiment providing for determination of the spectral and spatial dependence of the main optical characteristics of the aerosols: coefficient of 'scattering, indicatrix of scattering $\gamma_\lambda(h)$ and optical thickness $\tau_{a\lambda}(h)=\int_h^H \sigma_{a\lambda}(l)\,dl$.

Figure 1 illustrates the block-diagram for the measurements. Let us suppose that the observer is situated at a height H above the Earth surface. It

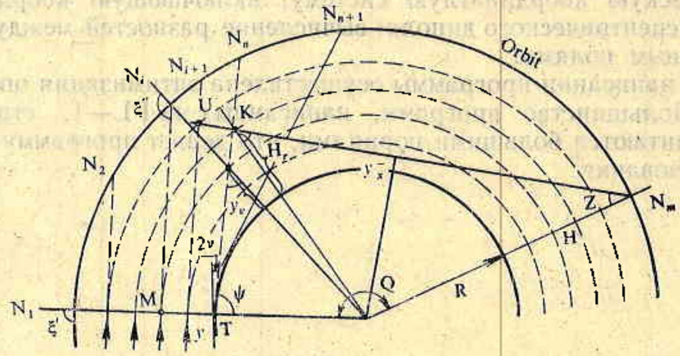

Fig. 1

is assumed that the atmosphere represents a sphere of radius $R_n > R$; (R — Earth radius) and is subdivided into n layers of radii $R_1, \ldots, R_n$ ($R_i = R + \Delta h_i$). We have incident parallel flux of solar irradiation at the outer atmospheric side. In the area of the terminator ($N_1 - N_n$) the experiment includes sequential measurements on the intensity of the scattered irradiation sunward and in nadir, and within the time interval $N_{n+1} = N_m$ when the space vehicle is in the earth shadow — scanning by horizon altitude was made. When the sun is spectrometered through the atmosphere, the intensity is determined by the unifold scattered and weakened by atmosphere irradiation $I_{1\lambda}$ and the intensity of the multifold scattered irradiation $I_{d\lambda}$:

$$(1) \qquad I_\lambda(s, y) = \frac{P_{u\lambda}}{M_y} \{I_{1\lambda}(s, y) + I_{d\lambda}(s, y)\},$$

where $P_{u\lambda}$ is a hatch transmission function (in observations from an orbiting station). $M(y)$ defines the weakening of the irradiation in the result of refraction divergence [1] at perigee height on the line of sight y, $I_{s\lambda}$ is the intensity of the solar irradiation outside the atmosphere for the spectral range of registration $\Delta\lambda$. Based on the transmission theory,

$$I_{1\lambda} = I_{s\lambda} e^{-2m_\xi \int_y^H \sigma_\lambda(l)\,dl} P_\lambda(y, s),$$

$$I_{d\lambda}(s, y) = \int_y^H e^{-(\tau_\lambda - \tau_{1\lambda})m_\xi} \cdot \sigma_\lambda \frac{(h)}{4\pi} \cdot \int_{4\pi} p_\lambda(s, s'; h) I'_\lambda(s, s'; h) P_\lambda(s, h) d\omega\, m_\xi\, dh,$$

where $\tau_\gamma = \int_y^H \sigma_\lambda(l)\,dl$, $\tau_{1\lambda} = \int_h^H \sigma_\lambda(l)\,dl$, $p_\lambda(s, s'; h)$ is a scattering function, $s(\xi, A)$ determines the direction of sight, ξ and A are zenith and azimuthal solar angles, $I'_\lambda(s, s'; h)$ is the intensity of a light flux, propagating at height h for direction s, $P_\lambda(s, y)$ is an absorption function of atmospheric gases into the investigated spectral range, $\sigma_\lambda(h)$ is a scatter cross-section, $\sigma_\lambda(h) = \sigma_{a\lambda}(h) + \sigma_{R\lambda}(h)$, $\sigma_{a\lambda}(h)$, $\sigma_{R\lambda}(h)$, are coefficients of aerosolic and Rayleigh scatter, m_ξ is an air mass. In a random point M of the terminator area, the solar irradiation intensity is determined with the expression:

$$(2) \qquad I'_\lambda(s, h) = I_{s\lambda} e^{-m_{\xi_T} \int_h^{-\infty} \sigma_\lambda(l)\,dl} P_\lambda(\xi_T, h).$$

In an elementary volume dV, including point M, there occurs irradiation scatter in all directions, as well as towards the observer. Along the path from the scattering point to the observer, the intensity of the light flux varies in the result of the scatter processes due to molecules and aerosolic particles and to absorption from atmospheric gases into the MN layer. For the intensity in point N_n within the terminator area we obtain:

$$(3) \qquad I_\lambda(H) = \int_0^H I'_\lambda(h) e^{-\tau_\lambda(h)} P_\lambda(h) \sigma_\lambda(\xi_T, h)\, dh,$$

where $\sigma_\lambda(\xi_T, h)$ is a volumetric angular coefficient of scattering at height h.

At the moment N_i the intensity registered in nadir is determined by the intensity of the solar irradiation, weakened in the layer (y_v, H) as the lower atmospheric layers are not illuminated by the sun and do not contribute to the scattering of the direct solar irradiation. Similar to (3), we obtain for the intensity in point N_i:

$$I_\lambda(y_v) = \int_{y_v}^{H} I''_\lambda(h) e^{-\int_h^H \sigma_\lambda(l)\,dl} P_\lambda(h)\sigma_\lambda(\omega, h)\,dh, \tag{4}$$

where y_v is determined by the crossing point of the line of sight with a solar beam with perigee $y=0$ km, $y_v = \frac{R \sin\psi}{\sin\varepsilon} - R$, ω is the angle of scatter; $\psi = 90 - 2\nu$, ν — angle of refraction.

$$I''_\lambda(\varepsilon, h) = \frac{I'_\lambda(h_1)}{M(h)} e^{-m_\varepsilon \tau_{5\lambda}(h)} P_\lambda(\varepsilon, h) + I_{d\lambda}(\varepsilon, y_v), \quad h_1 = h - y_v, \quad \tau_\lambda = \int_{h_1}^{y_v} \sigma_\lambda(l)\,dl. \tag{5}$$

The light scattered into the atmosphere becomes the main source of light after sunset, when the atmosphere is illuminated by the beams of the sunset. In addition, the lower atmospheric layers situated in the earth shadow are not illuminated by the sun and are not incorporated into the scatter from the direct solar irradiation. During the scanning at the horizon height (N_{n+1}, N_m), the observer is to be found into the planet shadow and the line of sight is located at the altitude y_x above the Earth surface and in point K at altitude H_r enters the sun-illuminated area. Based on the theory of transmission, following the propagation and scatter of irradiation along the beam path up to a random point U and into the direction of the line of sight KN, we obtain for the registred intensity at scanning by the horizon height:

$$I^{V}_\lambda(s, y_x) = P_{u\lambda} I^{IV}(s, y_x) e^{-m_z \tau_{6\lambda}} P_\lambda(s, h) + \int_{y_x}^{H} e^{-(\tau_{6\lambda} - \tau'_{6\lambda}) m_z} \frac{\sigma_\lambda(h')}{4\pi} \cdot \int_{4\pi} p(s, s'; h') I'^{IV}_\lambda(s, s'; h')\,d\omega \sec z\,dh', \tag{6}$$

where $\tau_{6\lambda} = \int_{y_x}^{H} \sigma_\lambda(l)dl$, $\tau'_{6\lambda} = \int_h^H \sigma_\lambda(l)\,dl$, $I_\lambda(s, h)$ is the intensity in the perigee of the line of sight y_x.

$$I^{IV}_\lambda(s, y_x) = I^{III}_\lambda(s, H_r) e^{-m_\gamma \tau_{5\lambda}} P_\lambda(s, y_x) + \int_{y_x}^{H_r} e^{-m_\gamma(\tau_{5\lambda} - \tau'_{5\lambda})} \frac{\sigma_\lambda(h)}{4\pi} \int_{4\pi} p(s, s', h) \cdot I'^{III}_\lambda(s, s', h)\,d\omega \sec\gamma\,dh, \tag{7}$$

$\tau_{5\lambda} = \int_{y_x}^{H_r} \sigma_\lambda(l)\,dl$, $\tau'_{5\lambda} = \int_h^{H_r} \sigma_\lambda(l)\,dl$, $I^{III}_\lambda(s, H_r)$ is the intensity in point K, determined as a sum of all the elements into direction KN.

$$(8) \qquad I_\lambda^{\mathrm{III}}(s, H_r) = \int\limits_{H_r}^{\infty} I_\lambda^{\mathrm{VI}}(s, h) e^{-m_\gamma \tau_{3\lambda}} p_\lambda(\gamma, h)\, \sigma_\lambda(\eta, h)\, dh,$$

$\tau_{3\lambda} = \int\limits_{H_r}^{h} \sigma(l)\, dt$, $I_\lambda^{\mathrm{VI}}(s, h)$ — irradiation intensity at random point U.

$$(9) \qquad I_\lambda^{\mathrm{VI}}(s, h) = \frac{I_{\lambda s}}{M(h)} e^{-m_{\xi''}\tau_{2\lambda}} P_\lambda(\xi'', y) + \int\limits_{y}^{h} e^{-\sec \xi''(\tau_{2\lambda} - \tau'_{2\lambda})} \frac{\sigma_\lambda(h')}{M(h')\, 4\pi} \int\limits_{4\pi} p(s, s'; h')$$

$$\cdot I'_\lambda(s, s', h')\, d\omega \sec \xi''\, dh',$$

$\tau_{2\lambda} = \int\limits_{y}^{h} \sigma_\lambda(l)\, dl$, $\tau'_{2\lambda} = \int\limits_{y}^{h'} \sigma_\lambda(l)\, dl$, η — angle of scatter, $\cos\eta = \cos\varepsilon \cdot \cos\gamma + \sin\varepsilon \cdot \sin\gamma \cos A$.

Equations (1), (3), (4), (6) are basic equations of transmission into the complex radiational experiment including spectrometry of direct solar irradiation, nadire measurements into the terminator area and scanning of the horizon. They represent sophisticated functional dependences of the measured intensities of the scattered solar irradiation due to the atmosphere optical properties, namely to layers where it propagates. Initially, the spectral, vertical and spatial dependence of $\sigma_{a\lambda}(h)$ is determined in unifold scatter approximation. It is assumed that in each sublayer of the atmosphere the aerosolic scatter coefficient is presented by exponential approximation $\sigma_{a\lambda}(y_i) = \sigma_{a\lambda}(y_{i-1})\, e^{-\beta h}$, which is effective at high resolution of the experiment by altitude. We obtain for the optical thickness in the i th sublayer:

$$(10) \qquad \Delta\tau_{a\lambda}(y_i) = \frac{\sigma_a(y_{i-1})\, (e^{-\beta_i y_{i-1}} - e^{-\beta_i y_i})}{\beta_i}.$$

But for the case of single scattering with regard to the registred direct solar irradiation in two subsequent moments N_i and N_{i-1}, we obtain for $\Delta\tau_a(y_i)$:

$$(11) \qquad \Delta\tau_{ai} = \frac{1}{2m_\xi} \ln \frac{I_\lambda(s_i, y_i) M(y_i)\, P_\lambda(y_{i-1})}{I_\lambda(s_i, y_{i-1}) M(y_{i-1}) P_\lambda(y_i)} - \int\limits_{y_{i-1}}^{y_i} \sigma_{R\lambda}(y_{i-1}) e^{-\alpha h}\, dh.$$

Hence, for the aerosolic scatter coefficient in i layer we define:

$$(12) \qquad \sigma_{a\lambda}(y_{i-1}) = \frac{\Delta\tau_{a\lambda_i}\, \beta_i}{e^{-\beta_i y_{i-1}} - e^{-\beta_i y_i}}.$$

The relationship between $\sigma_{a\lambda}(y_{i-1})$ and $\sigma_{a\lambda}(y_{i-2})$ is given with:

$$(13) \qquad \sigma_{a\lambda}(y_{i-1}) = \sigma_{a\lambda}(y_{i-2})\, e^{-\beta_{i-1} y_{i-1}}.$$

For the last layer (where we may assume lack of powerful aerosolic layers) $\beta_n = 1/H_0$, H_0 is the height of the isothermal atmosphere. For the other layers β_i is determined by (1). The method provides for high-accuracy definition of $\sigma_{a\lambda}(h)$ into the upper atmospheric layers, where the contribution of the multifold scatter is insignificant also for spectral range, distinguished by lack of absorption from molecules of gas with variable density (O_3, H_2O). The altitudinal adjustment of the spectrometric record when scanning the horizon is made by comparing the ratio between the atmospheric transmission

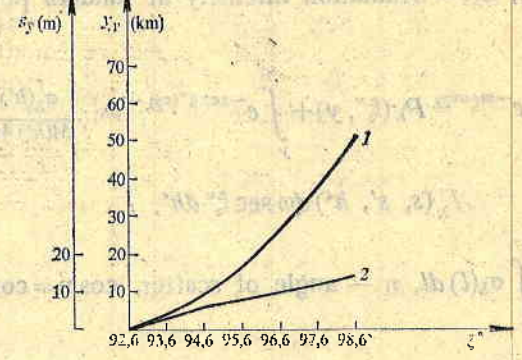

Fig. 2. Variation at the height of sight and the resolution in altitude in dependence on the fast performance, equipment sensibility and solar zenith angle. 1 — y_v; 2 — s_y

function in the i th layer and that at $y_x = y_{min}$ in the spectral range 0.76 μm and the ratio of the registred intensities within the same spectral range [2]. The method allows for precise altitudinal adjustment, since the transmission function of the oxygen is computed with high accuracy. It is necessary to make complex measurements in the optical and near IR ranges, as well as of the natural irradiation in the radio range for the spectral ranges specified with water vapour absorption. This allows to determine the integral water content required for the computations of the transmission function in the studied atmospheric layer.

The altitudinal resolution at nadir measurements in the terminator area depends on the fast performance and the sensitivity of the measuring equipment. Figure 2 shows the variation at the height of sight y_x and the resolution in altitude $s_{y_i} = y_{v_i} - y_{v_{i-1}}$ in dependence on the fast performance, the measurement equipment sensitivity and the zenith angle ξ of the sun. From the ratio of the registered intensity in two sequential moments for the optical thickness in the layer y_{v_i}, $y_{v_{i+1}}$ we obtain:

$$\Delta\tau_{a\lambda_i} = \frac{1}{m_\xi - 1} \ln \frac{I_{i\lambda} \int_{y_i}^{y_{i+1}} P_\lambda(\varepsilon, l)\, dl}{I_{i+1,\lambda} \int_{y_i}^{y_{i+1}} P_\lambda(l)\, dl} - \int_{y_i}^{y_{i+1}} \sigma_{R_\lambda}(l)\, dl. \tag{14}$$

The coefficient of the aerosolic scattering $\sigma_{a\lambda}(h)$ and β_i are computed on the basis of dependencies similar to (10)-(13).

The values obtained for the spatial and vertical dependencies of $\sigma^0_{a\lambda}(h)$ are used as input values for the solution of the transmission equations (1), (3), (4), (6) by the Monte Carlo simulating modelling method. The determined values of the spectral and vertical dependencies of $\sigma_{a\lambda}(h)$ are obtained by minimization of the functional:

$$\sum_{i=1}^{m}(\tilde{I}_{i\lambda}-I^k_{i\lambda}(\sigma^k_{a\lambda}(h)))^2=\delta, \tag{15}$$

where $\tilde{I}_{i\lambda}$ is the measured value in point $i(s_i, y_i)$, $I^k_{i\lambda}$ the value obtained for the intensity in the numerical modelling of the respective equation of transmission after the Monte Carlo method, where $\sigma^k_{a\lambda}(h)$ varies according a determined law, $\sigma^k_{a\lambda}(h)=\sigma^{k-1}_{a\lambda}(h)-f(\delta)$, k — number of iteration.

The proposed radiation experiment is partially realized aboard the SALYUT-6 [4] orbiting station, while the complex version between visible, near IR and radio ranges was made aboard METEOR-PRIRODA within the BULGARIA-1300-II project [3].

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Комплексный спутниковый эксперимент по исследованию оптических свойств аэрозоля в атмосфере

В. Д. Петрова

(Резюме)

Рассмотрены возможности спутникового радиационного эксперимента, позволяющего определить спектральный и пространственный ход основных оптических характеристик аэрозоля: коэффициент рассеяния, индикатриса рассеяния и оптическая толщина.

Предложенный эксперимент частично реализован на станции „Салют — 6", причем комплексирование видимого, ближнего ИК и радиодиапазона сделано на ИСЗ „Метеор — Природа" по проекту „Болгария — 1300".