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ON THE INFLUENCE OF SPATIAL FLUCTUATIONS OF THE WATER INHERENT OPTICAL PROPERTIES ON THE ENERGY OF A LIDAR ECHO SIGNAL COMING FROM A WATER

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Abstract

Theoretical models of the statistical characteristics of the lidar echo signal have been developed to interpret the results of optical sounding of heavily eutrophicated water bodies. Formulas are obtained for calculating the statistically average value and coefficient of variation of the energy of the elastic backscattering signal coming from the near-surface layer of water with randomly inhomogeneous absorption and scattering coefficients. Examples of the dependence of the indicated signal characteristics on the coefficients of variation of the optical characteristics of water are given. It has been established that fluctuations in the absorption coefficient lead to an increase in the average energy of the received signal, and fluctuations in the scattering coefficient to its slight decrease. A significant decrease in the average echo signal energy can be observed with cross-correlated fluctuations in the absorption and scattering coefficients, i. e. in the case when the attenuation coefficient fluctuates at a constant single scattering albedo. Considerations are made on how algorithms for estimating the average values of the optical characteristics of water and the parameters of their inhomogeneities from the average value and the coefficient of variation of the echo signal energy can be constructed.

Keywords: lidar, water, elastic light scattering, fluctuations in hydrooptical characteristics, statistical properties of lidar echoes

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О ВЛИЯНИИ ПРОСТРАНСТВЕННЫХ ФЛУКТУАЦИЙ ГИДРООПТИЧЕСКИХ ХАРАКТЕРИСТИК НА ЭНЕРГИЮ ПРИХОДЯЩЕГО ИЗ ВОДОЕМА ЛИДАРНОГО ЭХО-СИГНАЛА

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Аннотация

Разработаны теоретические модели статистических характеристик лидарного эхо-сигнала, предназначенные для интерпретации результатов оптического зондирования сильно эвтрофированных водоемов. Получены формулы для расчета статистически среднего значения и коэффициента вариации энергии сигнала упругого обратного рассеяния, приходящего из приповерхностного слоя воды со случайно-неоднородными показателями поглощения и рассеяния. Приведены примеры зависимости указанных характеристик сигнала от коэффициентов вариации оптических характеристик воды. Установлено, что флуктуации показателя поглощения приводят

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к увеличению средней энергии принимаемого сигнала, а флуктуации показателя рассеяния — к ее небольшому уменьшению. Значительное уменьшение средней энергии эхо-сигнала может наблюдаться при взаимно коррелированных флуктуациях показателей поглощения и рассеяния, т. е. в случае, когда флуктуирует показатель ослабления при неизменном альбедо однократного рассеяния. Высказаны соображения о том, каким образом могут быть построены алгоритмы оценки средних значений оптических характеристик воды и параметров их неоднородностей по среднему значению и коэффициенту вариации энергии эхо-сигнала.

Ключевые слова: лидар, вода, упругое рассеяние света, флуктуации гидрооптических характеристик, статистические свойства лидарных эхо-сигналов

1. Introduction

Interpreting the results of laser sounding in oceans and freshwater bodies relies on the theory of light propagation in homogeneous or horizontally homogeneous waters, as defined by specific profiles of the water inherent optical properties (IOP) [1–26]. However, in natural conditions, the water's IOP, including the absorption and scattering coefficients, may fluctuate widely and develop randomly in time and space. Particularly large IOP fluctuations (with spatial scales of the order of a decimeter or more[1]) emerge in inland water bodies during bloom periods [27–31], and these fluctuations should be accounted for when constructing algorithms for determining the dissolved and suspended matter concentrations in water from lidar echo signals. It has been observed that a turbid layer with a given amount of absorbing substances is minimally transparent when the absorber is uniformly distributed, and fluctuations in its concentration increase the average transparency of the layer, creating a "sieve" effect [32–34]. This effect, along with the effect of shadows from IOP inhomogeneities, should manifest in the laser sounding of an aqueous medium with randomly inhomogeneous optical properties. The purpose of this work is to theoretically study the effect of the water IOP fluctuations on the characteristics of the elastic backscattering signal, namely the statistically average signal and the dispersion of its relative fluctuations. The theory presented in this paper is inspired by the theory of spatial noise arising in optical tomograms of biological tissues due to fluctuations in their optical characteristics [35–37]. The difference between the two theories stems from the fact that in tomography studies, a two-dimensional spatial signal is analyzed, while in this case, a one-dimensional signal will be examined in the form of the received light pulse energy as a function of the horizontal lidar coordinate. It happens when the lidar does not allow medium response differentiation into partial echo signals coming from different depths, for example, for waters with low transparency or when registering fluorescence signals.

2. Formulation of the problem

We assume that the lidar is located at a height H above a flat water surface, and the radiation patterns of the emitter and receiver have a common axis oriented vertically[2]. When writing equations, we use the following notation: $W(\mathbf{r})$ is the energy of the elastic backscattering signal as a function of the coordinates of the point of intersection of the laser beam axis with the water surface $\mathbf{r}(x, y)$; W_1 is energy of the probing pulse; $2r_1$ and $2\vartheta_1$ are the diameter and divergence angle of the laser beam; $2r_2$ and $2\vartheta_2$ are the diameter of the entrance pupil and the angle of the field of view of the receiver; R_F is Fresnel reflection coefficient of the water surface; $n_w = 1.33$ is refractive index of water; $a(\mathbf{r}, z)$, $b(\mathbf{r}, z)$ and $c(\mathbf{r}, z) = a + b$ are the water absorption, scattering and attenuation coefficients in the point (x, y, z). The scattering phase function (SPF) is given as a combination of narrow $P^{\uparrow}(\theta)$ and isotropic $P^{\circ}(\theta) = 1$ SPFs with weight factors depending on the backscattering probability p_b:

$$P(\theta) = \left(1 - 2p_b\right) P^{\uparrow}(\theta) + 2p_b P^{\circ}(\theta)\,,\;\; p_b = (1/2)\int_{\pi/2}^{\pi} P(\theta)\sin\theta\, d\theta\,. \tag{1}$$

We assume that the conditions $(1/2)\int_{0}^{\pi} P(\theta)\sin\theta\, d\theta = 1$, $P^{\uparrow}(\theta > \pi/2) << p_b << 1$,

[1]The most rapid temporal changes in the IOP arise when the IOP inhomogeneities are transferred by currents. The characteristic time of these changes is equal to the ratio of the spatial scale of inhomogeneities to the flow velocity.

[2] In natural conditions, sounding is carried out at a certain angle to the vertical so that reflections from the water surface do not fall into the photodetector. However, this does not lead to noticeable changes in the signal coming from the water column.

$$\overline{\theta^2} = (1/2)\int_0^{\pi/2} \theta^2 P^{\uparrow}(\theta)\sin\theta\, d\theta << 1\,. \tag{2}$$

are satisfied.

The absorption and scattering coefficients are given in the form

$$a(\mathbf{r},z) = \bar{a}\left[1+\delta a(\mathbf{r},z)\right],\ b(\mathbf{r},z) = \bar{b}\left[1+\delta b(\mathbf{r},z)\right], \tag{3}$$

where $\bar{a}$ and $\bar{b}$ their statistically average values, while δa and δb are random relative deviations from average values. We consider fluctuations of the IOP to be spatially homogeneous and characterized by correlation functions of the form

$$B_a(\rho,\varsigma) = \overline{\delta a(\mathbf{r}+\boldsymbol{\rho}, z+\varsigma)\delta a(\mathbf{r},z)} = \overline{(\delta a)^2}\cdot R(\rho)Z(\varsigma)\ , \tag{4}$$

$$B_b(\rho,\varsigma) = \overline{\delta b(\mathbf{r}+\boldsymbol{\rho}, z+\varsigma)\delta b(\mathbf{r},z)} = \overline{(\delta b)^2}\cdot R(\rho)Z(\varsigma)\,, \tag{5}$$

$$R(\rho) = \exp\left(-\rho^2/\rho_0^2\right),\ Z(\varsigma) = ch^{-2}\left(\varsigma/\varsigma_0\right), \tag{6}$$

where $\overline{(\delta a)^2}$ and $\overline{(\delta b)^2}$ are variances of relative fluctuations of the absorption and scattering coefficients, parameters ς_0 and ρ_0 are radii of vertical and horizontal correlation of fluctuations of the specified IOP. Note that the function $ch^{-2}\left(\varsigma/\varsigma_0\right)$ in (6) differs insignificantly from $\exp\left(-\varsigma^2/\varsigma_0^2\right)$, but its use instead of the Gaussian function allows one to significantly simplify the analytical expressions for the statistical characteristics of the echo signal.

3. Model of random realization of an echo signal

The model for the backscattered signal assumes that the horizontal correlation of IOP fluctuations has a larger radius than the horizontal size of the water volume being illuminated, and the radius of vertical correlation of these fluctuations can be of any value. Based on this assumption, the equation for the signal energy $W(\mathbf{r})$ can be derived by integrating over time the well-known expression for the power of the pulsed elastic backscattered signal coming from a water medium with horizontally homogeneous IOP, which can vary arbitrarily with depth [1, 8, 38]. This equation looks like

$$W(\mathbf{r}) = \left(\pi W_1/4\right) r_2^2\theta_2^2 \int_0^{\infty} 2b_b(\mathbf{r},z)\left[\iint_{\infty} E_1\left(\mathbf{r},\mathbf{r}',z\right)E_2\left(\mathbf{r},\mathbf{r}',z\right)d^2\mathbf{r}'\right]dz\ , \tag{7}$$

$$b_b(\mathbf{r},z) = p_b b(\mathbf{r},z)\,, \tag{8}$$

where b_b is backscattering coefficient, E_1 is irradiance at a point $(\mathbf{r}',z)$ from an auxiliary continuous source of radiation with unit power and the same parameters $2r_1$ and $2\vartheta_1$ as for a real source, while E_2 distribution of irradiance in water from an auxiliary continuous source with unit power, aperture diameter $2r_2$ and beam angular width $2r_2$.

The effect of a stratified aqueous medium on a laser beam structure is described with good accuracy by the radiative transfer equation in the small-angle approximation [39]. However, this solution is a Fourier integral, which complicates the calculation of the statistical moments of the signal W. Therefore, here we use a less accurate, but very simple, model of irradiance fields $E_{1,2}$, built based on solving the radiative transfer equation in the small-angle diffusion approximation [39]:

$$E_i\left(\mathbf{r},\mathbf{r}',z\right) = \frac{1-R_F}{\pi d_i(z)}\exp\left[-\int_0^z \alpha\left(\mathbf{r},z'\right)dz' - \left(\mathbf{r}'-\mathbf{r}\right)^2/d_i(z)\right],\ i=1,2\,, \tag{9}$$

$$\alpha\left(\mathbf{r},z\right) = a\left(\mathbf{r},z\right) + 2b_b\left(\mathbf{r},z\right), \tag{10}$$

$$d_i(z) = r_i^2 + \theta_i^2\left(H + z/n_w\right)^2 + \frac{1}{3}\bar{b}\left(1-2p_b\right)\overline{\theta^2}\cdot z^3\,. \tag{11}$$

According to the model, the distribution of irradiance in the cross-section of a light beam follows the Gaussian function, and the exponential attenuation of the total beam power α is equal to the sum of the absorption and isotropic scattering coefficients. The third term on the right side of equation (11) accounts for the effect of beam broadening due to multiple forward scattering of light. In this case, the effect of fluctuations in the scattering coefficient on the variance of the irradiance distribution d_i is negligible. After substituting expressions (9)–(11) into equation (7), it takes the form

$$W(\mathbf{r}) = A\int_0^\infty 2b_b(\mathbf{r},z)\cdot\exp\left[-2\int_0^z \alpha(\mathbf{r},z')\,dz'\right]\frac{dz}{d(z)}, \tag{12}$$

$$A = \left(1-R_F\right)^2 W_1 r_2^2 \theta_2^2/4 .$$

$$d(z) = \left(r_1^2+r_2^2\right)+\left(\theta_1^2+\theta_2^2\right)\left(H+z/n_w\right)^2+\frac{2}{3}\bar{b}\left(1-2p_b\right)\overline{\theta^2}\cdot z^3 .$$

4. Equations for calculating the statistical characteristics of the echo signal

Let's describe the spatial signal $W(\mathbf{r})$ by its statistical moments of the first and second order, i. e. the average value $\overline{W}$ and the correlation function

$$B_W(\rho) = \overline{W(\mathbf{r}+\boldsymbol{\rho})W(\mathbf{r})}, \tag{13}$$

as well as the correlation function

$$B_{\Delta W}(\rho) = \overline{\Delta W(\mathbf{r}+\boldsymbol{\rho})\Delta W(\mathbf{r})} = B_W(\rho)-\overline{W}^2 \tag{14}$$

signal fluctuation $\Delta W(\mathbf{r}) = W(\mathbf{r})-\overline{W}$, dispersion of its fluctuations

$$d_W = B_{\Delta W}(0), \tag{15}$$

fluctuation spatial correlation coefficient

$$K(\rho) = B_{\Delta W}(\rho)/B_{\Delta W}(0) \tag{16}$$

and signal variation coefficient

$$\delta_W = \sqrt{d_W}\,/\,\overline{W} . \tag{17}$$

For a better understanding of why the fluctuations of different IOPs manifest themselves differently in the echo signal, the calculation of its statistical characteristics was performed for cases where fluctuates either one of the parameters a or b, or the attenuation coefficient $c = a + b$ while maintaining the single scattering albedo $\omega_0 = b/c$.

A. Only the absorbance fluctuates. Under the condition $\delta b = 0$ the equation (12) becomes

$$W(\mathbf{r}) = 2p_b\bar{b}A\int_0^\infty \exp\left[-2\Delta\tau_a\left(\mathbf{r},z\right)\right]F_a(z)dz , \tag{18}$$

$$\Delta\tau_a\left(\mathbf{r},z\right) = \bar{a}\int_0^z \delta a(\mathbf{r},z')\,dz' ,\quad F_a(z) = \exp\left[-2\left(\bar{a}+2p_b\bar{b}\right)z\right]/d(z) . \tag{19}$$

If we assume that the exponent $\varphi = -2\Delta\tau_a\left(\mathbf{r},z\right)$ on the right side of equation (18) is normally distributed, then the statistical averaging of the function W can be done using the relation

$$\overline{\exp(\varphi)} = \exp\left[\overline{\varphi^2}/2\right]. \tag{20}$$

This relation can also be used to find the function $B_W(\boldsymbol{\rho})$, assuming that $\overline{\quad\quad 2}\left[\;{}_a\left(\mathbf{r}\quad\boldsymbol{\rho},z_1\right)\quad\quad {}_a\left(\mathbf{r},z_2\right)\right]$.
As a result, we find:

$$\overline{W} = 2p_b\bar{b}A\int_0^\infty \exp\left[2\overline{\left(\Delta\tau_a(\mathbf{r},z)\right)^2}\right]F_a(z)dz , \tag{21}$$

$$B_{\Delta W}(\rho)=\left(2p_b\bar{b}A\right)^2\int_0^\infty\int_0^\infty\left[\exp\left(4\overline{\Delta\tau_a(\mathbf{r}+\boldsymbol{\rho},z_1)\Delta\tau_a(\mathbf{r},z_2)}\right)-1\right]\times$$
$$\times\left[\exp\left(2\overline{\left(\Delta\tau_a(\mathbf{r},z_1)\right)^2}+2\overline{\left(\Delta\tau_a(\mathbf{r},z_2)\right)^2}\right)\right]F_a(z_1)F_a(z_2)dz_1dz_2, \tag{22}$$

$$\overline{\Delta\tau_a(\mathbf{r}+\boldsymbol{\rho},z_1)\Delta\tau_a(\mathbf{r},z_2)}=\overline{(\delta a)^2}\,R(\rho)\left(\bar{a}\varsigma_0\right)^2\ln\frac{ch(z_1/\varsigma_0)ch(z_2/\varsigma_0)}{ch\left[(z_1-z_2)/\varsigma_0\right]}, \tag{23}$$

$$\overline{\left(\Delta\tau_a(\mathbf{r},z)\right)^2}=2\overline{(\delta a)^2}\left(\bar{a}\varsigma_0\right)^2\ln\left[ch(z/\varsigma_0)\right]. \tag{24}$$

B. Only the scattering coefficient fluctuates. Freezing $\delta a = 0$, equation (12) and the equations for calculating the statistical moments of the echo signal energy can be written as

$$W(\mathbf{r})=A\int_0^\infty 2b_b(\mathbf{r},z)\exp\left(-4\int_0^z b_b(\mathbf{r},z')\,dz'\right)\frac{\exp(-2\bar{a}z)\,dz}{d(z)}=$$
$$=(A/2))\int_0^\infty\left\{1-\exp\left[-4p_b\left(\bar{b}z+\Delta\tau_b(\mathbf{r},z)\right)\right]\right\}F_b(z)dz, \tag{25}$$

$$\Delta\tau_b(\mathbf{r},z)=\bar{b}\int_0^z\delta b(\mathbf{r},z')dz',\quad F_b(z)=-\frac{d}{dz}\left[\frac{\exp(-2\bar{a}z)}{d(z)}\right], \tag{26}$$

$$\overline{W}=(A/2))\int_0^\infty\left\{1-\exp\left[-4p_b\bar{b}z+8p_b^2\overline{\left(\Delta\tau_b(\mathbf{r},z)\right)^2}\right]\right\}F_b(z)\,dz, \tag{27}$$

$$B_{\Delta W}(\rho)=\left(A^2/4\right)\int_0^\infty\int_0^\infty\left[\exp\left(16p_b^2\overline{\Delta\tau_b(\mathbf{r}+\boldsymbol{\rho},z_1)\Delta\tau_b(\mathbf{r},z_2)}\right)-1\right]\times$$
$$\times\left[\exp\left(-4p_b\bar{b}(z_1+z_2)+8p_b^2\overline{\left(\Delta\tau_b(\mathbf{r},z_1)\right)^2}+8p_b^2\overline{\left(\Delta\tau_b(\mathbf{r},z_2)\right)^2}\right)\right]F_b(z_1)F_b(z_2)\,dz_1\,dz_2. \tag{28}$$

Expressions for the statistical moments of the function $\Delta\tau_b(\mathbf{r},z)$ are obtained from (23) and (24) by replacing $\overline{(\delta a)^2}\to\overline{(\delta b)^2}$, $\bar{a}\to\bar{b}$.

C. The attenuation coefficient fluctuates with the single scattering albedo unchanged. Assuming that the condition $\omega_0=b/c=\bar{b}/\bar{c}=\text{const}$ holds, and fluctuations of the attenuation coefficient $c = a + b$ are described by the equations

$$c(\mathbf{r},z)=\bar{c}\left[1+\delta c(\mathbf{r},z)\right], \tag{29}$$

$$B_c(\rho,\varsigma)=\overline{\delta c(\mathbf{r}+\boldsymbol{\rho},z+\varsigma)\delta c(\mathbf{r},z)}=\overline{(\delta c)^2}\cdot R(\rho)Z(\varsigma), \tag{30}$$

then equation (12) and equations for calculating the statistical moments of the echo signal energy can be written as

$$W(\mathbf{r})=C\int_0^\infty\left\{1-\exp\left[-2k\left(\bar{c}z+\Delta\tau(\mathbf{r},z)\right)\right]\right\}F_c(z)dz, \tag{31}$$

$$k=1-(1-2p_b)\omega_0,\quad C=\omega_0p_bA/k, \tag{32}$$

$$\Delta\tau(\mathbf{r},z)=\bar{c}\int_0^z\delta c(\mathbf{r},z')dz',\quad F_c(z)=-\frac{d}{dz}\left(d(z)\right)^{-1}, \tag{33}$$

$$\overline{W}=C\int_0^\infty\left[1-\exp\left(-2k\bar{c}z+2k^2\overline{\left(\Delta\tau(\mathbf{r},z)\right)^2}\right)\right]F_c(z)dz, \tag{34}$$

$$B_{\Delta W}(\rho) = C^2 \int_0^\infty \int_0^\infty \left[\exp\left(4k^2 \overline{\Delta\tau(\mathbf{r}+\boldsymbol{\rho}, z_1)\Delta\tau(\mathbf{r}, z_2)}\right) - 1 \right] \times$$

$$\times \left[\exp\left(-2k\overline{c}(z_1 + z_2) + 2k^2 \overline{\left(\Delta\tau(\mathbf{r}, z_1)\right)^2} + 2k^2 \overline{\left(\Delta\tau(\mathbf{r}, z_2)\right)^2} \right) \right] F_c(z_1) F_c(z_2)\, dz_1\, dz_2 \,. \quad (35)$$

Expressions for the statistical moments of the function $\Delta\tau(\mathbf{r}, z)$ are obtained from (23) and (24) by replacing $\overline{(\delta a)^2} \to \overline{(\delta c)^2}$, $\overline{a} \to \overline{c}$.

5. Numerical analysis of the statistical characteristics of the echo-signal

As follows from equations (12)–(35), the expressions for the statistical characteristics of the echo signal can be represented as functions of a dimensionless variable $\overline{c}\rho$ and dimensionless parameters $\hat{\omega}_0 = \overline{b} / \overline{c}$, $\overline{c}\rho_0$, $\overline{c}\varsigma_0$, $\overline{(\delta a)^2}$, $\overline{(\delta b)^2}$, $\overline{(\delta c)^2}$, $\overline{c}(r_1^2 + r_2^2)^{1/2}$, $\overline{c}H$. Figures 1, *a*; 2, *a* and 3, *a* show the results of calculating the parameter

$$N = \frac{\overline{W} - W_0}{W_0}, \quad (36)$$

which characterizes the difference between the statistically average energy $\overline{W}$ of a fluctuating echo signal and the energy W_0 of a regular signal, generated by an aqueous medium with spatially uniform optical characteristics $a = \overline{a}$, $b = \overline{b}$. The curves of these figures depict the dependence of the parameter N on the variation coefficients

$$\delta_a = \sqrt{\overline{(\delta a)^2}}, \ \delta_b = \sqrt{\overline{(\delta b)^2}} \ \ \delta_c = \sqrt{\overline{(\delta c)^2}} \quad (37)$$

of absorption coefficients, scattering and attenuation at three different values of the parameter $\hat{\omega}_0$ in $\overline{c}\varsigma_0 = 0.75$, $\overline{c}(r_1^2 + r_2^2)^{1/2} = 0.175$, $\overline{c}H = 5$ case. Figures 1, *a*; 2, *a* and 3, *a* illustrate the dependence of the coefficient of variation δ_W of the echo signal energy (equation (17)) on the value of parameters (37) and $\hat{\omega}_0$ for the above values of the other three parameters.

The figures show that the spatial fluctuations of different IOPs manifest themselves differently in the echo signal. Fluctuations in the absorption coefficient (with its fixed average value) can lead to a significant increase in the statistically averaged signal (Fig. 1, *a*), while fluctuations in the scattering coefficient reduce it, but very slightly (Fig. 2, *a*). With cross-correlated fluctuations in the absorption and scattering coefficients (i. e., fluctuations in the attenuation coefficient for a given single scattering albedo), the average signal can decrease significantly (Fig. 3, *a*).

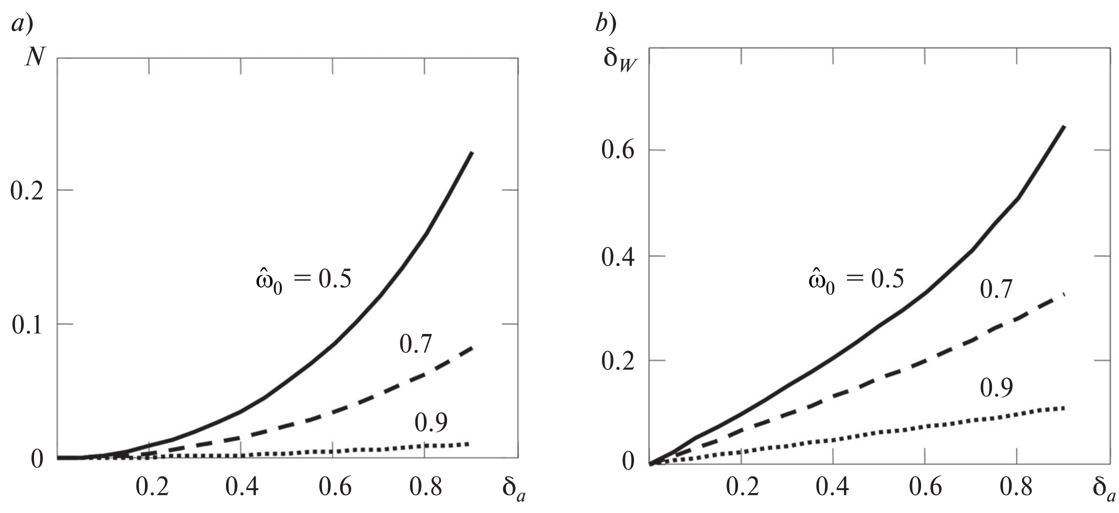

Fig. 1. Dependence of the parameters N (*a*) and δ_W (*b*) (see eq. (36) and (17)) on the absorbance variation coefficient δ_a at the values of the parameter $\hat{\omega}_0$, indicated in the figures and assuming $\overline{c}\varsigma_0 = 0.75$, $\overline{c}(r_1^2 + r_2^2)^{1/2} = 0.175$, $\overline{c}H = 5$.

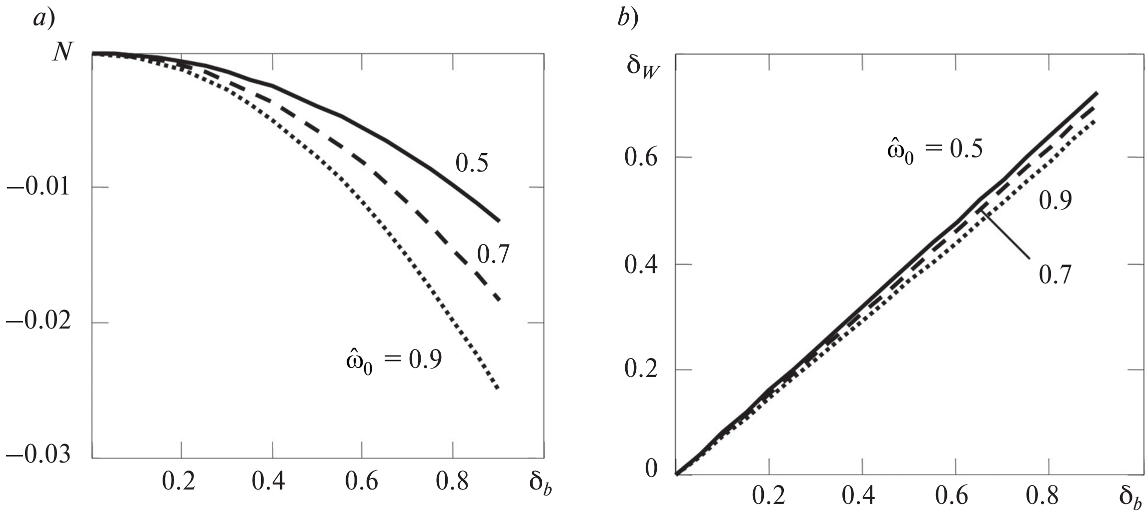

Fig. 2. Dependence of the parameters N (*a*) and δ_W (*b*) on the variation coefficient δ_b of the scattering coefficient under the conditions indicated in the caption to Fig. 1

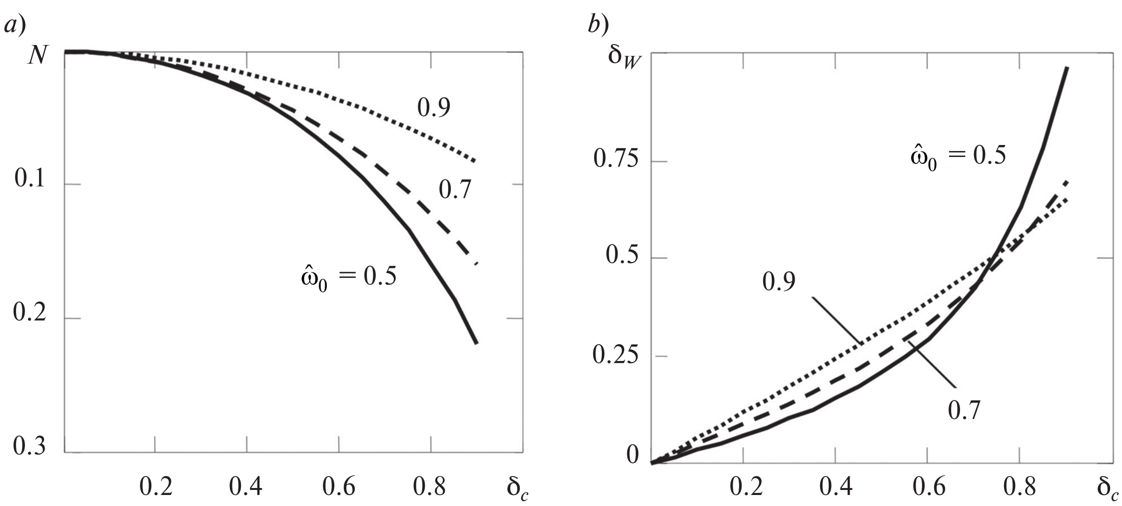

Fig. 3. Dependence of the parameters N (*a*) and δ_W (*b*) on the on the variation coefficient δ_c of the attenuation coefficient under the conditions indicated in the caption to Fig. 1

In the three cases under consideration, the numerical values of the coefficient of variation of the signal δ_W (assuming $\delta_a = \delta_b = \delta_c$) differ (Fig. 1, *b*; Fig. 2; *b*, Fig. 3, *b*), but not as significant as the parameter N values, characterizing the fluctuations' effect of the IOP on the average signal energy. The curves in Figures 1, *a* and *b*, depicting the dependence of the parameters N and δ_W on the coefficient of variation of the absorption index δ_a are very similar to each other, which is not true about the corresponding curves in Figures 2 and 3. Spatial fluctuations in the scattering coefficient cause strong variations in the echo signal (Fig. 2, *b*) but do not have a significant effect on its average value. The dependence $\delta_W(\delta_c)$ at $\hat{\omega}_0 = 0.5$ (Fig. 3, *b*) is similar to the dependence $\delta_W(\delta_a)$ (Fig. 1, *b*), and at $\hat{\omega}_0 = 0.9$ it almost coincides with the dependence $\delta_W(\delta_b)$ (Fig. 2, *b*).

Note that an increase in the average energy of the echo signal due to fluctuations in the absorption coefficient is a direct manifestation of the "sieve" effect, which leads to an increase in the thickness of the water layer from which the signal comes. While the decrease is due to fluctuations in the attenuation coefficient or scattering coefficient that occurs when the upper part of each of the clot of absorbing and scattering substances obscures its lower part.

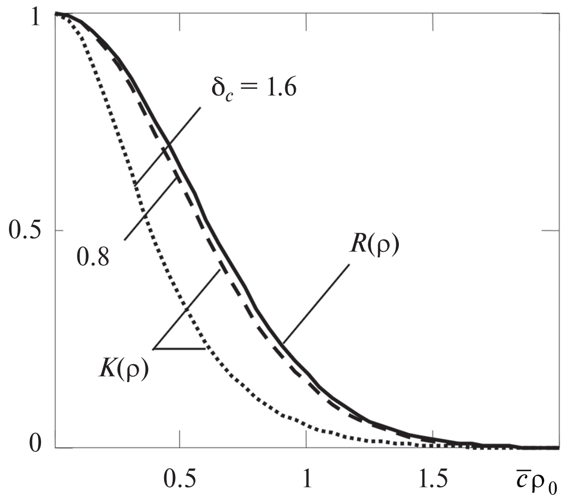

Fig. 4. The spatial correlation coefficient $K(\rho)$ of the echo signal fluctuations for the variation coefficient of the attenuation coefficient $\delta_c = 0.8, 1.6$; $R(\rho)$ is the horizontal correlation coefficient of attenuation coefficient fluctuation; $\overline{c}\rho_0 = 0.75$; $\omega_0 = 0.7$; $R(\rho)$ — see equation (6); other parameters are indicated in the caption to Figure 1

Figure 4 shows the calculated coefficient of spatial correlation $K(\rho)$ of echo signal energy fluctuations generated by inhomogeneities of the water attenuation coefficient (equations (16), (35)). The figure shows that in the case under consideration, the function $K(\rho)$ differs significantly from the coefficient of horizontal correlation $R(\rho)$ of the attenuation coefficient fluctuations only at very large values of its variation coefficient δ_c.

6. A possible method for estimating the optical properties of water by the average value and the coefficient of variation of the echo signal energy

Assuming for definitiveness that the fluctuating characteristic of water is the attenuation coefficient, then the form of the functions N and δ_W, shown in Fig. 3 will depend on the average values $\overline{c}$, $\overline{b}$ the attenuation and scattering coefficients, the backscattering probability p_b, the parameter of the scattering phase function θ^2 and the vertical correlation radius ς_0 of the attenuation coefficient fluctuations. By measuring two statistical parameters of the signal $\overline{W}$ and δ_W, we can complete only two equations for solving the inverse problem, which indicates the impossibility of solving it without using some a priori information about the optical characteristics of water.

As can be seen from Fig. 4, under the condition $\delta_c < 1$ the correlation radius of fluctuations in the echo signal energy ρ_W ((the function width $K(\rho)$ at the $1/e$ level) practically does not differ from the horizontal correlation radius ρ_0 of fluctuations of the attenuation coefficient (the function width $R(\rho)$ at the $1/e$ level). Therefore, assuming that fluctuations of the attenuation coefficient are isotropic, we can estimate the vertical radius of their correlation using relationship $\varsigma_0 = \rho_W$.

To reduce the number of unknown parameters in the echo-signal models, one could use empirical correlations between different IOPs, similar to the Levin-Kopelevich regressions [40, 41], which allow one to express the parameters $\overline{b}$, p_b and $\overline{\theta^2}$ through the attenuation coefficient $\overline{c}$. These regressions were obtained for marine waters with attenuation $\overline{c} = (0.3 \div 1)$ m^{-1} at a wavelength of 500 nm. The search for similar regressions for blooming inland water bodies is also underway [29]. Removing parameters $\overline{b}$, p_b and θ^2 from the theoretical expressions for $\overline{W}$, W_0, N and δ_W using empirical regressions, would allow the definition of the remaining two parameters $\overline{c}$ and δ_c using the equations

$$W_0(\overline{c})\left[1 + N(\overline{c},\delta_c)\right] = \overline{W'}, \ \delta_W(\overline{c},\delta_c) = \delta'_W, \qquad (38)$$

where $\overline{W'}$ and δ'_W are measured values of the statistical characteristics of the signal; $W_0 = \overline{W}(\delta_c = 0)$ is the energy of the signal coming from a reservoir with uniform optical properties. After finding the parameter $\overline{c}$ the rest of the IOPs are determined using the same regressions as for equations (38).

7. Conclusion

The main goal of this work was to study the effect mechanisms of spatial fluctuations of various IOPs on lidar echo signals, which required the maximum simplification of the water optical properties models. However, the proposed estimation method for the statistical characteristics of echo signals is also quite suitable for theory development for lidar sounding of natural water bodies. The study showed that fluctuations in the absorption, scattering, and attenuation coefficients (with the single scattering albedo unchanged) are approximately the same in echo signal fluctuations but produce a different effect on their average energy. Absorption coefficient fluctuations increase average energy, while fluctuations of attenuation and scattering coefficients decrease average signal energy at significantly different rates. Such manifestations of IOP fluctuations are qualitatively explained by two effects, an increase in the average transparency of the water layer due to fluctuations in the absorption coefficient ("sieve effect") and the formation of shadows behind the inhomogeneities of the attenuation coefficient, which decreases the reflectivity of the water layer. These effects should be accounted for when constructing algorithms for determining the optical characteristics of heavily eutrophicated waters from lidar signals.

Note that the water surface may have unwanted effects on the signal received by a surface lidar and requires special measures to eliminate these effects. The most obvious (but seldom available) option is to observe in calm conditions. Surface waves modulate the power and energy of the signal and become a source of multiplicative interference, which makes it difficult to measure the IOP. This interference can be addressed in a similar manner as when enhancing the visibility of underwater objects under natural light conditions in rough water [42]. The method involves removing signal distortions by utilizing information about the topography of the surface through which the scattered light enters the photodetector. This information can be obtained by analyzing images captured by a specialized video camera and processing them to determine the surface's relief [43].

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