RADIATIVE TRANSFER THROUGH A BOUNDED SCATTERING VOLUME IN BACKGROUND NOISE

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In this paper we study the signal–to–noise ratio (SNR) as a function of optical volume of a medium, reflectance of the underlying surface, and angle of illumination φ by external source. It has been shown that an increase in the angle of illumination by external source results in the increase of the SNR for any values of the reflectance of the underlying surface r larger than 0.2 *while the increase of the parameter φ and stronger asymmetry of the scattering phase function results in the decrease of the SNR.*

Propagation of optical radiation through disperse media is accompanied by multiple scattering of radiation. The multiply scattered light field produces noise that deteriorates recording of a valid signal. The higher is the noise level, the lower is the quality of an image observed through a scattering medium.

In the present paper we study the ratio of a signal, that has passed a medium without scattering, to a scattered light signal as a function of optical depth of the medium, its transverse optical dimensions, scattering phase function, absorptance by the medium, as well as the effect of external factors, namely, reflectance of a boundary surface and angle of illumination by external radiation source.

The signal–to–noise ratio (SNR) is defined in the following way:

$$\mathrm{SNR} = \frac{\exp(-\tau_x)}{I_\mathrm{d} + I_\mathrm{bg} - \exp(-\tau_x)},$$

where I_d is the valid light flux that has directly passed through a medium, I_bg is the light flux from the external background source, and τ_x is the optical thickness of the medium in the direction of propagation of a reference signal.

The radiation of the external source is incident on the disperse medium at an angle of φ to the direction of propagation of examined signal. The signal propagates along horizontal direction parallel to the underlying surface exhibiting the reflectance *r*. Let us study the SNR as a function of optical dimensions of the medium, quantum survival probability, and degree of anisotropy of the scattering phase function without regard for external radiation sources and reflecting surface.

Figure 1 shows the SNR as a function of the transverse optical dimensions of a medium ($\tau_y = \tau_z$) at different optical depths τ_x and quantum survival probabilities Λ (for spherical scattering phase function). The increase of $\tau_y = \tau_z$ in all cases results in the decrease of the SNR. This is explained by increasing intensity of a multiply scattered radiation field. This dependence becomes more pronounced as the optical depth of the medium τ_x increases. However, an increase in absorption by the medium markedly smooths this dependence.

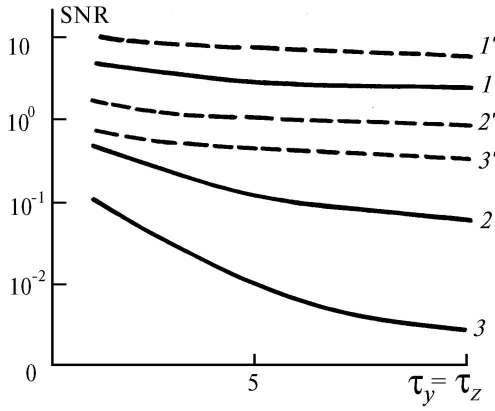

FIG. 1. The SNR–dependence on the transverse optical dimensions of a medium. $\tau_x = 1$ *(1 and 1′),* 5 *(2 and 2′), and* 10 *(3 and 3′).* Λ = 0.5 *(1′–3′) and* 1 *(1–3), a* = 1.

The results of analogous calculations of the dependence of the SNR on $\tau_y = \tau_z$ for a medium exhibiting anisotropic scattering phase function indicate that its stronger elongation results in practically complete independence of the SNR of the transverse optical dimensions of the medium. This effect can be explained by the fact that major portion of radiation is concentrated in the forward direction in the case of anisotropic scattering phase function and the increase of the transverse optical dimensions of the medium results in no considerable redistribution of the scattered radiation.

It also follows from the data shown in Fig. 1, that an increase in the optical depth of the medium τ_x results in the decrease of the SNR. The results of calculations show that this effect is most strongly pronounced in the case of anisotropic scattering phase function.

Figure 2 shows the SNR–dependence on τ_x for different quantum survival probabilities Λ, transverse optical dimensions of the medium, and degrees of elongation of the scattering phase function *a*. It may also be concluded that SNR increases with the increase of absorption in the medium.

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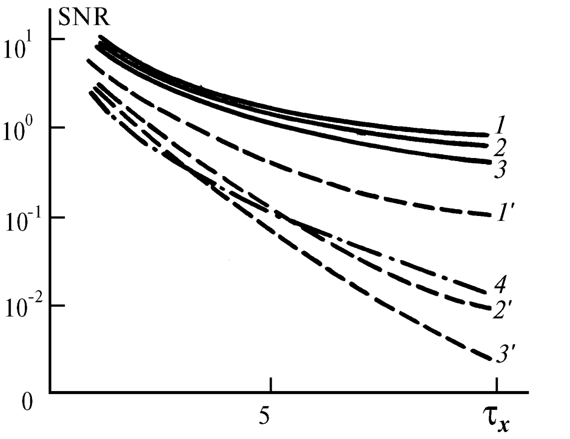

FIG. 2. The SNR–dependence on the optical depth of a medium. $\tau_y = \tau_z = 1$ *(1 and 1'),* 5 *(2 and 2'), and* 10 *(3 and 3').* $\tau_y = \tau_z = 1$–10 *(4).* $\Lambda = 0.5$ *(1'–3' and 4) and* 1 *(1–3).* $a = 1$ *(1 and 1', 3 and 3') and* 12.09 *(4).*

Let us study the behavior of the SNR with the optical volume of the medium, reflectance of the underlying surface, and angle of illumination by external source.

In this study we assume that the strength of the external sources is equal to that of the reference signal. The effect of the underlying surface was taken into account by the method reported in Ref. 1.

Figure 3 shows the SNR–dependence on the angle of illumination by external source φ (counted off from the direction of incidence of the reference signal) for different values of reflectance of the boundary surface r and quantum survival probabilities Λ in the case of spherical scattering phase function of the medium whose dimensions are 1×1×1.

For conservative medium ($\Lambda = 1$) an increase in the angle of illumination by external sources results in the increase of the SNR for any values of the reflectance of underlying surface larger than 0.2. When the illumination angles are larger than 90 °, the SNR saturates at a level of about 1.6. The analogous behavior of the SNR is observed in a medium with absorption. The SNR reaches a maximum at r approaching zero and small optical dimensions of the medium when the angles of illumination by external sources are close to 90 ° (see curves *1* and *5* in Fig. 3). This effect can be explained in the following way: the fraction of radiation exiting through the sides is small and hence the portion of scattered radiation that deteriorates the contrast characteristics of the reference signal is also small for small optical dimensions of the medium when the angle of illumination is close to 90 °. This results in larger values of the SNR in comparison with the angles being smaller or larger than 90 °, because at these angles the contribution of scattered radiation is comparatively larger. The effect of boundary surface exhibiting sufficiently high reflectance is equivalent to the increase of optical dimensions of the medium and results in monotonic behavior of the SNR–dependence on φ. Figure 3 *b* shows the SNR–dependence on φ for medium with 10×10×10 optical dimensions. For medium with such dimensions the decrease of the SNR can be seen as the angle of incidence of radiation from external sources increases for any values of the quantum survival probability Λ and reflectance of the boundary surface r. This fact is easy explained by the effect of multiple–scattering field formed in a medium having such dimensions.

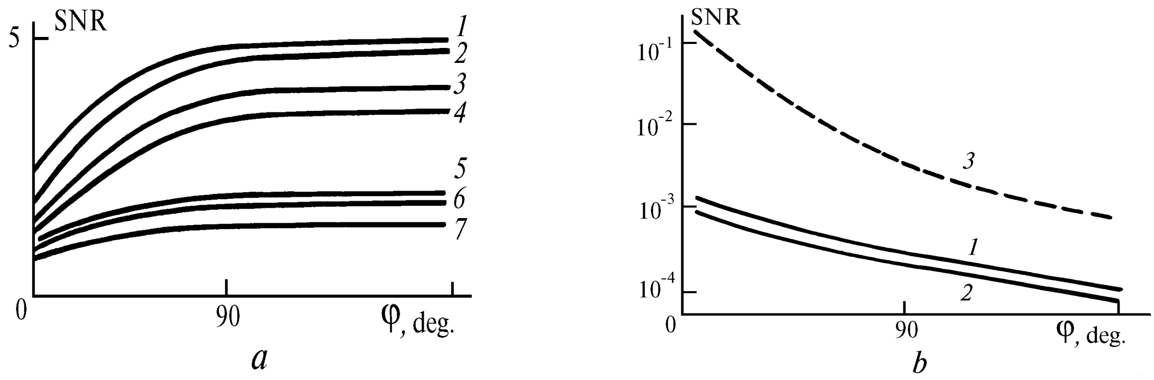

FIG. 3. The SNR–dependence on the angle of illumination by external source. a) $\tau_x = \tau_y = \tau_z = 1$, $a = 1$; $r = 0$ *(1 and 5),* 0.2 *(6),* 0.5 *(3), and* 0.8 *(4 and 7);* $\Lambda = 0.5$ *(1–4) and* 1 *(5–7). b)* $\tau_x = \tau_y = \tau_z = 10$, $a = 1$; $\Lambda = 0.5$ *(3) and* 1 *(1 and 2);* $r = 0.2$ *(1) and* 0.8 *(2).* $r = 0.2$–0.8 *(3).*

Figure 4 shows the SNR–dependence on the parameter r whose increase is followed by the decrease of the SNR. For the conservative medium the SNR becomes practically independent of the angle of incidence of radiation from external sources at $\varphi = 0$. As the angle φ increases with increasing absorption by the medium, the SNR–dependence becomes more pronounced. The decrease of the SNR with increase of the parameter r is caused by the fact that, as mentioned above, the effect of reflecting surface is equivalent to an increase in the optical dimensions of a medium that in its turn results in an increased level of multiple–scattering background which produced noise and deteriorates the contrast of the reference signal.

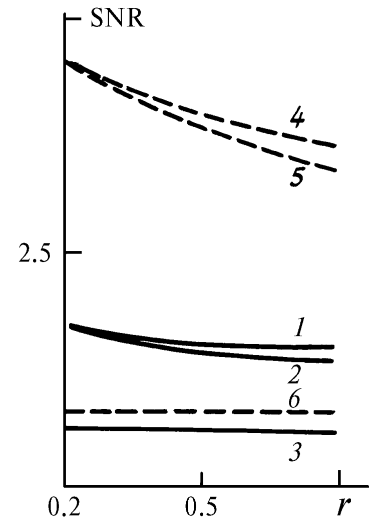

FIG. 4. The SNR–dependence on the reflectance of the underlying surface. $\tau_x = \tau_y = \tau_z = 1$, $a = 1$; $\varphi = 0$ *(6),* 90° *(2 and 5), and* 180° *(1 and 4);* $\Lambda = 0.5$ *(4–6) and* 1 *(1 and 3).*

The results obtained can be briefly summarized as follows:

– an increase in the transverse optical dimensions of a medium always results in the decrease of the SNR;

– absorption by the medium results in the increase of the SNR and markedly smooths its dependence on the transverse optical dimensions;

– stronger anisotropy of scattering phase function results in almost complete independence of the SNR of the transverse optical dimensions of a disperse medium;

– an increase in the longitudinal optical density of a disperse medium results in the sharp decrease of the SNR in the case of elongated scattering phase function;

– illumination by external sources and reflecting boundary surface deteriorates the SNR;

– when the angle of illumination by external sources increases, the SNR decreases for any values of the reflectance of boundary surface and quantum survival probability;

– increase of parameter r causes the decrease of the SNR in all the above–considered cases; and,

– the effect of external radiation source on the value of SNR is relatively weak for a medium exhibiting strongly elongated scattering phase function.

REFERENCES

1. B.V. Goryachev, V.V. Larionov, S.B. Mogil'nitskii, and B.A. Savel'ev, Opt. Spektrosk. **64**, No. 2, 407–409 (1988).

