

**DEPENDENCE OF THE
LIMITS OF
APPLICABILITY OF
BOUGUER' S LAW IN
WATER FOGS ON THE
ANGULAR APERTURE
OF THE RECEIVER
AND THE
PARAMETERS OF THE
LASER BEAM**

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Figure 1

Figure 1: Figure 1

Abstract**Full Text**

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PHYSICS

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DEPENDENCE OF THE LIMITS OF APPLICABILITY OF BOUGUER'S LAW IN WATER FOGS ON THE ANGULAR APERTURE OF THE RECEIVER AND THE PARAMETERS OF THE LASER BEAM*(Presented by Academician B. A. Vvedenskii, April 4, 1968)*

When a laser beam passes through water fog, the receiving system, along with the direct radiation attenuated according to the exponential law, records light scattered in the direction of propagation of the direct beam. It is of interest to determine the limits of applicability of the theory of single scattering, i.e., those optical thicknesses of the fog τ at which the intensity of the forward-scattered light is comparable with the intensity of the directly attenuated radiation.

Fig. 1. Variation of the ratio τ_{47}/τ_{15} as a function of the optical thickness of the fog for a parallel laser beam ($a-d = 60$ mm; $-d = 40$ mm; $-d = 25$ mm; $-d = 10$ mm). A —at $\psi = 5^\circ$, $-$ at $\psi = 24'$.

In the work of V. E. Zuev et al. ⁽¹⁾, it was shown experimentally that, when a narrow collimated light beam of diameter $d = 10$ mm and divergence $\varphi = 6'$ propagates in fog, the attenuation of the signal recorded by a receiving system with angular aperture $\psi \leq 28'$ is described, with sufficient accuracy, by the exponential law up to $\tau \cong 22$.

In the present work the following were clarified: 1) the dependence of the limits of applicability of Bouguer's law on the angular aperture of the receiver and on the parameters of the laser

beam; 2) the effect of forward-scattered light on the value of the attenuation coefficient at different optical thicknesses of the fog.

In contrast to [1], the method of the experiments carried out consisted in measuring the optical transparency of fog by means of two OKG-11 lasers ($\lambda = 0.63 \mu$)

Figure 2

Figure 2: Figure 2

simultaneously on two paths 15 and 47 m long. Provided Bouguer's law is valid, the ratio of the optical

Fig. 2. Change in the value of the ratio τ_{47}/τ_{15} as a function of the optical thickness of the fog for a diverging laser beam ($a - \varphi = 3'$, $b - \varphi = 8'$, $c - \varphi = 11'$). *A* – at $\psi = 5'$, *B* – at $\psi = 24'$.

thicknesses τ , measured simultaneously on the two paths, should be equal to the ratio of the lengths of these paths. The measurements were carried out in the artificial-fog chamber of the Branch of the Institute of Applied Geophysics [2], having a height of 18 m and a diameter of 15 m. The fog was produced by adiabatic expansion of the air after a preliminary increase of the pressure in the chamber to 1.5 atm. The duration of a separate experiment, from the moment of fog formation to its complete disappearance, was from 40 to 90 min. All measurements were performed at normal atmospheric pressure in the chamber and at a temperature of $+16 \div +25^\circ$. The large volume of the chamber and the conditions of the experiment ensured comparatively slow changes in the concentration of fog droplets, which to a considerable degree increased the accuracy of the experiments performed. The absolute error in measuring the attenuation coefficient was equal to $\pm 0.027 \cdot 10^{-3} \text{ cm}^{-1}$.

Table 1

ψ	5°	3°	$1^\circ 2'$	$0^\circ 55'$	$0^\circ 24'$
τ_{gr}	10.5	11.5	14.1	15.0	15.6

The laser-radiation beam, modulated at a frequency of 1000 Hz, was collimated by an OT-2 theodolite. The beam divergence was varied with the aid of a diopter tube from the OSK-2 set. The radiation receiver was an FEU-22 photomultiplier in combination with a low-frequency amplifier. The beam was focused onto the photocathode of the FEU-22 by a spherical mirror, the dimensions of which considerably exceeded the cross section of the beam. Triple passage of the radiation in the chamber over the 47 m path was accomplished by turning the beam with plane-parallel mirrors. To eliminate errors,

Table 2*

$\psi \backslash \tau$	13	14	15	16	17	18	19	20	21	22	23	24	25	30	40	50	60	70	80
5°	9.0	13.317	221.525	429.031	834.937	039.442	043.344	550.560	567.072	076.078	5								
3°	8.9	13.317	221.525	428.231	833.835	637.240	041.542	349.560	066.371	775.2									

$\psi \backslash \tau$	13	14	15	16	17	18	19	20	21	22	23	24	25	30	40	50	60	70	80	
1°2'			3.7	9.9	13.5	18.0	20.7	23.8	26.7	28.8	32.0	34.0	36.0	43.5						
0°55'				7.0	12.2	15.4	17.1	21.1	23.4	27.6	30.3	32.7	34.2	42.7						
0°24'				5.8	10.8	14.1	17.1	19.8	23.4	25.6	29.0	30.3	32.5							

* A dash denotes the absence of corresponding experimental data.

caused by the action of light backscattered onto the PMT, the angle between two neighboring ray directions was on the order of 5°. The angular aperture of the receiver was varied from 5°00' to 0°24', which was achieved by changing spherical mirrors with different focal lengths. For each value of the aperture angle, measurements were carried out: a) with a parallel radiation beam having diameters $d = 10; 25; 40,$ and 60 mm, and b) with a divergent beam with divergence angles $\varphi = 3', 8',$ and 11'. The angle $\varphi = 11'$ corresponds to the divergence of the OKG-11 laser beam.

Measurements of the optical transparency of the fog were accompanied by synchronous measurements of its microstructure with a photoelectric sensor⁽³⁾ and an integral analyzer of the droplet size spectrum⁽⁴⁾, developed at the Institute of Radio Engineering and Electronics of the Academy of Sciences of the USSR.

The droplet concentration in the course of an individual experiment decreased from several thousand particles at the beginning of the experiment to several tens in 1 cm³ by its end. The root-mean-square diameter of the droplets was in the range from 6 to 18 μ .

The results of the study of the limits of applicability of Bouguer's law for individual experiments are presented in Figs. 1 and 2. Along the abscissa is plotted the measured value of the optical thickness of the fog over the 47 m path (τ_{47}); along the ordinate, the ratio of the optical thicknesses on the two paths (τ_{47}/τ_{15}). The straight line corresponds to the value of the path-length ratio, equal to 3.14. In the range of optical thicknesses not exceeding the value τ_{gr} , corresponding to the limit of applicability of Bouguer's law, the ratio τ_{47}/τ_{15} in all experiments is on average 3.14 with a root-mean-square deviation of no more than $\pm 15\%$. This does not exceed the limits of measurement error. For $\tau_{47} > \tau_{gr}$, a decrease in the value of the ratio τ_{47}/τ_{15} is observed with increasing particle concentration, associated with the influence of multiple-scattering effects. The dependence of τ_{gr} on the laser-beam diameter d is weakly expressed; the most noticeable increase in τ_{gr} with decreasing d from 60 to 10 mm occurs at $\psi = 5^\circ$ and amounts to $\Delta\tau_{gr} \approx 1.6$. The dependence of τ_{gr} on the beam divergence in the range φ from 3 to 11' is practically absent, even for angular apertures on the order of 5°. The mean values of τ_{gr} over all experiments for different aperture angles ψ are given in Table 1.

When ψ is changed from 5° to $24'$, the value of τ_{gr} corresponding to the limit of applicability of Bouguer's law for laser sources changes approximately from 10 to 16.

The experimental procedure makes it possible, in addition to determining the limits of applicability of Bouguer's law, to estimate quantitatively the influence of multiply scattered light on the magnitude of the attenuation coefficient at different optical thicknesses of the fog. The relative error in measurements of the attenuation coefficient, which determines the deviation from Bouguer's law due to the influence of scattered light, has the form

$$\delta\alpha = \frac{\alpha_{\text{p.p}} - \alpha_{\text{meas}}}{\alpha_{\text{p.p}}} \cdot 100\%,$$

where $\alpha_{\text{p.p}}$ is the attenuation coefficient of the direct radiation beam entering Bouguer's law; α_{meas} is the measured value of the attenuation coefficient.

The results of calculations of $\delta\alpha$, in percent, for different aperture angles ψ at different optical thicknesses of the fog τ , are presented in Table 2. The deviation from Bouguer's law in the propagation of laser radiation in water fogs does not exceed 25% up to $\tau \approx 17$ for $\psi \approx 3^\circ - 5^\circ$, and up to $\tau \approx 21$ for $\psi < 1^\circ$.

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

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