DETECTION OF DEEP SEA WATER LAYERS WITH ENHANCED TRANSPARENCY BY PULSED LASER DETECTION AND RANGING METHOD

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Maximum depths of detection of oceanic layers with enhanced transparency have been analyzed. The method is based on the estimation of the depth for which the signal-to-noise ratio is equal to the threshold level of a photoelectric recording system. The mathematical relations derived by A.P. Ivanov [Izv. Ross. Akad. Nauk, Fiz. Atmos. Okeana **32**, *No.* 4, 514–522 (1996)*] in the diffusion and small-angle diffusion approximations of the radiative transfer theory have been used. The method takes into account the optical properties of the water column and of the detected layer, the parameters of the transceiving system, and external illumination. Among the regularities considered, the conditions are revealed under which the maximum detection depth does not depend on the energetic characteristics of a light source and receiver, duration of light pulses, noise of transceiving channel, and external illumination.*

As a rule, natural and artificial water reservoirs are inhomogeneous with depth. Layers with enhanced turbidity can appear at different depths in the water due to different hydrological and biophysical processes or, by contrast, water at some depth becomes more transparent than in the subsurface layer. The last case is typical of subpolar waters of the Global Ocean and many inland water reservoirs. Detection of such layers of enhanced transparency is of great interest, because systems of submarine television, communication, and information transfer harnessing a light beam operate more efficiently in such layers.

The problem can be successfully solved by pulsed laser detection and ranging method. The technique for calculating the return signal power in the case of pulsed detection and ranging of a stratified water medium was suggested in Ref. 1. The maximum depths of bathymetric measurements and detection of individual objects by the aforementioned method, taking into account the actual noise and external illumination, were estimated in Refs. 2–4.

The analytical technique for estimating the conditions of detecting inhomogeneous water layers on the basis of the diffusion and small-angle diffusion approximations of the radiative transfer theory was suggested in my recent papers.[5,6] Some examples were also given there on the influence of different parameters on the maximum depth of layer detection. The formulas obtained there can be used to estimate the maximum depths of detecting the layers with enhanced or reduced turbidity compared with that of the subsurface water layer. However, a specific analysis was carried out only for the first case. Let us now analyze the maximum depths of detecting the layers with enhanced transparency in the oceanic water by laser detection and ranging method based on the technique developed in Ref. 6.

The water medium is modeled in the form of two homogeneous plane-parallel layers. The first (upper) layer of the thickness h_1 is characterized by the scattering phase function $x_1(\gamma)$, the extinction coefficient $\varepsilon_1 = \sigma_1 + \chi_1$, and the single scattering albedo $\Lambda_1 = \sigma_1/(\sigma_1 + \chi_1)$, where σ_1 and χ_1 are the scattering and absorption coefficients, respectively. The second (lower) layer, practically infinitely thick (which is the case for the majority of real conditions), has the characteristics $x_2(\gamma)$, ε_2, and Λ_2. Here, $\varepsilon_2 < \varepsilon_1$.

A pulsed light source and a photodetector are collocated and situated under the water surface. Then the problem is reduced to the determination of the maximum depth of detecting the layer with the enhanced transparency for which the signal-to-noise ratio δ becomes equal to the threshold value δ^{th} of the examined photoelectron system.

The signal-to-noise ratio can be written as

$$\delta = \frac{1}{\sqrt{(1/\delta_{\text{sh}})^2 + (1/\delta_{\text{p}})^2}}, \qquad (1)$$

where

$$\delta_{\text{sh}} = \bar{k}\sqrt{A\, n\, \bar{\eta}\, t_{\text{r}}} \qquad (2)$$

is the signal-to-noise ratio for the shot noise,

$$\delta_{\text{p}} = \bar{k}/k_{\text{lf}} \qquad (3)$$

is the signal-to-noise ratio for the noise of the transceiving channel. Here,

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$$\bar{k} = \bar{B}_{sm}/(\bar{B}_{sm} + 2\bar{B}_b + 2\bar{B}_i) \quad (4)$$

is the contrast,

$$\bar{\eta} = (\bar{B}_{sm} + 2\bar{B}_b + 2\bar{B}_i)/2W \quad (5)$$

is the energy transfer coefficient, and

$$A = 2WS\, S_\lambda \omega / e\ . \quad (6)$$

is the energetic parameter of the transceiving system.

In these formulas, k_{lf} is the low-frequency variation coefficient of the number of photons coming to the detector; W is the energy of a transmitted light pulse; n is the number of pulses; S and ω are the area and the solid field-of-view angle of the detector, respectively; S_λ is the spectral sensitivity of the photocathode; e is the electronic charge; $\bar{B}_{sm}$, $\bar{B}_b$, and $\bar{B}_i$ are the values of brightness of the received radiation corresponding to the signal maximum recorded from the examined layer, backscattered background illumination (BBI), and external illumination averaged over the area S, angle ω and time lag of the detector $t_r = 1/\Delta f$, where Δf is the bandwidth of the receiving channel. Since the layer with the reduced turbidity is detected in this case, a dip rather than a spike is observed on the signal waveform at the appropriate moment. The dip maximum is equal to $\bar{B}_{sm}$.

The formulas for $\bar{B}_{sm}$ and $\bar{B}_b$ were obtained in Ref. 6 taking into account broadening of the initial pulse of duration t_0 due to the multiple light scattering in the medium. The assumptions used in calculations were also specified there.

The regularities of variations of the maximum depth of detecting the layers of enhanced transparency h_1^m as functions of different parameters presented below were analyzed at $\delta^{th} = 3$ corresponding to sufficiently high probability (reliability) of detection. The parameter n was always equal to unity and $W = 1$ J. It was shown in Ref. 6 that, in principle, the optimum value of t_r can be different, but the use of t_r of the order of 100 ns for the majority of situations decreases the sought-after value h_1^m no more than by 5–10%. So in the present paper $t_r = 100$ ns everywhere. In addition, the following statistical correlation relationships[5] are used to decrease the number of the optical parameters of the problem:

$$\Lambda = 0.955 - 0.035/\varepsilon\ ,$$

$$1 - F = \frac{10^{-3}(0.4 + 7.83\varepsilon + 3.05\varepsilon^2)}{0.955\varepsilon - 0.035}\ , \quad (7)$$

where ε is expressed in m^{-1} and $1 - F$ is the fraction of light scattered by volume element into the backward hemisphere. It depends on $x(\gamma)$ and is included into Eqs. (4) and (5). The parameter Λ is also included in these formulas. Application of Eq. (7) results in using only two parameters ε_1 and ε_2.

To begin with, we investigate the effect of the relationship between ε_1 and ε_2 on h_1^m (Fig. 1). Let us consider the illumination of the medium by a δ-pulse. To generalize, here $\varepsilon_2 \gtrless \varepsilon_1$. Naturally, $h_1^m = 0$ at $\varepsilon_2 = \varepsilon_1$. The depth of detection increases as $|\varepsilon_1 - \varepsilon_2|$ increases. However, this increase is limited. If one extinction coefficient is 3–5 times greater than another, the increase of h_1^m sharply slows down. The great detection depth retaining even if ε_2 and ε_1 are close to each other without channel noise has engaged our attention. It cannot be the case in real practice, because $k_{lf} \neq 0$ in any event. The families of curves at $\varepsilon_1 = 0.15$ and $0.3\ m^{-1}$ behave similarly; they are only displaced along the x axis by different amounts. The values h_1^m decrease as ε_1 increases, all other factors being the same. Curves *1–3* were obtained at $A = 10^{17}\ m^2$. In order to have an idea of real parameters it corresponds, let us give an example: $W = 1$ J, $S_\lambda = 6.5\cdot 10^{-2}\ A\ W^{-1}$, $S = 0.0764\ m^2$, and $\gamma = \sqrt{\omega/\pi} = 10^0$. Curves *4* were obtained at $A = 10^{10}\ m^2$. It is seen that h_1^m decreases not too strongly as the energetic parameter decreases by 7 orders of magnitude. It is especially well seen at $\varepsilon_1 = 0.3\ m^{-1}$.

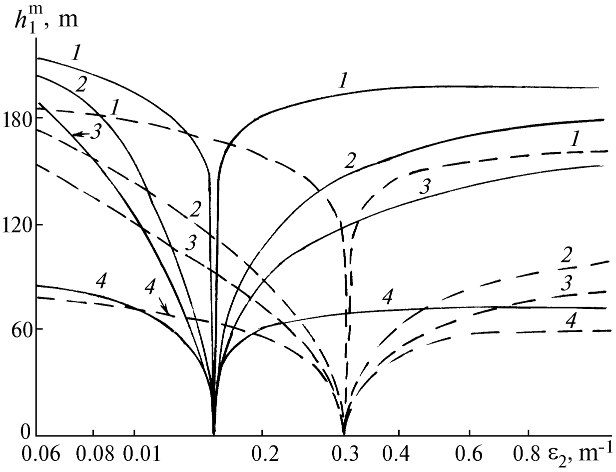

FIG. 1. Dependence of h_1^m on ε_2 at $\bar{B}_i = 0$ and $\varepsilon_1 = 0.15$ (solid curves) and $0.3\ m^{-1}$ (dashed curves); $k_{lf} = 0$ (1), 0.04 (2), and 0.06 (3 and 4); $A = 10^{17}$ (1–3) and $10^{10}\ m^2$ (4).

The effect of A on h_1^m is illustrated in more details by Fig. 2. The values A are expressed in m^2. The cases of the δ-pulse and the pulse with duration $t_0 = 50$ ns were considered. It is seen from the figure that at $k_{lf} = 0$ the dependence $h_1^m = f(\log A)$ is nearly linear. Starting from some values of A, the energy coefficient practically does not affect the maximum depth of detection of the layer as k_{lf} increases. If $k_{lf} = 0.025$, the parameter h_1^m remains constant at any A. It is connected with the fact that the transceiving channel noise is prevalent over the short noise. The effect of t_0 is especially noticeable for detection of small depths, when pulse broadening is not observed. Here, the finite t_0 decreases the h_1^m. By contrast, when the layer is detected at the great depth, the pulse will be broadened by hundreds of nanoseconds due to the multiple scattering, and the effect of the small initial value of t_0 will be insignificant. It is especially well seen in Fig. 3, which shows the range of variation of durations of laser shots really used for detection and ranging of water media. It is seen from the figure that if the transparent layer is well pronounced and is detected from very great depth, the transition from the δ-pulse of illumination to the pulse of duration t_0 = 100 ns (really it can be significantly longer) will not decrease the value h_1^m. So an attempt to decrease the duration of the initial pulse aimed at the increase of the detection depths is not always expedient.

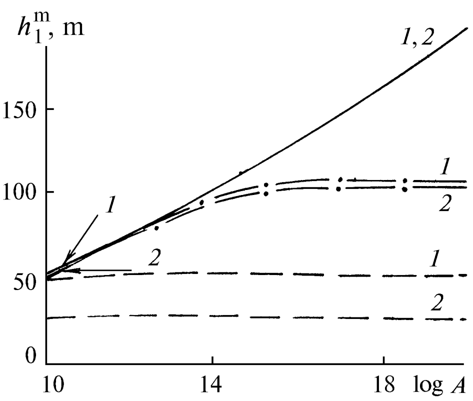

FIG. 2. Dependence of h_1^m *on* $\log A$ *at* $\varepsilon_1 = 0.3$ m^{-1}, $\bar{B}_i = 0$, $t_0 = 0$ *(1) and* 50 ns *(2), and* $k_{lf} = 0$ *(solid curves),* 0.01 *(dot-and-dash curves), and* 0.025 *(dashed curves).*

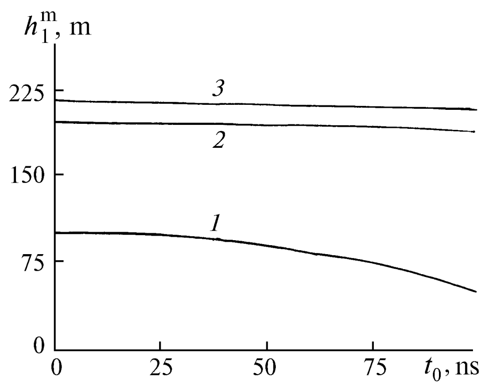

FIG. 3. Dependence of h_1^m *on* t_0 *at* $A = 10^{17}$ m^2, $k_{lf} = 0.04$, $\bar{B}_i = 0$, $\varepsilon_1 = 0.15$ m^{-1}, *and* $\varepsilon_2 = 0.125$ *(1),* 0.068 *(2),* 0.047 m^{-1} *(3).*

Before an analysis of the effect of low-frequency noise of the transceiving channel, let us consider the possibility of estimation of the parameter k_{lf}. This characteristic is determined by noise of the light source, the medium through which light propagates (due to the fluctuations of its optical properties), and the detector. The variance of the aforementioned noise components is proportional to the number of photoelectrons detected in a time t_r. In principle, if the optical properties of the upper layer of water, the parameters of the transceiving system, the diameter and the brightness coefficient of a disk diffusely reflecting the light radiation are known, by measuring the signal-to-noise ratio for different submerged depths of the disk, one can determine k_{lf} by analytical methods for calculating δ in case of pulsed detection and ranging of objects in turbid media.[2,3,7] Unfortunately, the accuracy of determining k_{lf} in such a way is low, because it is necessary to specify a large number of parameters, each known with some error. However, in the majority of real situations the channel noise is principally determined by the detector rather than by the light source and the water medium. As for the television system, its threshold contrast k^{th} is rather high for intense light fluxes, in contrast to the eye, and reaches approximately 0.1. So, according to Eq. (3), $k_{lf} = k^{th}/\delta_p = 0.1/3 = 0.033$ for recording systems of this type without shot noise. This value gives the order of magnitude of k_{lf} for the recording system. One can assume that the real range of variation of the parameter k_{lf} is 0.02–0.05.

Let us consider now the dependence of h_1^m on the channel noise at different values of the transparency of the detected layer (Fig. 4). To study in ample detail, the range of variation of the parameter k_{lf} is taken much wider than the aforementioned one. It is seen from Fig. 4 that, if the difference between ε_1 and ε_2 is great and the parameter k_{lf} is small, the layer will be detected from the great depth, and the range of values k_{lf} that do not affect the parameter h_1^m will be much wider than when the difference $\varepsilon_1 - \varepsilon_2$ is not great.

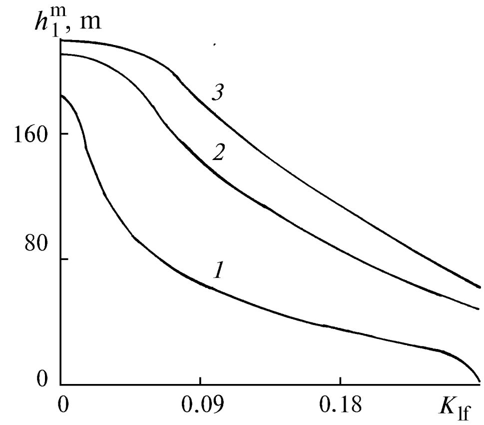

FIG. 4. Dependence of h_1^m *on* k_{lf} *at* $A = 10^{17}$ m^2, $t_0 = 0$, $\varepsilon_1 = 0.15$ m^{-1}, $\bar{B}_i = 0$, *and* $\varepsilon_2 = 0.125$ *(1),* 0.068 *(2), and* 0.047 m^{-1} *(3).*

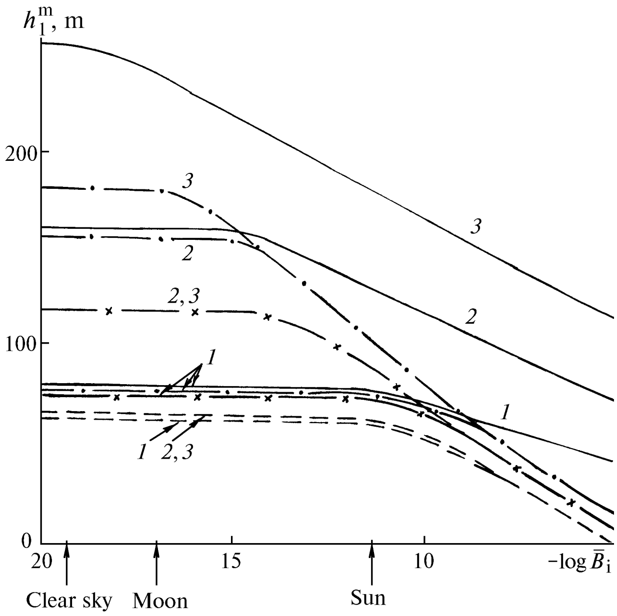

FIG. 5. Dependence of h_1^m *on* $(-\log \bar{B}_i)$ *at* $\varepsilon_1 = 0.2\ m^{-1}$, $\varepsilon_2 = 0.08\ m^{-1}$, $t_0 = 30$ ns, *and* $A = 10^{10}$ *(1),* 10^{15} *(2), and* 10^{20} m^2 *(3)*: ——, $k_{lf} = 0$; —·— , 0.04; —×—, 0.1; ----, 0.2.

Very often detection and ranging should be performed in the presence of external illumination of the medium. This case is shown in Fig. 5. The parameter $\bar{B}_i$ is shown on logarithmic scale and is expressed in J·sr·m^{-2}·ns^{-1}. The arrows on the x axis correspond to the values of brightness produced by the night sky, Moon, and Sun under conditions of the clear atmosphere on the detector of radiation located in the water depth. The following conditions were considered: the Moon and Sun elevation angles were close to 90°, and the reflection coefficient of the water column in the blue–green wavelength range was equal to 0.03. The spectral range of 1 nm was selected centered at a wavelength of 530 nm. The ranges of variations of k_{lf} and A were sufficiently wide. The fact has engaged our attention that whereas one has succeeded in detecting the layer of the enhanced transparency at very great depth for large A or small k_{lf}, the appearance of even small night illumination decreases the value h_1^m. At the same time, when the depth of detection is relatively small, the parameter $\bar{B}_i$ does not affect h_1^m for the wide range of its variation.

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