LIDAR SIGNAL FLUCTUATIONS IN SOUNDING THE SEA THROUGH A ROUGH SURFACE

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We developed a rigorous calculation procedure for the characteristics of lidar signal fluctuations in sounding the upper sea layer through a surface disturbed by one-dimensional wind waves. We study the dependence of the mean value, dispersion and variation coefficient of the signal from a monostationary monoaxial lidar with identical source and receiver parameters on the sounding depth, wind velocity, and lidar beamwidth. The dependence of the correlation coefficient of the lidar signal on the sounding depth is analyzed. A physical interpretation of the results is given.

Pulsed optical sounding of the sea through a randomly inhomogeneous air–water interface is associated with a number of specific effects due to double-pass transmission of light radiation through correlated surface areas. The best studied effect is the amplification of the backscattering signal (BSS), according to which the mean statistical power of the echo signal transmitted through a disturbed interface can, under certain conditions, exceed the power of the echo signal transmitted through a smooth surface (see, e.g., [1–4]). Among the less investigated problems we mention the problem of defining the second statistical moments of a lidar BSS, in particular, its variation coefficient and correlation function with respect to the sounding depth. In [4, 5], the lidar signal fluctuations were studied in terms of a "single-lens model" based on the assumption that the air–water interface at the input of the sounding beam and at the output of the light rays reflected by the water medium and received by the lidar photo receiver is a lens with a random curvature. The relations found there for the second statistical moments of the signal power backscattered by the sea showed, in particular, the nonmonotonic nature of the dependence of the signal fluctuation dispersion on the sounding depth. An advantage of this model is its obvious physical simplicity, and the main disadvantage is the absence of the possibility of obtaining correct quantitative estimates in most actual sounding situations. A more general approach for the problem of BSS second-moment determination was developed in [6–8]. In this approach, the propagation of optical radiation is considered in terms of geometric optics and using the radiation transfer equation under the assumption that the air–water interface is random and has a Gaussian statistics. However, in the calculation of the fluctuation dispersion of a lidar BSS the authors of [6, 8] used a linear (with respect to wave gradients) approximation based on the assumption of smallness of the relative signal fluctuations. The small-fluctuation condition is satisfied when the angular deflection mechanism of light rays due to their refraction on a rough air–water interface has a smaller action on the formation of the underwater light field than the light scattering effects in the water medium. Obviously, this condition also limits the set of sounding conditions for which this approach applies.

The objective of this paper is to obtain rigorous relations for calculation of the first and second statistical moments of a lidar BSS (without using the linear approximation) and study the dependences of the variation coefficient and BSS correlation function on the sounding depth, wind velocity for one-dimensional wind waves, and lidar parameters.
1. FORMULATION OF THE PROBLEM

Assume that at a height $H$ in the plane $z_1$, which is parallel to the plane $z_2$ of the undisturbed air–water interface (Fig. 1), we have a pulsed source of light with the luminosity distribution

$$B_s(\vec{r}_1, \vec{\Omega}_1, t) = B_s D_s(\vec{r}_1, \vec{\Omega}_1) D'_s(t),$$

where $B_s = W_s/(\Sigma_s \Delta_s)$, $W_s$ is the energy of the emitted pulse, $\Sigma_s$ is the aperture area of the source, and $\Delta_s$ is the solid angle of emission. Hereafter $\vec{\Omega}_1$ denotes the projection of the unit vector $\vec{\Omega}$ onto the plane $z = \text{const}$, and $\vec{r}_1$ are the coordinates of the points in the plane $z_1$. The aperture function of the source satisfies the conditions

$$D_s(\vec{0}, \vec{0}) = 1, \quad \int_{-\infty}^{\infty} D'_s(t) \, dt = 1.$$

The light source irradiates the randomly-inhomogeneous interface at small angles to the vertical line. The light radiation penetrating into the water through a disturbed surface is scattered and is partially absorbed by the water medium. Part of the scattered radiation returns to the atmosphere and enters the lidar receiver with the receiving beamwidth $D_r(\vec{r}_1', \vec{\Omega}_1')$, $D_r(\vec{0}, \vec{0}) = 1$.

The relationship between the BSS and the characteristics of the radiation propagation path (lidar equation) was derived in [7]. This equation shows, in particular, that the temporal structure of the echo signal is described by a convolution of the source function $D'_s(t)$ with the function $P(h)$, which determines the signal power reflected from a homogeneous scattering shield at a depth $h$ under conditions of continuous illumination. This permits switching from the nonstationary problem to a stationary one.

2. INITIAL EQUATIONS

A random realization of the power of a lidar signal transmitted through a disturbed surface from the depth $h$ [7] can be described by

$$P(h) = \frac{B_s R_d}{\pi m^2} \int_{-\infty}^{+\infty} E_s(\vec{r}_3, h) E_r(\vec{r}_3, h) \, d\vec{r}_3,$$  \hspace{1cm} (1)

where

$$E_{sr}(\vec{r}_3, h) = \int_{-\infty}^{+\infty} D_{sr}(\vec{r}_1, \vec{\Omega}_1) e_{sr}(\vec{r}_1 \rightarrow \vec{r}_3, \vec{\Omega}_1, h) \, d\vec{r}_1 \, d\vec{\Omega}_1,$$

$$e_{sr}(\vec{r}_1 \rightarrow \vec{r}_3, \vec{\Omega}_1, h) = \int_{-\infty}^{+\infty} G_a(\vec{r}_1 \rightarrow \vec{r}_2, \vec{\Omega}_1 \rightarrow \vec{\Omega}_{12}) G_n(\vec{\Omega}_{12} \rightarrow \vec{\Omega}_2, \vec{r}_2) e_c(\vec{r}_2 \rightarrow \vec{r}_3, \vec{\Omega}_2, h) \, d\vec{r}_2 \, d\vec{\Omega}_{12} \, d\vec{\Omega}_2,$$

$G_a$ is the Green function of the radiation transfer equation in the atmosphere, which determines the brightness of the light field at the point $\vec{r}_2$ in the direction $\vec{\Omega}_{12}$ when the medium is irradiated by a point monodirectional, unit-power source located at the point $\vec{r}_1$ and radiating in the direction $\vec{\Omega}_1$ (Fig. 1), $G_n$ is the Green function of the interface describing the deformation of the brightness body when the light radiation passes through a rough surface, $e_c$ is the scattering function of the water medium, $m$ is the refractive index of the water, $R_d = \sigma_\pi \, dh/4$ is the diffuse reflection coefficient of a water layer of thickness $dh$, and $\sigma_\pi$ is the scattering coefficient of an elementary volume of water for the scattering angle $180^\circ$.

Sounding into the nadir corresponds to the conditions of a small-angle approximation. In terms of this approximation, expression (1) has the form [7]

$$P(h) = \frac{B_s R_d}{\pi m^2} \frac{1}{(2\pi)^{\frac{3}{2}}} \int_{-\infty}^{+\infty} \tilde{E}_s(\vec{k}, h) \tilde{E}_r(-\vec{k}, h) \, d\vec{k},$$  \hspace{1cm} (2)

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