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Abstract

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ON NONMOLECULAR SCATTERING OF LIGHT IN THE HIGH LAYERS OF THE ATMOSPHERE

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The first quantitative data on local scattering of light at great altitudes by means of searchlight sounding were obtained by Hulburt ([1]) and Johnson with coauthors ([2]). According to ([1], [2]), the fraction of aerosol scattering of light, gradually decreasing with altitude, becomes negligibly small in comparison with molecular scattering at altitudes of 8-11 km. I. A. Khvostikov introduced into the equation of searchlight sounding a term making it possible to take into account the effect of attenuation of light by intermediate layers of air ([3]). I. A. Khvostikov and A. M. Semchinova ([4]) carried out determinations of the coefficients of scattering by air up to an altitude of about 2 km.

If the condition of horizontal homogeneity of the atmosphere is satisfied, then for monochromatic light of wavelength λ the equation of searchlight sounding, taking into account the attenuation of light in the atmosphere, is written as follows:

$$\alpha_\lambda(h) = \alpha_{0,\lambda}(h) \exp\left[\chi \int_0^h \alpha_\lambda(h)\, dh\right], \qquad (1)$$

where α_λ is the scattering coefficient at altitude h; $\chi = \dfrac{1}{\sin\beta} + \dfrac{1}{\sin\omega}$; β and ω are, respectively, the elevation angles of the instrument and of the searchlight. We shall assume that the light receiver is a photometer with a photocell (photomultiplier) placed at the focus of the searchlight mirror. In the simplest case, if: a) the angular dimensions of the searchlight beam are small and its image is wholly contained on the photocathode, and b) the sensitivity along the surface of the photocathode is constant, then ([1], [2])

$$\alpha_{0,\lambda} = \frac{b\cos\beta_0}{\Delta\beta_0 \cdot S} \frac{E_\lambda(h)}{\Phi_{0\lambda}} \frac{4\pi}{f_\lambda(\varphi)}, \qquad (2)$$

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

where $E_\lambda(h)$ is the luminous flux incident on the entrance aperture of the instrument of area S; $\Phi_{0\lambda}$ is the initial luminous flux of the searchlight; $\frac{1}{4\pi} f_\lambda(\varphi)$ is the scattering function (with integration over the solid angle 4π,

$$\frac{1}{4\pi} \int f_\lambda(\varphi) \, d\Omega = 1$$

); φ is the scattering angle; b is the distance between the searchlight and the photometer; $\Delta\beta_0$ is the field of view of the photometer in the vertical plane, and $\beta_0 = \pi/2 - \omega$ (see Fig. 1).

However, the conditions under which the simple expression (2) for $\alpha_{0,\lambda}$ was obtained are in fact not satisfied: a) the radiation of the searchlight consists of a bright narrow beam, which we shall call the beam proper, and of a comparatively weak but broad background, which, gradually decreasing, extends over approximately 40°; b) the sensitivity

along the surface of the photocathode is not constant. The background is taken into account by introducing into the equation of searchlight sounding an additional term E'_β, which accounts for the scattered light of the beam background entering the photometer when it is directed at an elevation angle β. The expression for E'_β is found by integration along the line of sight of the photometer within the limits of the searchlight-beam background, taking into account the variation of the scattering coefficient as a function of height (Fig. 2). Within the angle of view of the photometer (in width) $\Delta\lambda_0$, the background may be regarded as constant.

Fig. 1

Fig. 2

Expressing the variables h and φ, for a given β, as functions of the angle ω (for the beam axis $\omega = \omega'$), one may denote the product

$$\alpha_\lambda \frac{1}{4\pi} f(\varphi) \exp\left[-\left(\frac{1}{\sin\beta} + \frac{1}{\sin\omega} \right) \int_0^h \alpha_\lambda \, dh \right]$$

by $Z = Z(\omega)$; then

$$E'_\beta = \frac{\Delta\beta_0 \cdot S}{b\sin\beta}\,\Delta\lambda_0 \int_{\omega_1}^{\omega_2} I_0(\omega) Z(\omega)\, d\omega, \tag{3}$$

where $I_0(\omega)$ is the primary luminous flux of the background per unit solid angle; the limits of integration ω_1 and ω_2 are determined by the boundaries of the background; the remaining notation is as indicated above. For the total flux $F = E_\lambda + E'_\beta$, measured by the photometer, we obtain

$$F = \frac{\Delta\beta_0 \cdot S}{b\cos\beta_0}\Phi_{0,\lambda}\alpha_\lambda \frac{1}{4\pi} f(\varphi) \exp\left[-x\int_0^h \alpha_\lambda\, dh\right] + \frac{\Delta\beta_0 \cdot S}{b\sin\beta}\Delta\lambda_0 \int_{\omega_1}^{\omega_2} I_0(\omega) Z(\omega)\, d\omega. \tag{4}$$

Let us consider the case in which E'_β is much smaller than E_λ. At the first stage of solving the problem one may confine oneself to an approximate allowance for the presence of the background in the searchlight beam, assuming that for each given β, within the limits $\omega_1 < \omega < \omega_2$, the function $Z(\omega)$ varies linearly with ω, and using the symmetry property of the function $I_0(\omega)$ with respect to the beam axis. The variation of sensitivity along the cathode of the photoelement is taken into account with the aid of functions P and K, which are determined experimen-

tially and, for a given ω, depend on β. Then from (4) we obtain the approximate and exact equations:

$$\alpha_1(h) = \frac{iP}{\Phi_{0,\lambda}} \frac{b\cos\beta_0}{\Delta\beta_0 \cdot S} \frac{4\pi}{f(\varphi)} \exp\left[\chi \int_0^h \alpha_1(h)\, dh\right]; \tag{5}$$

$$\alpha_2(h) = \left[\frac{i}{\Phi_{0,\lambda}} \frac{b\cos\beta_0}{\Delta\beta_0 \cdot S} - \frac{c}{\sin\beta}\Delta\lambda_0 \int_{\omega_1}^{\omega_2} \frac{I_0(\omega)}{\Phi_{0,\lambda}} Z(\omega)\, d\omega\right] K \frac{4\pi}{f(\varphi)} \exp\left[\chi \int_0^h \alpha_2(h)\, dh\right]. \tag{6}$$

Here i denotes the photometer readings, c is a constant. Measurements of the scattered light of the beam and of the primary flux $\Phi_{0,\lambda}$ are made with the same photometer (the corresponding attenuation of $\Phi_{0,\lambda}$ is achieved by using a system of reflection from two screens). Introducing the notation

$$\alpha_{0,1}(h) = \frac{iP}{\Phi_{0,\lambda}} \frac{b\cos\beta_0}{\Delta\beta_0 \cdot S} \frac{4\pi}{f(\varphi)},$$

$$\alpha_{0,2} = \left[\frac{i}{\Phi_{0,\lambda}} \frac{b\cos\beta_0}{\Delta\beta_0 \cdot S} - \frac{c}{\sin\beta}\Delta\lambda_0 \int_{\omega_1}^{\omega_2} \frac{I_0(\omega)}{\Phi_{0,\lambda}} Z(\omega)\, d\omega\right] K \frac{4\pi}{f(\varphi)},$$

Fig. 3

Figure 3: Fig. 3

equations (5) and (6) may be rewritten as follows:

$$\alpha_1(h) = \alpha_{0,1}(h) \exp\left[\chi \int_0^h \alpha_1(h)\, dh\right], \tag{7}$$

$$\alpha_2(h) = \alpha_{0,2}(h) \exp\left[\chi \int_0^h \alpha_2(h)\, dh\right]. \tag{8}$$

First the approximate equation (5), (7) is solved; then, from the $\alpha_1 = \alpha_1(h)$ found, the values of the integral

$$\int_{\omega_1}^{\omega_2} \frac{I_0(\omega)}{\Phi_{0,\lambda}} Z(\omega)\, d\omega$$

in (6), (8) are calculated and the limits of applicability of equation (5), (7) are determined*. The described method of estimating the background in the presence of multiple scattering of light makes it possible to eliminate its influence.

As can be shown, the curve $\alpha_{0,1} = \alpha_{0,1}(h)$ obtained on the basis of experimental data corresponds to two curves for the scattering coefficient: $\alpha_1' = \alpha_1'(h)$ and $\alpha_1'' = \alpha_1''(h)$. The solution of equation (5), (7) is found by the method of successive approximations. The function $\alpha_{0,1}$ is used as the zero approximation. The scattering function in the lower layers of the atmosphere differs considerably from the Rayleigh one, and, moreover, it is not known how it varies with height; therefore, in practice, equation (5), (7) can be solved if the boundary conditions are specified not at the ground, but at a sufficiently high level. By carrying out measurements with two searchlights and using two equations of the type (5), (7), one can determine the optical thickness

$$\int_0^h \alpha_1(h)\, dh$$

independently of the form of the indicatrix for

Fig. 3

* The beam background can be determined experimentally by measuring the total brightness of the beam itself and the background, and separately the brightness of the background near the beam itself.

Fig. 4

Figure 4: Fig. 4

lower, most turbid 5-6 km (Fig. 3). Above this level the actual scattering indicatrix also differs from the Rayleigh one; however, if in the measurements the scattering angles $\varphi > \pi/2$ and the true solution is the solution corresponding to α_1' ($\alpha_1' < \alpha_1$), then one can estimate the lower limit of the values of α_1. It is more expedient to solve equations (5), (7) from the data on the measurement of the optical thickness of the entire atmosphere, which is determined by methods known in astrophysics. In this case it is practically sufficient to carry the altitude of the searchlight sounding up to the level of 35 km, since the difference

$$\int_0^{35\text{ km}} \alpha_1\,dh$$

from

$$\int_0^{\infty} \alpha_1\,dh$$

–of the order of 1%–may be neglected.

Fig. 4. 1 –from measurements of 20-21 IX 1949, $b = 4.65$ km; 2 –23-24 IX 1949, $b = 12.50$ km; 3 –3 XI 1950, $b = 10.33$ km; 4 –values of α according to Rayleigh

The results of determining $\alpha_1 = \alpha_1(h)$ from the data of three searchlight measurements are presented in Fig. 4 for an effective $\lambda = 0.485\,\mu$ (with a half-width of the spectral interval of about $0.07\,\mu$). Along the abscissa axis are plotted the values of α_1 in km^{-1}, and along the ordinate axis–the height above the earth' s surface in km. The scatter of individual points of the experimental curves lies within the measurement error.

Moscow Oblast. The limits of applicability of the approximate equation (5) may be judged from the ratio $\alpha_{0,1}/\alpha_{0,2}$. The results of calculating $\alpha_{0,1}/\alpha_{0,2}$ for different heights from the smoothed curves $\chi_1 = \alpha_1(h)$ are given in Table 1.

Table 1

20-21 IX 1949, $b = 4.65$ km	20-21 IX 1949, $b = 4.65$ km	23-24 IX 1949, $b = 12.50$ km	23-24 IX 1949, $b = 12.50$ km
h, km	$\alpha_{0,1}/\alpha_{0,2}$	h, km	$\alpha_{0,1}/\alpha_{0,2}$
30.8	2.06	39.1	1.50
25.2	1.39	30.5	1.05
20.4	1.08	25.4	1.03

20–21 IX 1949, $b = 4.65$ km	20–21 IX 1949, $b = 4.65$ km	23–24 IX 1949, $b = 12.50$ km	23–24 IX 1949, $b = 12.50$ km
13.2	1.01	19.5	1.01
9.45	1.01	15.5	0.99
		11.1	0.99

The deviations observed in Fig. 4 of the experimental curves 1, 2, 3 from the theoretical curve 4 for pure air below the 30 km level exceed the limiting measurement errors, while above the 30 km level they prove comparable with them. Thus, up to an altitude of 30 km above the earth' s surface (and, apparently, even up to 40 km), the presence of nonmolecular scattering of light has been detected in the scattered light of the searchlight beam.

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CITED LITERATURE

1. E. O. Hulbert, J. Opt. Soc. Am., **27**, No. 11, 377 (1937).

2. E. A. Johnson, R. C. Meyer, R. E. Hopkins, W. H. Mock, J. Opt. Soc. Am. **29**, 512 (1939).

3. I. A. Khvostikov, Izv. AN SSSR, ser. geofiz. i geograf., **9**, No. 5–6, 445 (1945).

4. I. A. Khvostikov, A. M. Semchinova, Izv. AN SSSR, ser. geofiz. i geograf., **9**, No. 5–6, 425 (1945).

Note: Figure translations are in progress. See original paper for figures.