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V. E. Zuev, M. V. Kabanov, B. A. Savel' ev

Experimental Investigation of the Limits of Applicability of Bouguer' s Law for Describing the Attenuation of Narrow Collimated Light Beams in Scattering Media

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1. A broad range of problems connected with the use of optical quantum generators (OQG) in communication systems, information transmission, and other devices requires knowledge of the laws governing the propagation of narrow collimated light beams in scattering and absorbing media. Of particular importance is the investigation of the limits of applicability of Bouguer' s law to describing the attenuation of such beams in scattering media. The validity of Bouguer' s law, as is known, is a criterion for the applicability of the theory of single scattering.

The existing mathematical apparatus of the transport equations and the formulas of the theory of single scattering are not applicable to describing the attenuation of the intensity of a narrow collimated light beam as a function of the optical thickness of the medium (⁀1). Thus, only appropriate experimental investigations can make it possible to establish the limits of applicability of Bouguer' s law to describing the attenuation of narrow collimated beams in scattering media.

2. The apparatus constructed for carrying out the investigations included the following main elements: 1) optical quantum generators with operating wavelengths of 6328 Å (a gas laser in continuous-emission mode, beam diameter about 10 mm, divergence angle 6′) and 6943 Å (a pulsed ruby laser, beam diameter 20–100 mm, divergence angle 30″–40″); 2) collimated thermal sources equipped with narrow-band interference filters; 3) a receiving system consisting of a collimator and a system of diaphragms, which ensured photometric measurement of separate portions of the focal image of the source and of the background in the direction of small scattering angles.

The focal image was recorded photographically or photoelectrically, depending on the method of diaphragming the focal image. In the latter case, the directly

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measured quantity was either the flux of scattered radiation in the angular range $8'$-$28'$ relative to the initial direction of the beam, or the flux of direct radiation.

In the direction of small angles there propagates direct radiation, carrying information about the radiation source, and scattered radiation (in the general case, the background of multiple scattering) (^1). When the brightnesses of the image of the source and of the multiple-scattering background are equal, the information carried by the direct radiation is lost. It is evident that the applicability of Bouguer' s law to describing the attenuation of the intensity of a narrow collimated beam in a scattering medium can be discussed when the brightness of the image of the source exceeds the brightness of the background many times over.

The measurements were carried out in a chamber of volume 30 m^3, in which it was possible to create scattering media containing particles of different sizes: wood smokes (particle diameter 1-2 μ) and artificial water fogs

(root-mean-square droplet diameter 8-15 μ). The choice of scattering media was dictated by the desire to obtain data suitable for analyzing the regularities in the propagation of narrow collimated beams in the terrestrial atmosphere. The luminances of the direct and scattered radiation were measured by means of two measuring arrangements. In one variant, the radiation source and the receiving system were arranged along one straight line (direct-beam arrangement). In this case the beam path length was 4 m. In the second, the light beam from the source was turned by a plane mirror and directed into a receiving device located next to the source (reflected-beam arrangement). In this case the beam path length was increased to 8.3 m; the angle of rotation of the beam by the mirror φ could be varied from $1°30'$ to $8°30'$.

Fig. 1. Dependence of the luminance of the total background on the optical thickness of the medium (*a*—evaporation fogs, *b*—wood smokes)

Simultaneous measurement of the luminance of the direct radiation from the laser and from the thermal source in the scattering medium made it possible to investigate the specific character of the attenuation of coherent radiation as compared with incoherent radiation.

3. The results of measurements in artificial water fogs and smokes, obtained with the reflected-beam arrangement using the gas laser, are presented in Fig. 1. All measurements were processed relative to the initial luminance of the source $B = 1$. Straight line 1 characterizes the attenuation of the luminance of the direct radiation, or of the luminance of the source,

Fig. 2

Figure 2: Fig. 2

according to Bouguer' s law.

As is seen from Fig. 1, at optical thickness $\tau = 0$ the background luminance is not zero. It may be assumed that the attenuation of the initial background of the source is described by Bouguer' s law (straight line 2). To find the background luminance due solely to scattering of light, it is necessary to subtract the luminance of the initial background of the source from the measured total background luminance. The contribution of the latter to the total background proves to be substantial for fogs at $\tau < 4$ and for smokes at $\tau < 14$. Taking these remarks into account, one may state that the background luminance becomes equal to the luminance of the direct radiation at optical-thickness values $\tau \simeq$ 22–24 both for fogs and for smokes—media that differ greatly in the sizes of the scattering particles. In the range of optical thicknesses from approximately 2 to 13, the background luminance in fogs is approximately 1-$1\frac{1}{2}$ orders of magnitude ...

of the order of magnitude greater than in smokes. Beginning with a certain value of the optical thickness, in smokes and fogs a bend occurs in the background-brightness curves. In smokes this occurs at a smaller value of τ than in fogs. At optical thicknesses greater than 20, the background-brightness curves for both smokes and fogs practically coincide and do not depend on the value of τ.

The results of measurements of background brightness in fogs and smokes presented in Fig. 1 were obtained using the reflected-beam scheme. This means that, in the measurements, not only the background due to scattering at small angles forward was recorded, but also the background caused by scattering at small angles backward during propagation of the beam from the source to the turning mirror. It was of interest to obtain the brightness values of both components of the background. For this purpose

Fig. 2. Dependence of the brightness of the total background (*a*) and of the background scattered backward (turning angle of the beam by the mirror $\varphi = 8°30'$) (*b*) on the optical thickness of the medium. The solid curve is the background brightness calculated by the formula of the theory of single scattering ([3])

the turning mirror was covered, and measurements were made of the background brightness due only to backward scattering. The results of such measurements with a gas laser in fogs are shown in Fig. 2.

It is seen from Fig. 2 that the brightness of the background caused by backward scattering of light varies with the value of τ in fogs substantially less than the brightness of the background due to scattering of light at small angles forward. The absolute values of these brightnesses differ greatly in the range of optical thicknesses 0–14. In this case the background brightness from radiation scattered forward is greater. At larger optical thicknesses, on the contrary, the total background brightness is due to light scattered backward. This means that, in measurements by the direct-beam scheme in fogs and smokes, one should expect disappearance of the contrast between the image of the source and the background at values of τ greater than 22–24. Measurements performed of the brightnesses of the source image and of the background by the direct-beam scheme in fogs and smokes fully confirmed this assertion. It turned out that up to the limiting value of the optical thickness $\tau = 22$ (this value is determined by the sensitivity limit of the receiving apparatus), the brightness of the source image was substantially greater than the background brightness.

This means that, in propagation through fogs or clouds of a narrow collimated beam of light with a divergence of less than $6'$, and when using receivers with an aperture $\Psi \leqslant 28'$, the attenuation of the signals recorded by the receiving system will, with high accuracy, be described by Bouguer' s law at least up to an optical thickness of $\tau \cong 22$. This conclusion refines and makes more specific the estimates of the limits of applicability of Bouguer' s law made in the work of G. V. Rosenberg [(2)].

It is interesting to note that the course of the experimentally determined dependence of the background brightness on the optical thickness τ is well described by the curve (see the solid curve in Fig. 2) obtained from calculations according to the theory of single scattering [(3)], up to values of τ at which the total scattering background is determined chiefly by backscattering. In view of the absence of a method for calculating the absolute values of the brightness of singly scattered light in the propagation of narrow collimated beams in scattering media, the comparison of the experimental background-brightness data with the calculated data in Fig. 2 has been carried out in relative units.

Siberian Physicotechnical Institute
named after V. D. Kuznetsov
at Tomsk State University

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CITED LITERATURE

[1] V. V. Sobolev, *Transfer of Radiant Energy in the Atmospheres of Stars and Planets*, Moscow, 1956.
[2] G. V. Rosenberg, DAN, **145**, No. 6, 1269 (1962).
[3] A. A. Gershun, *Selected Works on Photometry and Lighting Engineering*, Moscow, 1958.

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