ANGULAR DISTRIBUTION OF THE RADIATION FROM A DIFFUSE SOURCE AFTER SCATTERING

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The distribution produced in a scattering medium by an isotropic source provides some information on radiation transport. Few papers have been published on this. Results have been given [1] on the decay of the intensity at the center of a diffusely emitting object in a turbid medium, and this evidence allows one to estimate the intensity due to a source at a given depth over fairly wide ranges in source size and in parameters of the medium. However, one needs to know the angular distribution of the scattered radiation in order to calculate contrast characteristics. The thickness dependence of the contrast also allows one to estimate the limiting depth for observation of a luminous object, which provides estimates of the limiting depths for objects that are not selfluminous when the contrast is reduced by scattering.

Mathematical difficulties prevent one from deriving exhaustive answers to these problems from the transport equation, and one has to resort to experiment. Duntley [2] has given the angular distribution of the scattered intensity as measured in sea water at various depths for a spherical diffuse source, but the measurements were designed mainly to reveal the difference in scattering indicatrices for diffuse and collimated sources. No information was given on the relation between the scattering and absorption parameters for sea water, although this is very important in such measurements.

Here we report measurements on the scattering indicatrix for a medium exposed to an isotropic stationary source for a fairly wide range in the characteristics of the medium and the source.

The tests were done on models, but the results can [3] be used to describe real systems (water, the atmosphere). The water tank was 10 × 2 × 2 m with an attenuation parameter $\varepsilon = \sigma + k$* and the survival probability $\Lambda = \sigma/\varepsilon$ varied scattering matter (milk) or an absorber (nigrosine dye).

The apparatus was much as in [1]. The tank contained the diffuse source (a flat uniformly emitting surface with a circular shape and a brightness distribution close to the Lambert one [4]) whose diameter d was varied by means of stops. Sources with very small emitting surfaces were provided by DRSh-250 or DRSh-100 lamps in an underwater housing. The meter consisted of an I-11M lens, an aperture stop, and FEU-37 photomultiplier, a rotation system, and a recorder. The photomultiplier signal passed via a U1-2 amplifier to an EPP-09-M1 recorder. As the meter turned, the chart recorded a curve showing the brightness as a function of the angle of observation γ. The lens diameter was 4 cm and the reception angle $2\gamma_{re}$ was 2-3'.

We took as $\gamma = 0°$ the position where the axis of the meter passed through the center of the disc normal to the surface. The distribution curves are symmetrical around this direction, so values are given only for γ to one side of 0°.

The dependence on γ out to 30° was exponential if d < 0.1. The linear dependence of log B on γ applied up to optical thicknesses $\tau = \varepsilon h$ of 4.5-5 (h is the geometrical distance in the medium between detector and source). The fall in B was slower for $\tau > 5$; also, the limiting τ increased as d decreased, so we needed to examine the scattered radiation only over a small range in γ in order to establish the distribution over a wide range. This arose because the scattered radiation was dominated by photons that had been scattered only a few times. The mean order of scattering increased with τ, and the behavior of B ceased to be exponential.

*We used the ε calculated with logarithms to the base 10.

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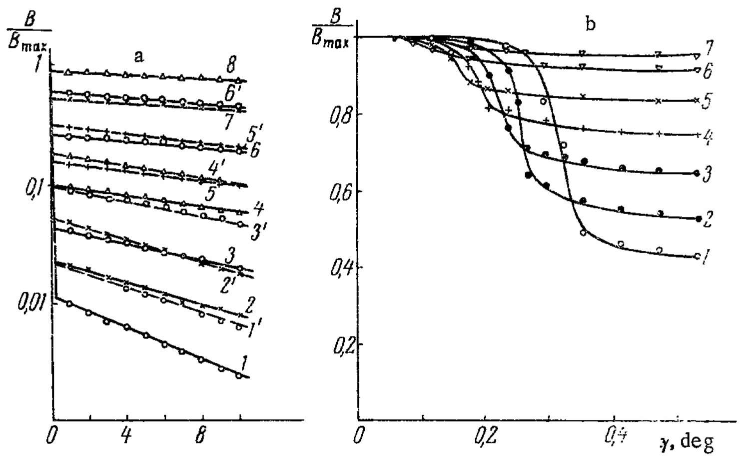

Fig. 1. Angular distribution of B/B_{max} for various τ and three optical diameters of the source: a) d = 0.001 (DRSh-100 lamp, solid curves) and d = 0.003 (DRSh-250, broken lines); b) d = 0.03, = 1 m^{-1}, Λ = 0.8; 1) τ = 2.5; 2) 3; 3) 3.5; 4) 4; 5) 4.5; 6) 5; 7) 5.5; 8) 6.

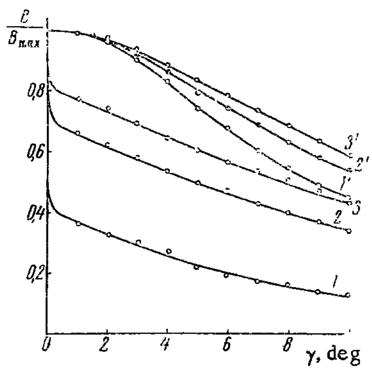

Fig. 2

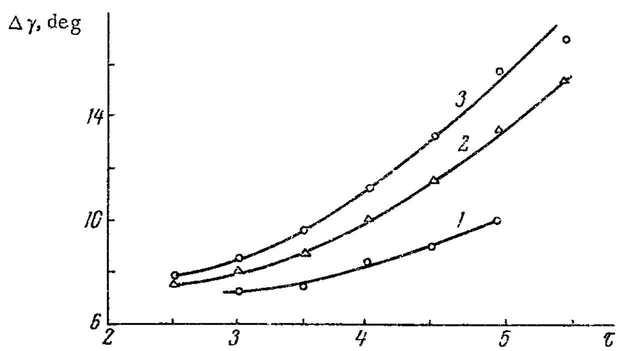

Fig. 3

Fig. 2. Angular distribution of B/B_{max} for various Λ with = 1 m^{-1}; τ = 4; 1, 2, 3) d = 0.015; 1', 2', 3') 0.5; 1, 1') Λ = 0.7; 2, 2') 0.8; 3, 3') 0.9.

Fig. 3. Angular width $\Delta\gamma$ at B/B_{max} = 0.8 as a function of τ for various Λ with = 1 m^{-1}, d = 0.5; 1) Λ = 0.7; 2) 0.8; 3) 0.9.

Figure 1 shows B(γ) for various τ for three types of source. The curves have been normalized to unity at $\gamma = 0°$ for convenience. Figure 1a represents the result with DRSh-250 and DRSh-100 lamps (sources respectively about 3 mm and 1 mm in diameter). A small displacement from $\gamma = 0°$ took the source out of the field of view of the meter, and the intensity fell sharply. The difference between the direct and scattered intensities increased with decreasing τ.

Figure 1b shows in more detail the energy distribution at small γ for εd = 0.03. The trend is much the same for the various τ: at first B does not vary with γ, then it falls sharply, and then it varies only slowly again. The first part is due to direct radiation, the second to direct and scattered radiation, and the third to scattered radiation alone. The angular width of the first plateau was much the same as the apparent size of the source at the point of observation. The source became indistinguishable against the scattered background at a certain τ. This τ decreased as the source became larger. Increase in Λ has much the same effect.

Figure 2 shows the effect of Λ on B. Realistic values for actual water tanks are 0.7-0.9 for Λ, and for these we give the indicatrices for large and small sources. The scattered intensity for d = 0.5 was larger than that for d = 0.015, but the Λ dependence was weaker, because direct radiation makes a larger contribution to the total when the optical diameter is large. The results of Fig. 2 are for τ = 4, and they

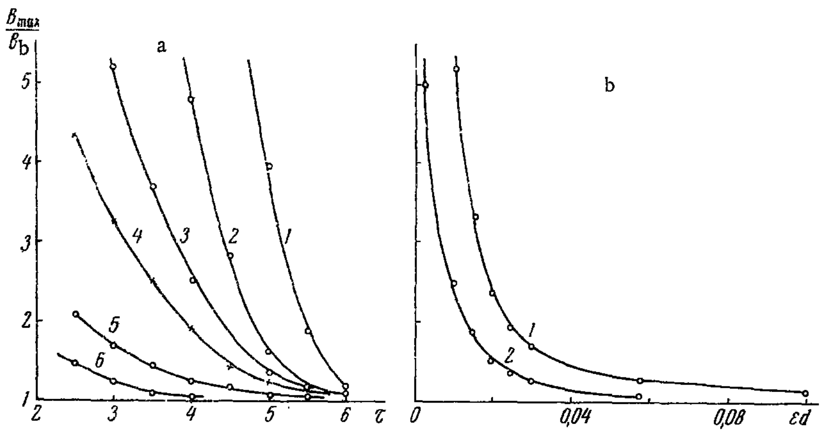

Fig. 4. Contrast B_{max}/B_b as a function of: a) optical depth, b) source diameter for $= 1\ m^{-1}$, $\Lambda = 0.8$. a) 1) $d = 0.001$; 2) 0.003; 3) 0.01; 4) 0.015; 5) 0.03; 6) 0.057; b) 1) $\tau = 3$; 2) 4.

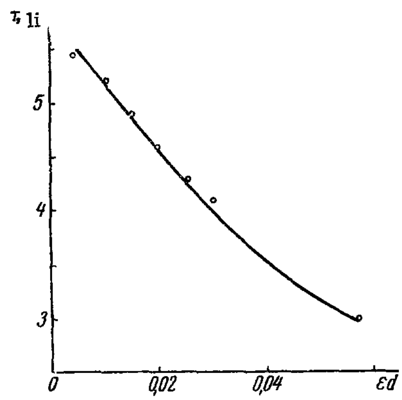

Fig. 5. Dependence of τ_{li} on εd for $B_{max}/B_b = 1.25$; $= 1\ m^{-1}$; $\Lambda = 0.8$.

show that at this depth the detector no longer shows a marked step in B between the source and the background (i.e., between B_{max} and B_b). If the ratio of these is greater than one, the object can be observed in the scattering medium because the distribution of B is bell-shaped and has its peak in the direction of the object. Also, the width $\Delta\gamma$ of the $B/B_{max} = f(\gamma)$ curves varies with τ and Λ, but increase in εd does not cause pronounced broadening of the curve, especially when τ is large.

Figure 3 shows that $\Delta\gamma$ does not increase appreciably with τ for τ small, because the direct radiation then predominates, and there is a pronounced fall in B at the edge of the source, which is thus detectable against the background. This is confirmed by the fact that the τ out to which $\Delta\gamma$ does not vary much increases as Λ decreases; at larger τ, the scattered light increasingly predominates, and the constant level in B/B_{max} occurs at larger γ, so $\Delta\gamma$ increases. There is a strict relation between $\Delta\gamma$ and Λ. It is possible to deduce either τ or Λ if the other is known by measuring $\Delta\gamma$ for some constant level in the indicatrix when the object is not distinguishable against the background.

It is necessary to know quantitatively the contrast when there is a brightness difference between source and background in order to design a viewing system for any particular conditions. Figure 4 shows B_{max}/B_b as a function of: a) τ, b) source diameter where B_b has been taken as the B at a γ where the source is outside the field of view of the meter. There is a very pronounced increase in the contrast as εd decreases, and $B_{max}/B_b \to \infty$ as $d \to 0$.

Increase in τ or εd increases the intensity of the scattered radiation and so reduces the contrast.

These results give the limiting depth τ_{li} for source detection, which is dependent on the characteristics of the source, the medium, and the meter, as well as on the minimum detectable difference between B_{max} and B_b. The limit of detection is set by the noise in the radiation detector, and the minimum detectable excess of the signal over the noise is dependent on the type of detector. We took $B_{max}/B_b = 1.25$ as representing the threshold of detection in examining the effects of d (Fig. 5). It is clear that τ_{li} increases as d decreases, though τ_{li} is reduced somewhat for εd small on account of observations in the optical system and the finite lens aperture.

The present results are for sources having nearly a Lambert brightness distribution. Results for highly collimated sources [5, 6] indicate τ_{li} several times those for diffuse ones.

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