DEPENDENCE OF THE CONTRAST OF AN IMAGE, RECORDED THROUGH A LAYER OF A SCATTERING MEDIUM, ON THE POSITION OF THE LAYER ALONG THE OBSERVATION PATH

A.N. Valentyuk, Yu.A. Lebedinskiĭ, and V.G. Sinchenko

Mogilev Department of Institute of Physics,
BSSR Academy of Sciences
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There are three types of dependences of the contrast of a recorded image on the distance of the layer from . the object plane. Depending on the ratio of the side of the observed object and the parameters of the scattering layer the following dependences are possible: nonmonotonic dependence with a minimum at some intermediate positions of the layer or monotonic decrease (increase) of the contrast.

In the last few years a number of investigators have analyzed the dependence of the contrast of an image, recorded through a layer of scattering medium, on the position of the layer along the observation path[1–7]. In Ref. 1 it was shown that as the distance between the scattering layer and the object plane increases the optical transfer function (OTF) of the layer decays monotonically, and it was established in a series of works [2–5], based on Monte-Carlo calculations, that the OTF is a nonmonotonic function of the distance between the layer and the object: the OTF first decreases, reaches a minimum for some intermediate position of the layer, and then increases. In these works qualitative conclusions were drawn about the character of the dependence of the image contrast on the position of the layer along the observation path depending on the Fourier spectrum of the object. In this paper we present the results of calculations of the image contrast in the small-angle approximation and the results of measurements of the contrast of test objects consisting of optical focusing crosses our results confirm the previously drawn qualitative conclusions.

To simplify the discussion we shall study the case of a one-dimensional object. Let L be the width of the object and L_0 the characteristic scale of brightness fluctuations over the surface of the object (element of the image). It is obvious that the presence of the scattering layer along the observation path will cause blurring of the elements of the image. The degree to which the layer affects the image of the object can be characterized by the width R of the line spread function (LSF) of the layer. It is obvious that for $R \sim L_0$, when the traverse diffusion distance of the photons is of the order of size of the image element, the image contrast, will decrease as R increases. This will happen as long as $R \leq L$. When $R > L$ another factor will come into play – transverse diffusion of photons beyond the limits of the image obtained in unscattered light. In this case the image contrast will increase as R increases.

It is well known[7] that R increases monotonously as the layer moves away from the surface of the object. It is thus obvious that three situations are possible when objects are viewed through a scattering layer.

1. $R \leq L$ along the entire observation path. In this case as the layer moves away from the object the image contrast will decrease monotonically.
2. $R \geq L$ along the entire observation path. In this case as the layer moves away from the object the image contrast will increase monotonically.
3. The scattering layer is located near the object $R \leq L$, the scattering layer is located at intermediate positions $R \geq L$. In this case as the layer moves away from the image contrast will first decrease, and then at some intermediate position it will start to increase.

The specific values of L for which the situations 1–3 can be realized can be determined from a formula following from Refs. 7–8:

$$R^2 = \frac{\sigma^*}{6}\overline{\gamma^2}[(l+\delta)^3 - l^3],$$

where $\overline{\gamma}^2$ is the second moment of the scattering phase function; $\sigma^* = \sigma(1 - \Phi)$ is the scattering Index of the layer; σ is the geometric thickness of the layer; Φ is a parameter defined in Ref. 8; and, I is the distance between the surface of the object and the closest surface of the layer.

The results of the qualitative physical analysis are confirmed both by calculations of the image contrast for standard test objects and by experiments. In this work we employed a test object consisting of a cross-shaped focusing pattern. The calculations and experiments were performed for a scattering medium consisting of a suspension of milk in water with optical thickness $\tau \sim 3.0$. The image contrast K was calculated using the formula $K = (E_1 - E_2)/(E_1 + E_2)$, where E_1 is the illumination intensity at the center of the image of the cross and E_2 is the illumination intensity at the center of the test object. The quantities E_1 and E_2 were calculated using to formulas that are valid when the condition for foreshortening invariance holds in the medium:

$$E_1 = 2\int_0^{\infty} B(\omega)\, T(\omega)\, \cos\omega\,\Delta\, d\omega,$$

$$E_2 = 2\int_0^{\infty} B(\omega)\, T(\omega)\, d\omega, \tag{1}$$

where $B(\omega) = \frac{1}{\omega}[\sin\omega(\Delta + 0.5\Delta_0) - \sin\omega(\Delta - 0.5\Delta_0)]$ is the Fourier spectrum of the brightness distribution of the test object; Δ is the distance from the center of the test object to the center of the cross; Δ_0 is the width of the cross; $T(\omega)$ is the OTF of the scattering layer; and, ω is the spatial frequency. The OTF of the scattering layer was calculated using the following formula from Refs. 7 and 8:

$$T(\omega) = \exp\left\{-\Lambda^{*}\tau + \frac{\Lambda^{*}\tau}{Q_0}\sum_{n=1}^{2}\frac{A_n}{a_n}\left[\frac{l+\delta}{[\alpha_n^2+\omega^2(l+\delta)^2]} - \frac{l}{(\alpha_n^2+\omega^2 l^2)^{1/2}}\right]\right\}, \tag{2}$$

where $\tau = \varepsilon\delta$; $\Lambda^{*} = \Lambda(1 - \Phi)$; Λ is the photon survival probability for a single scattering act; and a_n and A_n are parameters describing the scattering phase function $x(\gamma) = \sum_{n=1}^{2} A_n^{-\alpha} e^{\gamma_n}$, $Q_0 = \sum_{n=1}^{2} A_n / \alpha_n^2$ in the form of the following approximation $A_1 = 5043.4$, $\alpha_1 = 118.4$, $A_2 = 15.38$, $\alpha_2 = 4.87$, $Q_0 = 0.04$. Comparing the OTF calculated from the formula (2) for scattering layers with optical thickness τ ~ 3.0 with the Monte-Carlo results showed that the computational error associated with the formula (2) equals ~ 5%.

The calculations of the contrast of test objects of different size are in complete agreement with the physical considerations presented above. As the distance between the layer and the object surface increases the image contrast increases monotonically for large objects, and first decreases and then increases for objects of intermediate size (Fig. 1).

A series of experiments was performed in order to confirm the indicated behavior experimentally. The image of test objects of different size was formed by Yupiter-8 photographic objective. The center of the test objects was placed on the optical axis of the objective. Diffuse illumination of the test objects was achieved by passing a beam of light from an incandescent lamp of the KGM-type through frosted glass. The illuminating beam was modulated with a frequency of 1.6 kHz. The scattering layer consisted of a 0.3 m thick container, which was moved along the path observation. The image of the test object was scanned in the image plane of the objective with an analyzing slit. The signal recorded by the photomultiplier was amplified, synchronously detected, and then fed into a plotter, which plotted the distribution of the illumination intensity in the image of the test object for a fixed value of *l*. The image contrast was evaluated by analyzing this image.

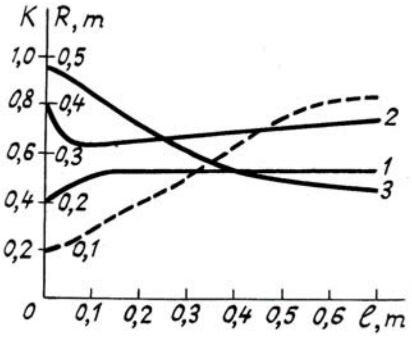

FIG. 1. The contrast of an image of a focusing cross versus the distance between the layer and the surface of the object (solid line) for Δ = 0.3 cm and Δ_0 = 0.075 cm (1), Δ = 8 cm and Δ_0 = 2 cm (2), and Δ = 30 cm and Δ_0 = 7 cm (3). The broken line shows the dependence of the width of the LSF on the distance 1. The optical and geometric thicknesses of the layer τ = 3.0 cm and δ = 30 cm, respectively.

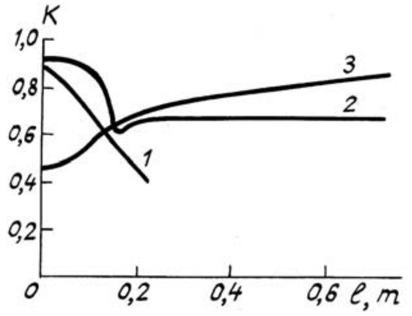

FIG. 2. The contrast of the image of a test object versus the position of the scattering layer along the observation path. (1) Test object 2, L = 0.52 m; (2) test object 2, L = 1.5 m; and, (3) test object 1, L = 1.5 m.

The experiments were performed using a focusing cross with the following parameters: Δ = 0.0109 m and Δ_0 = 0.0096 m for test object 1; Δ = 0.08 m and Δ_0 = 0.02 m for test object 2. The curves 2 and 3 were confirmed experimentally for a distance L = 1.5 m between the object and the optical system. In this case a slit 10 μm wide and 3 mm high was employed to analyze the image. The curve 1 corresponds to a distance L = 0.52 m between the object and the optical system and an analyzing slit 200 μm wide.

The conditions of observation of the test objects can be evaluated numerically by analyzing the curve of the contrast of the recorded image versus the position of the layer along the observation path. The results, obtained by analyzing the experimental distributions of the illumination intensity, are presented in Fig. 2.

As one can see from the figure, the situations 1–3 are clearly observed experimentally for the corresponding ratios of the parameters of the test objects and of the scattering layer.

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