

*This work is dedicated to the memory of our colleagues —  
Maksim Anatolyevich Rodionov  
and Yuri Anatolyevich Goldin*

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### **Profiling lidars. Marine lidar survey results and future directions for scientific and applied implementation**

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#### **Abstract**

This paper reviews the principal results of recent studies conducted in Russian marine waters utilizing marine profiling lidars developed at the P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences (IO RAS) and its Saint Petersburg branch. Field experiments with IO RAS shipborne and airborne lidars were carried out in the coastal zones of the Barents, Kara, Okhotsk, and Black Seas, as well as in Avacha Bay in the Pacific Ocean, and focused on addressing contemporary problems of lidar remote sensing.

The use of marine lidars for the assessment of hydrooptical characteristics of the near-surface layer, the detection and parameterization of internal waves, and the investigation of the effect of survey-track length on bathymetric lidar mapping in remote high-relief coastal areas are examined. A distinctive feature of the IO RAS systems (shipborne PLD-1 and airborne APL-3) — is their two-channel receiving subsystem, which enables separate recording of the polarized components of lidar signals. The implementation of the developed digital signal-processing modules has permitted automation of the lidar-surveying workflow.

The scientific relevance and practical importance of these issues underline the need to advance domestic remote-sensing technologies, in particular for lidar surveys conducted from autonomous, unmanned underwater, surface, and aerial vehicles.

**Keywords:** radiometric lidar, profiling lidar, polarization lidar, hydrooptical characteristics, internal waves, bathymetry

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### **Радиометрические лидары. Результаты лидарного зондирования морских акваторий и перспективы применения для решения научных и прикладных задач**

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#### **Аннотация**

В работе представлен обзор основных результатов современных исследований в акваториях морей России, выполненных с использованием морских радиометрических лидаров, разработанных в Институте океанологии им. П.П. Ширшова РАН (ИО РАН) и его Санкт-Петербургском филиале. С лидарами ИО РАН с борта судна

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и авианосителя были проведены натурные исследования в прибрежных районах Баренцева, Карского, Охотского, Черного морей и Авачинского залива Тихого океана, направленные на решение актуальных задач лидарного зондирования.

Рассматриваются результаты применения морских лидаров для оценки гидрооптических характеристик приповерхностного слоя, регистрации внутренних волн и оценки их параметров, а также для исследования влияния протяженности трассы зондирования на проведение лидарной съемки рельефа дна в труднодоступных высокогорных прибрежных районах. Особенностью созданных в ИО РАН лидаров судового (ПЛД-1) и авиационного (АПЛ-3) базирования стало использование двухканальной приемной системы для регистрации поляризованных компонент лидарных эхо-сигналов. Применение разработанных модулей цифровой обработки информации позволило автоматизировать процесс лидарной съемки.

Актуальность и практическая значимость рассматриваемых задач определяет необходимость развития отечественных технологий в области дистанционного зондирования, в частности для использования в лидарной съемке автономных необитаемых подводных, надводных и воздушных аппаратов.

**Ключевые слова:** радиометрический лидар, профилирующий лидар, поляризационный лидар, гидрооптические характеристики, внутренние волны, батиметрия

## 1. Introduction

Currently, passive and active methods for ocean remote sensing are undergoing intensive development. Lidar sensing is a prominent active remote-sensing technique. Marine profiling lidars (or radiometric lidars) are used to record the time dependence of the backscattered signal power at the laser (unshifted) wavelength. This signal originates within the water column when it is probed by a short, high-power pulse of narrowly directed laser radiation. The most significant advantage of lidar methods over other remote-sensing techniques (such as acoustic or radar) is their ability to perform measurements across the air-water interface. Laser radiation in the blue-green spectral range propagates effectively through both air and the underwater segments of the sounding path, crossing the interface with relatively low losses. This enables the deployment of lidars on airborne platforms, vessels, and autonomous underwater vehicles (AUVs).

Profiling lidars are employed to investigate the spatial distribution of hydrooptical characteristics both depth-wise and along the carrier's trajectory, particularly for the identification and localization of various frontal zones [1–4]. Airborne lidars are utilized to study the distributions and parameters of subsurface layers with enhanced light scattering, which are typically associated with elevated concentrations of zoo- and phytoplankton [5–8]. In fisheries research, profiling lidars are applied to obtain quantitative assessments of pelagic fish biomass and to map the spatial distribution of fish concentrations [9–11]. A number of studies utilizing profiling lidars have demonstrated the fundamental feasibility of observing internal waves via lidar sensing [12–14]. A distinct and practically significant area of application is lidar bathymetric surveying of coastal marine areas. Currently, several bathymetric lidar systems have been developed and implemented as certified measurement instruments [15–17].

At present, scientific research in the field of profiling lidar sounding is being conducted by approximately a dozen research groups from the USA [1, 18], Austria [19], China [4, 8, 20], Russia [2, 3], and several other countries. Lidar technology is undergoing continuous advancement. However, a number of unresolved issues remain in the study of lidar sounding and its various applications. Key challenges include the development of algorithms for extracting information on the hydrooptical characteristics of the near-surface layer from lidar echo signals and the advancement of methods for the lidar registration of dynamic processes in near-surface layers, including internal waves in waters with different types of hydrooptical and hydrological stratification. Furthermore, investigation is required into how the amplitude and shape of echo signals reflected from water layers and the seabed depend on the lengths of the atmospheric and underwater segments of the sounding path during lidar bathymetric surveys.

The results of contemporary research on the hydrooptical characteristics of the near-surface layer, internal waves, as well as solutions for fisheries and laser bathymetry, are reflected in several scientific reviews [16, 18, 21, 22]. However, these publications do not sufficiently cover the contributions of Russian authors. At the Laboratory of Ocean and Atmosphere Optics of the St. Petersburg Branch of the Shirshov Institute of Oceanology of the Russian Academy of Sciences (SPbB IO RAS), in collaboration with colleagues from the Laboratory of Ocean Optics of the IO RAS, a lidar sensing research group was established. Since 2015, this group has developed a series of next-generation marine lidars [23–25]. Utilizing these lidars, measurements were conducted in

the Barents [26], Kara [3], Okhotsk [27], and Black [28] Seas, as well as in the Avacha Bay of the Pacific Ocean [25] and the Gulf of Finland in the Baltic Sea. A number of significant scientific results have been obtained, contributing substantially to the advancement of lidar sensing methods. The objective of the present work is to review the primary results of experimental research conducted in Russian seas by the lidar sensing group of the SPbB IO RAS and IO RAS using the developed marine lidars.

## 2. Design of profiling lidars

Most profiling lidars are constructed according to a standard configuration, which includes a pulsed laser transmitter, a laser power supply and cooling system, a receiving system, a lidar control unit, a signal digitization device, and a visualization unit with long-term measurement data recording [1, 21–23]. The deployment of a lidar on an airborne or shipborne platform imposes additional requirements on its performance characteristics. In the case of airborne deployment, high pulse energy is required due to energy losses over the extended atmospheric segment of the sounding path. Shipborne placement of a lidar above the water surface results in a reduced atmospheric path length (from 200–500 m to 4–15 m), an increased angle of sounding (due to the presence of wake foam near the vessel's hull), and a change in the survey regime; specifically, the reduction in carrier speed lowers the required pulse repetition frequency while increasing the duration of continuous measurement cycles.

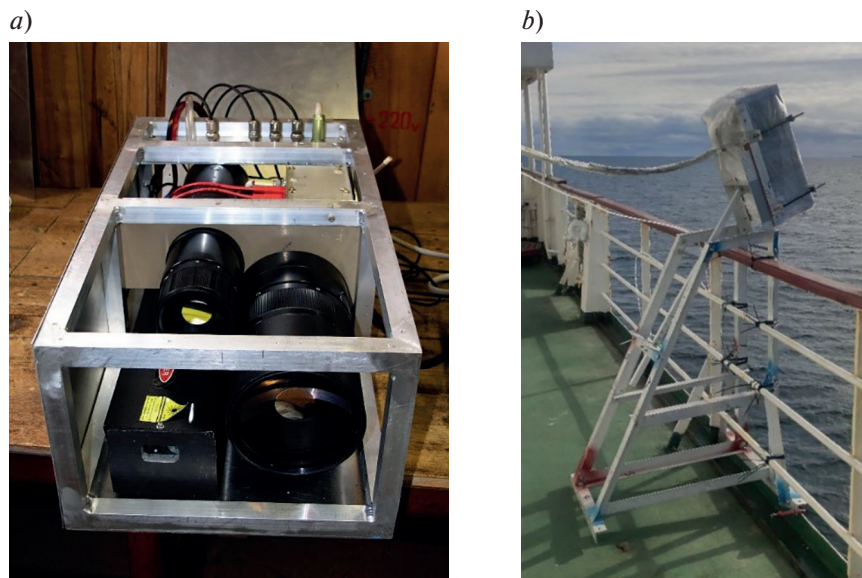
The performance characteristics of marine lidars utilized for practical bathymetric surveying differ from those of research-grade systems by higher pulse repetition frequencies, shorter pulse durations, and more stringent requirements for signal digitization [15, 29]. These specifications are dictated by the rigorous accuracy standards essential for bathymetric mapping. Typically, bathymetric lidars are certified as measuring instruments and are manufactured in small-scale production runs.

Researchers from the IO RAS lidar sounding group have designed and constructed prototypes of marine lidars for shipborne (PLD-1) [24] and airborne (APL-3) [25] platforms using modern component technology. The main technical specifications of these lidars are presented in Table. The systems feature dual-channel receiving units designed to record the co-polarized and cross-polarized components of the backscattered signal. Polarization selection is achieved using thin-film polarizers installed in front of the receiving objectives. Recording the temporal evolution of the polarization state of the lidar return signal provides crucial supplementary information, enabling a more comprehensive and accurate determination of the distribution of hydrooptical properties and inhomogeneities within the water column [1, 6, 7, 30, 31]. The external appearance of the lidars is shown in Figs. 1 and 2. Each lidar incorporates a custom-designed digital processing unit responsible for system control, echo-signal digitization, data logging to permanent storage, positioning, and real-time processing of sounding results directly during the survey. The lidars are characterized by relatively compact dimensions and low power consumption.

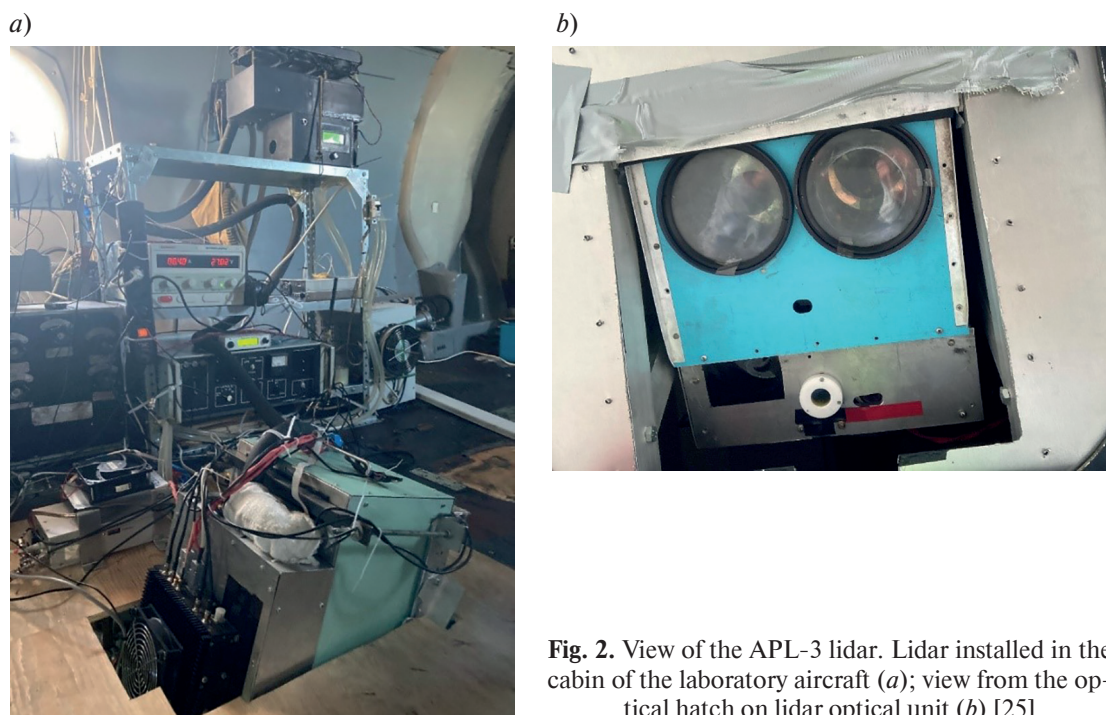
Table

**Main technical characteristics of the PLD-1 and APL-3 lidar systems**

| Characteristic                                                                                                     | PLD-1   | APL-3   |
|--------------------------------------------------------------------------------------------------------------------|---------|---------|
| Wavelength of the sounding radiation, nm                                                                           | 532     | 532     |
| Duration of the sounding pulse, ns                                                                                 | 7       | 7       |
| Energy of the sounding pulse, mJ                                                                                   | 20      | 45      |
| Sounding frequency, Hz                                                                                             | 1       | 1–30    |
| Divergence of the sounding beam $\gamma_L$ , mrad                                                                  | 5       | 5       |
| Field of view angle of the receiving optical system of the co-polarized channel $2\gamma_{co}$ , deg. (mrad)       | 2 (35)  | 2 (35)  |
| Diameter of the input objective of the co-polarized channel, mm                                                    | 63      | 100     |
| Field of view angle of the receiving optical system of the cross-polarized channel $2\gamma_{cross}$ , deg. (mrad) | 2 (35)  | 2 (35)  |
| Diameter of the input objective of the cross-polarized channel, mm                                                 | 100     | 100     |
| ADC bit depth, bits                                                                                                | 14      | 14      |
| Digitization frequency of lidar echo signals, GHz                                                                  | 2.5     | 1.3     |
| Operating supply voltage, V                                                                                        | 220, AC | +27, DC |



**Fig. 1.** View of the PLD-1 lidar — optical unit of the PLD-1 lidar (a), optical unit of the lidar mounted on the pointing device (b) [3]



**Fig. 2.** View of the APL-3 lidar. Lidar installed in the cabin of the laboratory aircraft (a); view from the optical hatch on lidar optical unit (b) [25]

### 3. Application of lidar systems for solving oceanological problems

#### 3.1. Measurement of the hydrooptical characteristics of the near-surface layer

The lidar signal contains information regarding the inherent optical properties of seawater. Several approaches exist for developing methods to extract this data. One such approach involves designing the sounding configuration so that a specific parameter of the lidar return signal depends solely on a single hydrooptical characteristic [1, 2, 4]. For instance, when using sufficiently large fields of view in shipborne lidar receiving

systems ( $2\gamma \sim 15^\circ\text{--}20^\circ$ ), the lidar attenuation coefficient  $\alpha$  numerically approaches the absorption coefficient of seawater  $a$  [1, 4]. However, at such wide angles, information concerning the inhomogeneities in the vertical distribution of hydrooptical characteristics becomes blurred.

Another research direction involves the application of radiometric lidars employing a “classic” configuration with a sufficiently narrow field of view for the receiving system, coupled with the establishment of regression relationships between lidar signal parameters and hydrooptical characteristics [3]. A drawback of this method is the applicability of the derived regression relationships exclusively to the specific sounding configuration employed. In studies [1, 3], regression dependencies have been identified between lidar signal parameters and hydrooptical characteristics for the co-polarized component of the echo signal, or without accounting for the polarization of the received radiation. Of particular interest is the identification of such regression dependencies for both orthogonally polarized components of the lidar signal, along with the detection of potential features introduced by polarization considerations. Such investigations were conducted during the first stage of the 89th cruise of the R/V “Akademik Mstislav Keldysh” in the western part of the Kara Sea from September 5 to 19, 2022 [26]. Hydrooptical characteristics in the study area exhibited wide variability: the seawater beam attenuation coefficient  $c$  ranged from  $0.17\text{ m}^{-1}$  to  $1.1\text{ m}^{-1}$ , the absorption coefficient  $a$  from  $0.10\text{ m}^{-1}$  to  $0.20\text{ m}^{-1}$ , and the single-scattering albedo  $\omega_0$  from 0.38 to 0.84. The investigations utilized the shipborne polarization lidar PLD-1 (Table). Lidar sounding was accompanied by a suite of auxiliary measurements conducted both at stations and underway.

An analysis of the array of co- and cross-polarized components of lidar signals recorded in waters of varying clarity revealed that, in both instances, the decay of the cross-polarized component is more gradual than that of the co-polarized component [32]. This phenomenon is particularly pronounced in turbid waters. The decay of the lidar signal in vertically homogeneous waters is governed by two processes: the attenuation of the sounding radiation attributed to absorption and scattering during its propagation from the surface to a given depth and back, and the depolarization process, which facilitates the transfer of light from one polarized component to another during scattering. Depolarization within the water column occurs due to single scattering by non-spherical particles as well as multiple scattering. While the impact of attenuation within the water column is identical for both orthogonally polarized components, the influence of depolarization differs significantly along the initial segments of the sounding path. This discrepancy is linked to the difference in the amplitudes of the co- and cross-polarized components of the return signal. In clear waters, the degree of return signal depolarization  $g(t)$  at depths of 20–30 m ranges from 0.8 to 0.9 [7]. Consequently, as a first approximation, the depolarization process can be neglected when characterizing the initial decay segment of the co-polarized component, allowing its shape to be described by an approximation function derived from the lidar equation. The lidar equation in the quasi-single scattering approximation, as presented, for example, in [23, 33, 34], is expressed as:

$$P\left(t = \frac{2Z}{c_w}\right) = \frac{c_w W_0 A T_O (1-r)^2}{2(nH + Z)^2} \beta'(\pi, Z) \exp\left[-2 \int_0^Z \alpha(Z') dZ'\right], \quad (1)$$

where  $Z$  and  $H$  are the lengths of the underwater and atmosphere sections of the sounding path,  $c_w$  is the speed of light in seawater,  $n$  is the refractive index of seawater,  $W_0$  is the energy of the sounding pulse,  $A$  is the area of the receiving aperture,  $T_O$  is the transmission coefficient of the receiving system,  $r \approx 0.02$  is the Fresnel reflection coefficient for the air-sea water boundary,  $\alpha(Z)$  is the lidar attenuation coefficient,  $\beta'(\pi, Z)$  is the effective value of volume scattering function  $\beta(\theta, Z)$  in backward direction at the scattering angle  $\theta = 180^\circ$ . The true depth  $z$  can be recalculated from  $Z$  taking into account the sounding angle  $\varphi$ . The time  $t$  is measured from the moment the water surface is crossed by the sounding pulse.

In the case of vertically homogeneous distributions of hydrooptical characteristics, the approximating function for the co-polarized component of the echo signal takes the form:

$$P_{\text{co}}\left(t = \frac{2Z}{c_w}\right) = \frac{A}{(nH + Z)^2} \exp(-2\alpha_{\text{co}}Z), \quad (2)$$

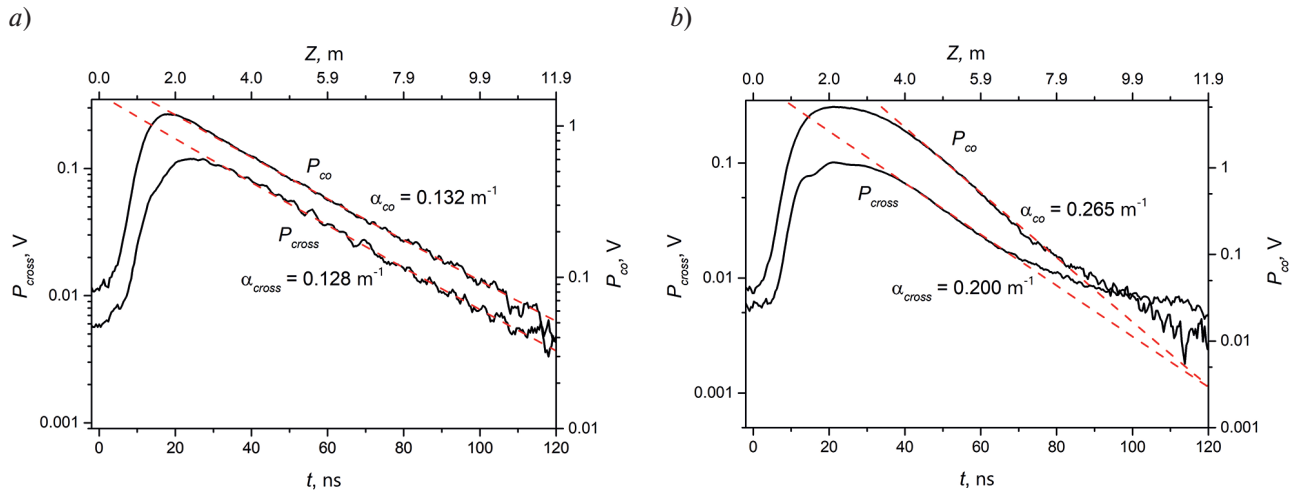
where  $\alpha_{\text{co}}$  is the attenuation coefficient of the co-polarized echo signal component, and  $A$  is the depth-independent approximation coefficient.

For the formation of the initial segments of the decay of the cross-polarized component, the contribution of the depolarization process is substantial. Therefore, strictly speaking, it is not permissible to use the lidar Eq. (1) to describe it. At the same time, the analysis of a large number of experimental data obtained during the study showed that on short initial segments of the echo signal decay, similar approximating functions of the form (2) with the lidar echo signal attenuation coefficient  $\alpha_{\text{cross}}$  describe the shape of the decay of the cross-polarized component with sufficient accuracy:

$$P_{\text{cross}} \left( t = \frac{2Z}{c_w} \right) = \frac{B}{(nH + Z)^2} \exp(-2\alpha_{\text{cross}} Z), \quad (3)$$

where  $B$  is the depth-independent approximation coefficient.

The appearance of co- and cross-polarized components of lidar echo signals recorded in waters of varying transparency is presented in Fig. 3. Dashed lines indicate the approximating functions of the form (2) and (3). These approximating functions accurately describe the shape of the decay of the polarized echo signal components and enable the determination of the values of  $\alpha_{\text{co}}$  and  $\alpha_{\text{cross}}$ , which characterize the decay rate.



**Fig. 3.** The examples of co- and cross-polarized components of the echo signal recorded in waters with varying transparency and the corresponding approximation functions:  $a - c = 0.17 \text{ m}^{-1}$ ,  $b - c = 1.1 \text{ m}^{-1}$  [32]

Upon processing the lidar survey data, the value of  $\alpha$  was determined for each recorded echo signal. The thus obtained values of  $\alpha_{\text{co}}$  and  $\alpha_{\text{cross}}$  were employed to establish regression relationships between these quantities and various hydrooptical characteristics. In the case of transparent waters (Fig. 3a), characterized by a seawater beam attenuation coefficient  $c = 0.17 \text{ m}^{-1}$ , the values of  $\alpha_{\text{co}}$  and  $\alpha_{\text{cross}}$  are close to each other, indicating a relatively minor contribution of the depolarization process to the formation of the polarized components. With an increase in the scattering coefficient  $b$ , the differences in the shapes of the echo signal decays become more pronounced. For turbid waters, characterized by a seawater beam attenuation coefficient  $c = 1.1 \text{ m}^{-1}$ , the values of  $\alpha_{\text{co}}$  and  $\alpha_{\text{cross}}$  exhibit noticeable divergence (Fig. 3b), signifying a substantial contribution of the depolarization process to the formation of the polarized echo signal components. The dependence of the ratio  $\alpha_{\text{co}}/\alpha_{\text{cross}}$  on  $c$  is presented in Fig. 4, with the points color-coded by the single scattering albedo  $\omega_0$ . A dashed line represents the linear approximation of the obtained data, yielding a coefficient of determination  $R^2 = 0.78$ . The comparison of  $c$  and  $\omega_0$  reveals that the increase in the seawater beam attenuation coefficient  $c$  is primarily driven by the rise in the scattering coefficient  $b$ . This increase leads to enhanced contribution from multiple scattering and, consequently, the depolarization process in shaping the cross-polarized echo signal component. As evident from the plot in Fig. 4, the ratio  $\alpha_{\text{co}}/\alpha_{\text{cross}}$  monotonically increases with  $c$  and reaches values of 1.3–1.4 in relatively turbid waters.

Figure 5 presents scatter plots of the values of  $\alpha_{\text{co}}$ ,  $\alpha_{\text{cross}}$  versus  $c$ . Solid lines indicate the approximation functions, while dashed lines denote the 95 % confidence intervals. The figure demonstrates a linear

relationship between  $\alpha_{co}$  and  $c$ , with a coefficient of determination  $R^2 = 0.95$ . For the cross-polarized component, at values of  $c > 0.8 \text{ m}^{-1}$ , a deviation from linear approximation is observed ( $R^2 = 0.75$ ). This deviation becomes particularly pronounced at  $c > 1.0 \text{ m}^{-1}$ . This may be attributed to the increasing contribution of the depolarization process to the formation of the cross-polarized component. The magnitude of this contribution is governed by multiple scattering, primarily double scattering, whose probability is proportional to  $b^2$  [35]. Employing a second-degree polynomial as the approximation function provides a substantially better description of the  $\alpha_{cross}$  dependence on  $c$  ( $R^2 = 0.88$ ). The issue of the interplay between attenuation and depolarization processes in shaping the cross-polarized echo signal component warrants further investigation.

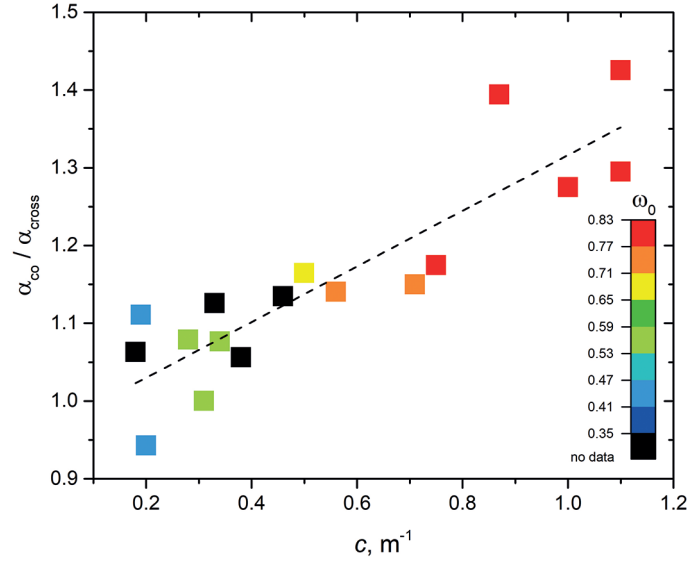


Fig. 4. The relationship between the ratio  $\alpha_{co}/\alpha_{cross}$  and  $c$ . The color of the points indicates the values of  $\omega_0$  [32]

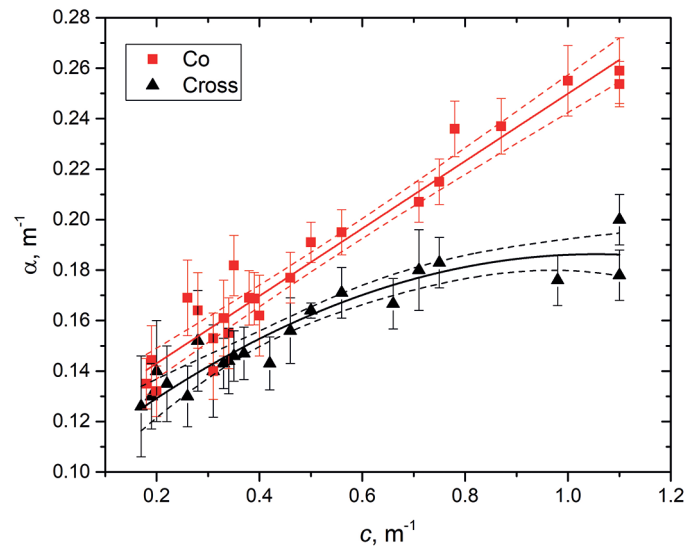


Fig. 5. Correspondence diagram of  $\alpha_{co}$ ,  $\alpha_{cross}$  and  $c$ . Approximation functions are shown with solid lines, and 95 % confidence intervals are indicated by dashed lines [32]

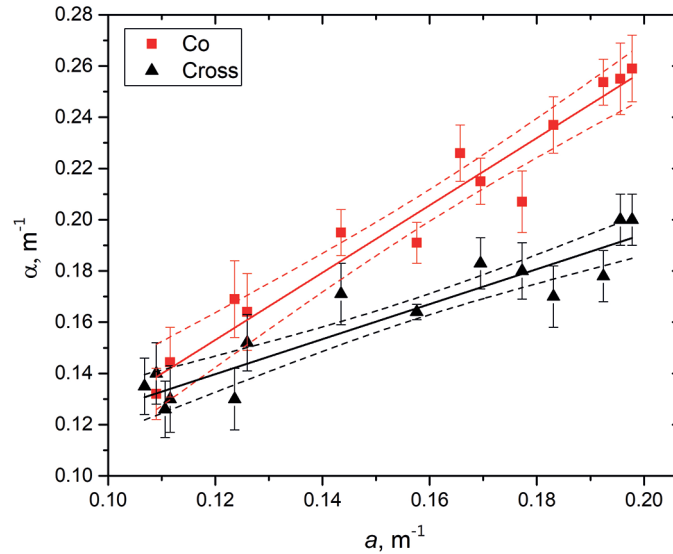
Based on the functional dependencies shown in Fig. 5, regression equations have been derived for the co- and cross-polarized components, enabling estimation of  $c$  from the values of  $\alpha_{co}$  and  $\alpha_{cross}$ . As reported in [32], these equations take the form:

$$c_L^{co} = 7.10 \cdot \alpha_{co} - 0.81; \quad (4)$$

$$c_L^{cross} = 62.71 \cdot \alpha_{cross}^2 - 6.93 \cdot \alpha_{cross} + 0.034, \quad (5)$$

where  $c_L$  represents the seawater beam attenuation coefficient calculated from lidar sounding data. The precision of the regression coefficients determined by the least squares method is  $7.10 \pm 0.37$  and  $0.81 \text{ m}^{-1} \pm \pm 0.07 \text{ m}^{-1}$  for co-polarization, and  $62.71 \pm 3.34 \text{ m}$ ,  $6.93 \pm 0.63$  и  $0.034 \text{ m}^{-1} \pm 0.001 \text{ m}^{-1}$  for cross-polarization. The relative error in determining  $c$  from lidar data is 10 % for the co-polarized component and 12 % for the cross-polarized component. The derived regression relationships are valid over an attenuation coefficient range from  $0.17 \text{ m}^{-1}$  to  $1.1 \text{ m}^{-1}$ .

Correspondence diagrams of  $\alpha_{co}$ ,  $\alpha_{cross}$  values and the absorption coefficient  $a$  are presented in Fig. 6. The figure demonstrates a linear relationship between  $\alpha_{co}$ , and  $a$  ( $R^2 = 0.95$ ) and between  $\alpha_{cross}$  and  $a$  ( $R^2 = 0.88$ ).



**Fig. 6.** Correspondence diagram of  $\alpha_{co}$ ,  $\alpha_{cross}$  and  $a$ . Approximation functions are shown with solid lines, and 95 % confidence intervals are indicated by dashed lines [32]

The regression equations for the co- and cross-polarized components, which allow for the estimation of the absorption coefficient  $a$  from the values of  $\alpha_{co}$  and  $\alpha_{cross}$  as presented in [32], are as follows:

$$a_L^{co} = 0.74 \cdot \alpha_{co} + 0.008, \quad (6)$$

$$a_L^{cross} = 1.28 \cdot \alpha_{cross} - 0.06, \quad (7)$$

where  $a_L$  is the light absorption coefficient calculated from lidar sounding data. The precision of the regression coefficients determined by the least squares method is  $0.74 \pm 0.05$  и  $0.008 \text{ m}^{-1} \pm 0.001 \text{ m}^{-1}$  for the co-polarization, and  $1.28 \pm 0.14$  and  $0.06 \text{ m}^{-1} \pm 0.01 \text{ m}^{-1}$  for the cross-polarization. The relative error in determining the absorption coefficient  $a$  from lidar sounding data is 10 % for the co-polarized component and 12 % for the cross-polarized component.

Regression Eqs. (4) and (5) allow for the conversion of spatial distributions of  $\alpha$ , obtained from lidar surveys along the vessel's route, into spatial distributions of the seawater beam attenuation coefficient  $c$ . The distribu-

tions of hydrooptical and hydrological characteristics obtained along one of the transects are shown in Fig. 7. The transect between the stations was performed in the northwestern tip of the Yamal Peninsula in waters influenced by desalinated river runoff, which is manifested by a decrease in salinity and the presence of several frontal zones.

A comparison of the spatial distributions of  $c_{co}$ ,  $c_{cross}$ , and the seawater beam attenuation coefficient values  $c_{ft}$  measured using the flow-through system of the IO RAS [36] along the considered transect is shown in Fig. 7a. The corresponding distributions of salinity  $S$ , temperature  $T$ , and fluorescence intensity of colored dissolved organic matter (CDOM)  $I_{CDOM}$  are presented in Fig. 7b. Red triangles in Fig. 7a denote the values of  $c$  recorded by a transmissometer at the stations within the 2–3 m and 4–8 m layers. At the beginning of the transect, the values of  $c$  in these layers coincide, while at the end, they differ slightly. At the station located at the beginning of the transect, an absorption coefficient value of  $a = 0.15 \text{ m}^{-1}$  ( $\omega_0 = 0.63$ ) was recorded at a depth of 5 m; at the end of the transect, at the same depth,  $a = 0.24 \text{ m}^{-1}$  (the  $\omega_0$  value corresponding to  $c_p = 1.0 \text{ m}^{-1}$  was 0.76). Two frontal divisions were recorded along the transect, where the value of  $c$  increases first from  $0.35 \text{ m}^{-1}$  to  $0.70 \text{ m}^{-1}$ , and then from  $0.70 \text{ m}^{-1}$  to  $1.25 \text{ m}^{-1}$ . The lidar survey data accurately reflect the positions of these fronts. The observed discrepancies between the values of  $c_{co}$  and  $c_{ft}$ , as well as  $c_{cross}$  and  $c_{ft}$ , are approximately 10 % of the measured quantities, which falls within the established error margin of the regression dependencies used. Each front corresponds to a decrease in salinity  $S$  and an increase in the CDOM fluorescence intensity signal  $I_{CDOM}$ . A negative correlation is observed in the distribution of these variables. As shown in [37], the presence of a negative correlation between  $S$  and  $I_{CDOM}$  serves as an indicator of the influence of river runoff.

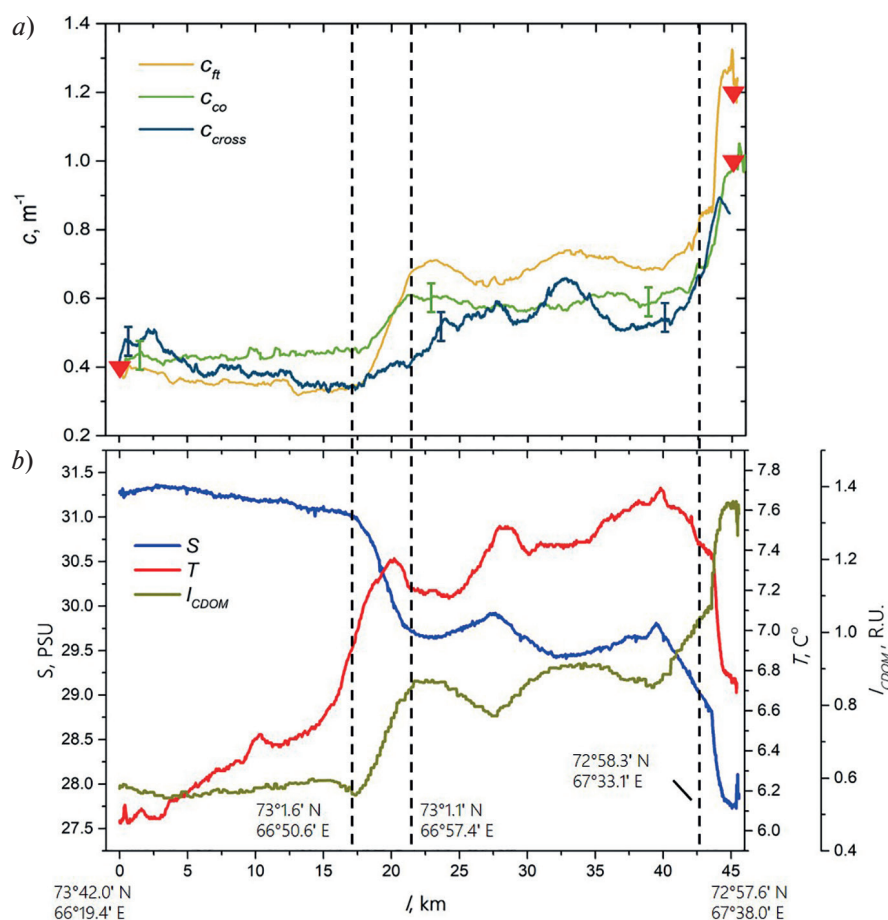


Fig. 7. Spatial distributions of  $c_{co}$ ,  $c_{cross}$  и  $c_{ft}$ (a); salinity  $S$ , temperature  $T$ , and CDOM fluorescence intensity  $I_{CDOM}$  (b) along the transect between stations [38]

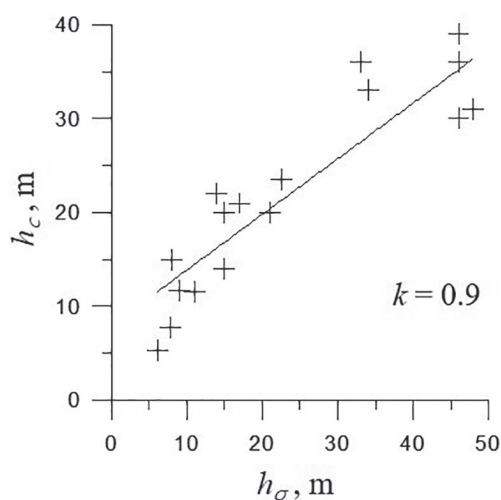
The established regression relationships enable the use of lidar survey data, acquired underway from a moving vessel or aircraft carrier, for assessing the spatial distributions of hydrooptical characteristics. Due to the high spatial resolution, it becomes possible to perform detailed registration of variability in bio-optical fields and to promptly detect frontal zones characterized by high spatial gradients of hydrooptical characteristics. The obtained data can be utilized to identify sub- and mesoscale inhomogeneities in the near-surface layer of seawater, as well as to address tasks of operational monitoring of marine waters.

An important direction for further research in the field of lidar registration of hydrooptical characteristics is the expansion of the applicability range of regression relationships. In the course of continued studies, it is necessary to conduct lidar surveys of various marine waters differing in hydrooptical characteristic values (primarily  $c$  and  $\omega_0$ ), for example, areas subject to significant desalination processes or regions characterized by oceanic waters with high transparency and elevated salinity values. The specific features of waters in such regions may necessitate certain corrections to the obtained regression relationships. It would also be of interest to conduct studies varying the lidar technical characteristics, primarily the field-of-view angle of the receiving optical system. Its reduction would allow an increase in the  $\alpha/c$  ratio and, accordingly, a reduction in the errors of  $c$  determination by the lidar method. An increase in the field-of-view angle, in turn, would enable approaching unity for the  $\alpha/a$  ratio.

### 3.2. Observation of internal waves

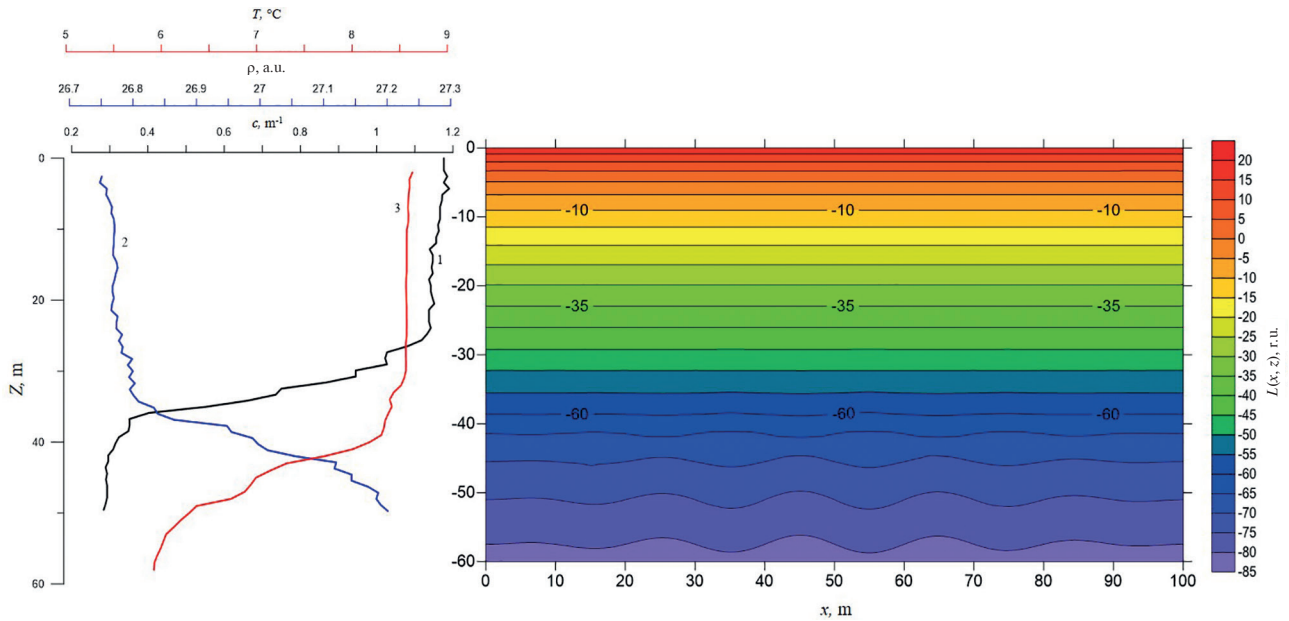
Lidar registration of vertical profiles of hydrooptical characteristics enables the observation of internal waves and the assessment of their parameters. For a number of Russian seas (White Sea, coastal areas of the Barents Sea, Kara Sea), researchers from the Laboratory of Ocean and Atmospheric Optics of the St. Petersburg Branch of the Shirshov Institute of Oceanology RAS, using a specially developed transmissometer [39], conducted large-scale studies of the variability of hydrological and hydrooptical characteristics [40], aimed at establishing correlational relationships between these distributions. From 2006 to 2010, during 10 expeditions, more than 400 joint measurements of hydrological and hydrooptical characteristics were performed — in the central and southeastern parts of the Barents Sea, approximately 150 measurements; in the White Sea — about 200; in the southwestern part of the Kara Sea and the Kara Gates Strait — about 70 [40]. Figure 8 shows a correspondence diagram of the pycnocline depth values  $h_\sigma$  and the depth of the layer with the maximum vertical gradient of the seawater beam attenuation coefficient  $h_c$  (based on measurement data from coastal areas of the Barents Sea, 2010). Based on these measurements, a high correlation was revealed between the horizon of the maximum gradient of the seawater beam attenuation coefficient and the pycnocline depth (correlation coefficient equal to 0.9) [41]. The presence of such correlations allows estimating the pycnocline depth from lidar sounding data, and, with appropriate organization of lidar surveys, registering internal waves and assessing their characteristics.

Theoretical studies of lidar images of internal waves under different types of stratification were conducted in [42, 43]. Based on the obtained relationships for real stratifications of hydrological and hydrooptical characteristics observed in experiments, lidar images of internal waves were constructed [44]. A lidar image is defined as a two-dimensional map of the quantitative assessment of the power of the lidar echo-signal  $P$  as a function of the horizontal coordinate of the



**Fig. 8.** Diagram of the correspondence between pycnocline depth values  $h_\sigma$  and the depth of the layer with the maximum gradient of the seawater beam attenuation coefficient  $h_c$  [41]

lidar position  $x$  and the depth  $z$  from which the signal arrives [42]. To form a lidar image, a model density profile  $\rho(z)$  and the corresponding seawater beam attenuation coefficient profile  $c(z)$  are specified. Variations of the profiles under the influence of an internal wave are implemented using a periodic function with parameters calculated for the given stratification  $\rho(z)$ . Figure 9 presents profiles of vertical distributions of temperature, density, and  $c(z)$ , along with a lidar image of an internal wave in the form of contour lines of the quantity  $L(x, z) = 10\log P(x, z)$  ( $P$  – echo-signal power in watts), corresponding to the stratification of the specified characteristics. It is evident that at depths below the pycnocline layer, periodic changes in the power of the lidar echo-signal are observed.



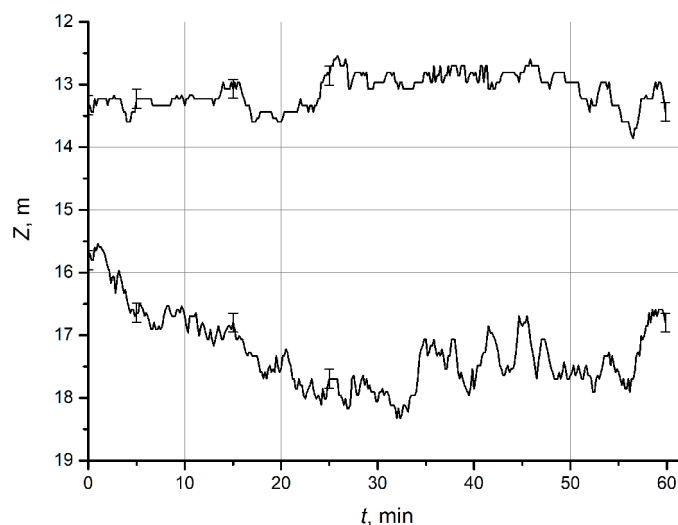
**Fig. 9.** Profiles of the vertical distributions of temperature, density and seawater beam attenuation coefficient (*left*) and the lidar image of the internal wave corresponding to the stratification of the specified parameters (*right*) [44]

The theoretical studies considered above indicate that the observation of internal waves using the lidar method is feasible under various stratifications of hydrological and hydrooptical characteristics. In this regard, particular interest is presented by research aimed at the experimental investigation of the applicability of marine lidars for registering internal waves in various seas under different conditions, as well as solving inverse problems to assess their characteristics.

In the case of the most common two-layer stratification of hydrooptical and hydrological characteristics, an approximation approach [14] can be employed to determine the position of the boundary between layers. This approach is based on the use of analytical approximation functions of the form of the lidar Eq. (1) to describe the shape of the lidar echo signal. Another method of processing lidar sounding data is based on spectral analysis of changes in the amplitudes of echo signals at a fixed depth, which carries information about the backscattering coefficient value. In this case, the analysis of lidar sounding data represents the task of detecting quasi-periodic changes in the backscattering signal amplitude at specified horizons. The application of wavelet analysis, in contrast to the Fourier transform, enables not only the detection of periodic processes within a given frequency interval but also the identification of their temporal positions.

In [45], to record quasi-periodic processes occurring in the near-surface layer of seawater and to determine their parameters using marine lidars, an integrated use of approximation functions and wavelet analysis is proposed. When processing large volumes of lidar sounding data, it is suggested that an initial rapid analysis be carried out using wavelet methods, while detailed processing based on approximation functions should be performed only for those survey segments in which quasi-periodic processes are detected. This approach makes it possible to obtain the most comprehensive information in a relatively short time.

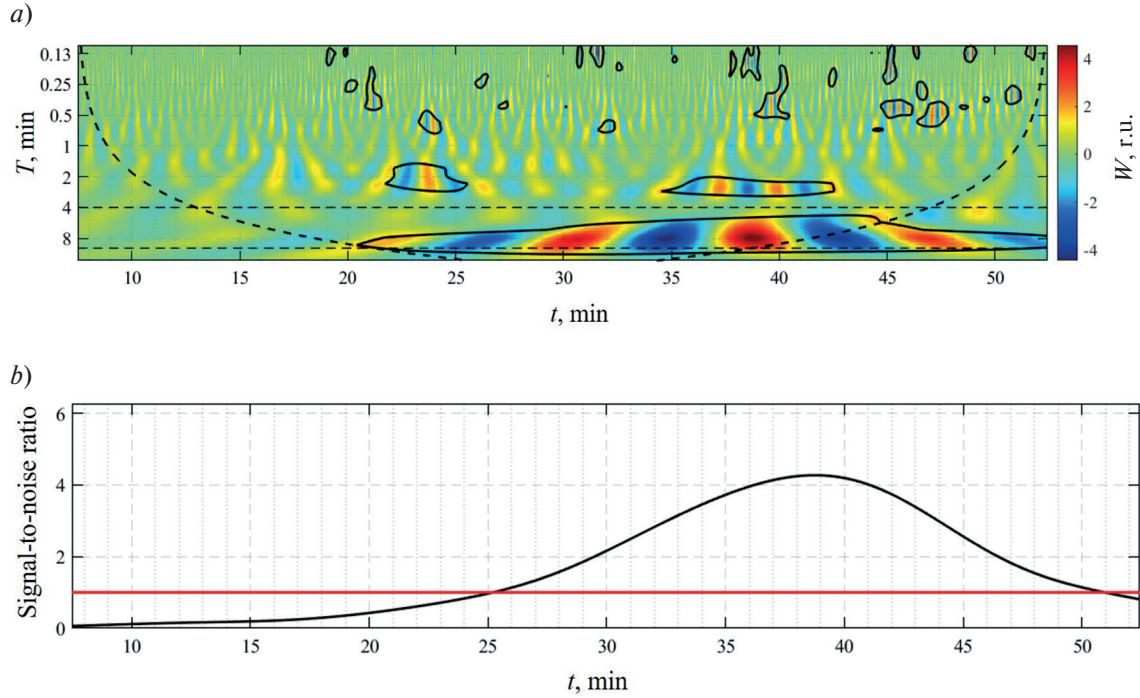
Using this integrated approach, shipborne lidar survey data acquired in coastal areas of the Black Sea near the eastern coast of the Crimean Peninsula were processed. Figures 10–12 present the results of processing one of the survey records. The results obtained using the approximation functions are shown in Fig. 10. The upper curve corresponds to the position of the upper boundary of the layer characterized by a high vertical gradient of the seawater beam attenuation coefficient, whereas the lower curve corresponds to its lower boundary. The processing results indicate that the position of the upper layer boundary remains nearly constant over the entire transect, while a clearly pronounced periodic structure is observed at the lower boundary. The mean oscillation period is 5 min, with an amplitude on the order of 1 m.



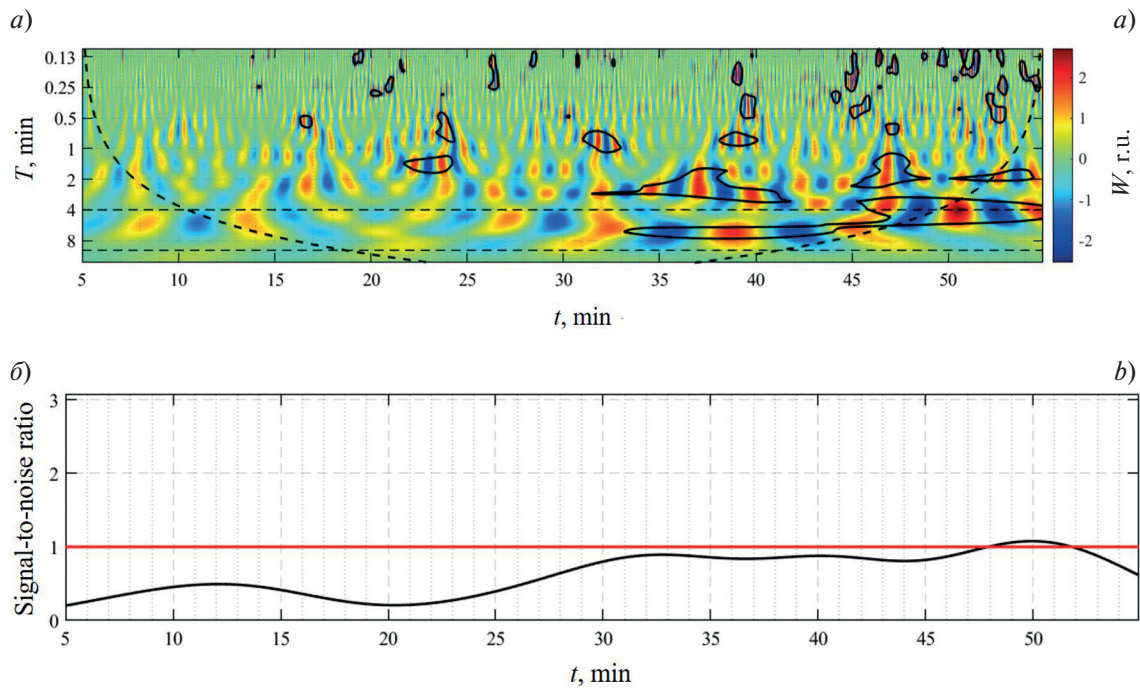
**Fig. 10.** Positions of the upper and lower boundaries of the studied layer obtained from processing using approximating functions [45]

Wavelet analysis of the considered lidar sounding data was performed for the depth range from 14 m to 24 m with a step of 1 m as a function of time at a fixed depth. The most distinct result was obtained for a depth of 17 m, which is close to the thermocline position. The result of the wavelet analysis for this horizon is shown in Fig. 11. Figure 11a graphically presents the local wavelet transform coefficients: the abscissa represents the recording time of the lidar echo-signal series, and the ordinate represents the period. All characteristic features of the process are visible — the scale and intensity of periodic changes in the lidar echo signal amplitude at a given depth, as well as the presence, location, and duration of regions corresponding to elevated wavelet coefficient values. The solid black line highlights statistically significant segments of the signal with a 95 % confidence level relative to the background red noise. In the lower right part of the figure, a statistically significant signal segment is distinguished with a central period of 6 min and a duration of approximately 30 min. This indicates the presence of a quasi-periodic process with the corresponding characteristics, manifested as a change in the amplitude of lidar echo-signals at the specified depth. From the 25<sup>th</sup> to the 50<sup>th</sup> minute, the values of the global wavelet power spectrum exceed the power of the red noise, confirming the significance of the oscillations within this time interval.

The results of the wavelet analysis for the lidar echo signal amplitude samples obtained from a depth of 14 m are shown in Fig. 12. Oscillations within the considered range of periods are also evident at this depth; however, the calculation of the power spectrum averaged over time scales from 4 to 8 min, as shown in Fig. 12b, allows for an assessment of the significance of these oscillations. Throughout almost the entire transect, the averaged power spectrum remains below unity, indicating that although these signals exhibit some periodicity, their statistical significance is low. This result is consistent with the behavior of the upper boundary of the investigated layer, the position of which was determined using the approximation method (Fig. 10). Certain discrepancies in the location and periods of the identified oscillations are due to non-strict periodicity and a limited number of cycles, which complicates the spectral analysis.



**Fig. 11.** Results of processing of echo signal amplitudes from a fixed depth of 17 m using wavelet analysis: *a* — amplitudes of the wavelet transform coefficients; *b* — scale-averaged wavelet power spectrum, normalized to the 95 % significance level relative to the background brown noise [45]



**Fig. 12.** Results of processing of echo signal amplitudes from a fixed depth of 14 m using wavelet analysis: *a* — amplitudes of the wavelet transform coefficients; *b* — scale-averaged wavelet power spectrum, normalized to the 95 % significance level relative to the background brown noise [45]

The parameters of internal waves in the fields of hydrooptical and hydrological characteristics are determined by the gradients of the corresponding quantities. Internal waves detected by the lidar method during the conducted experiments were characterized by amplitudes of 1–2 m and temporal periods ranging from several to the first tens of minutes. In the future, it is of interest to assess the feasibility of observation internal waves using the lidar method in waters with various hydrological and hydrooptical characteristics and different types of stratification.

The application of the proposed integrated approach for processing airborne lidar survey data appears promising, as it offers several advantages, including high efficiency and the ability to obtain a nearly instantaneous snapshot of dynamic processes occurring in the near-surface layer of seawater. Utilizing marine lidars from moving shipborne and airborne carriers, as well as from stationary offshore platforms and anchored or free-drifting buoys, will provide new information regarding the spatio-temporal structure of internal waves across different scales. Integrating a lidar channel into systems for the operational recording of sub- and meso-scale processes will help identify the specific manifestations of internal waves within the fields of hydrooptical characteristics.

### 3.3. Lidar bathymetry

Laser bathymetry represents the most advanced branch of lidar sounding. A number of lidar bathymetric systems have been developed and certified as measurement instruments [15–17, 19, 46, 47]. Such systems are employed for registering variations in the bottom depth of shallow coastal marine waters, monitoring fairway conditions, as well as investigating the bottoms of inland water bodies and rivers [19, 47]. In bathymetric lidars, the bottom depth  $z_b$  is determined by measuring the time difference between the reception of pulses formed by elastic scattering from the water surface and from the bottom.

The lidar sounding path comprises atmospheric and underwater segments. Typically, during lidar surveys, the lidar altitude is fixed, resulting in a scarcity of experimental data on the dependence of survey results on altitude. Nevertheless, the extent of the atmospheric segment substantially influences the amplitude and shape of the lidar echo signal decay. In studies [48, 49], utilizing an analytical solution to the radiative transfer equation in the small-angle approximation, the impact of the sounding path length on the magnitude of the bottom-reflected echo signal was investigated. The dependencies of the amplitudes of echo-signals reflected from the surface, water column, and sea bottom on the sounding path length, derived from calculations [48, 49], deviate from the conventional inverse quadratic dependence and exhibit a more complex character.

In study [50], experimental results were presented for the first time regarding the dependence of the amplitude and shape of echo-signals reflected from water layers and the bottom on the lengths of the atmospheric and underwater segments of the sounding path. Measurements were conducted using the airborne polarization lidar APL-3 (Table). Field experiments took place in August 2018 in the vicinity of Bechvinskaya Bay, Avacha Bay, Kamchatka Peninsula. The bay is surrounded by mountains approximately 1 km in height. During the bathymetric survey, four aircraft runs were performed at flight altitudes of 500, 700, 900, and 1200 m. The bay bottom is characterized by variable depths, enabling the acquisition of lidar echo signals corresponding to bottom depths ranging from 3 to 22 m over a relatively small water area [25].

The dependence of the echo-signal power  $P$  on the sounding path length in the lidar Eq. (1) is determined by the so-called geometric factor  $(nH + Z)^{-2}$ . Equation (1) is formulated under the assumption of single back-scattering. It is also assumed that the receiver field-of-view angle is much larger than the initial laser-beam divergence,  $\theta_1^2 \ll \theta_2^2$ , and sufficiently large to collect all radiation reflected from the water layer at the corresponding depth. Under field conditions, however, owing to multiple scattering along the path from the water surface to the target layer and back, this assumption is not always satisfied. A more general expression is therefore required for the case in which the laser spot at the depth of the studied layer is not fully encompassed by the angular field of view of the photodetector. An expression meeting this requirement is given in [51] as follows:

$$P(Z) = \frac{(c_w W_0 / 4\pi n_w^2) A \theta_2^2 T_0 (1-r)^2}{\theta_2^2 (H + Z / n_w)^2 + 2D(Z)} \cdot b_b(Z) \cdot \exp\left(-2 \int_0^Z \alpha(z) dz\right), \quad (8)$$

$$D(Z) = \frac{2}{q^2} \int_0^Z b_f(z)(Z-z)^2 dz, \quad (9)$$

where  $2\theta_2$  is the photodetector's field-of-view angle;  $b_b(Z) = 2\pi\beta'(\pi, Z)$  is the backscattering coefficient;  $\alpha(Z) = a(Z) + 2b_b(Z)$ ,  $a(Z)$  is the absorption coefficient;  $D(Z)$  is the variance of the irradiance distribution in the cross-section of an infinitely narrow light beam after propagating through a water layer of thickness  $Z$ ;  $b_f(Z) = b(Z) - 2b_b(Z)$  is the forward scattering coefficient, with  $b(Z)$  being the total scattering coefficient;  $q$  is the parameter of the forward section of the scattering phase function, which defined as:

$$x_f(\theta) = \frac{2q}{\theta} \exp(-q\theta). \quad (10)$$

Equation (8) differs from Eq. (1) by the presence of the term  $2D(Z)$ , which accounts for the broadening of the effective radiation patterns of the transmitter and receiver due to forward multiple scattering of light during its two-way passage through a water layer of thickness  $Z$ . For  $b_1 = \text{const}$ , the function  $D(Z)$  can be expressed as:

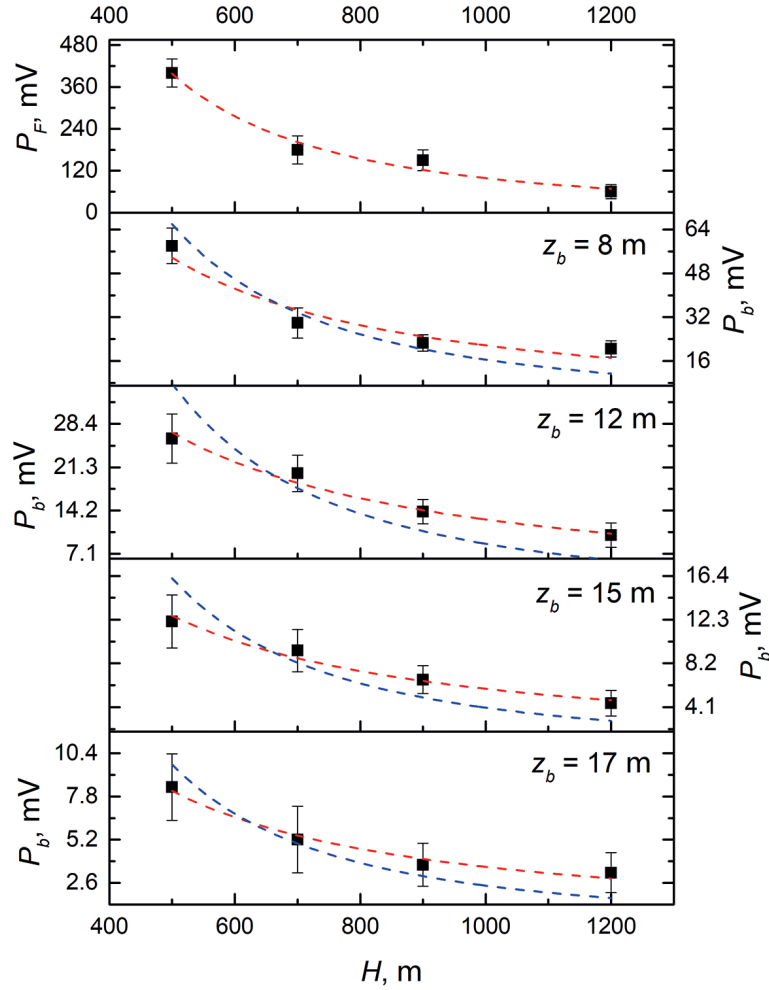
$$D(Z) = \frac{2}{3q^2} b_1 Z^3. \quad (11)$$

The *in situ* measurement dataset acquired in the waters of Bechevinskaya Bay makes it possible to assess the applicability of the lidar equation formulations based on Eqs. (1) and (8) for describing the backscattered signal power from the seabed and from the water column at a prescribed depth. The processing of the bathymetric lidar data was performed using the standard method employed in bathymetric surveys [15]. The analysis used the lidar echo-signal amplitude values recorded for bottom depths of 8, 10, 12, 15 and 17 m at flight altitudes of 500, 700, 900 and 1200 m. For each of the four altitudes, for the specified depths, sounding locations were selected that were close in spatial position and similar in the value of the lidar echo-signal attenuation index  $\alpha$ , which depends on the hydrooptical properties. It was also assumed that the bottom reflectance coefficient  $R_b$  does not vary at the selected locations. The bottom amplitude  $P_b$  was determined for each sounding and then averaged over 10 consecutive soundings.

Figure 13 illustrates the averaged echo signal amplitudes for Fresnel reflection from the water surface  $P_F$ , alongside the  $P_b$  values recorded for depths of 8, 12, 15 and 17 m at various sensing altitudes. The blue dashed line represents the approximation of the experimental data using Eq. (8), while the red line indicates the approximation based on Eq. (1). In the case of Fresnel reflection from the water surface  $P_F$ , the approximation curves coincide; however, they diverge in all other instances. It is evident that for bottom returns at depths exceeding 8 m, the approximation curve derived from Eq. (8) demonstrates superior agreement with the field measurement data.

The value  $D(z) \approx 0$  was obtained under the assumption that the echo signal is formed due to single scattering from a Lambertian surface located at depth  $Z$ , given the small divergence of the laser beam  $\theta_1$  and the field-of-view angle of the receiving system  $\theta_2$ , which is substantially larger than the divergence of the laser beam ( $\theta_1 \ll \theta_2$ ). In this case, the diameter of the illuminated area on the bottom  $D_b$ , illuminated by the laser beam, equals the product of the sounding path length and the divergence of the laser beam. This condition is satisfied by Fresnel reflection from the water surface, when the diameter of the illuminated area is determined solely by the divergence of the laser beam and is sufficiently small. In the case where the bottom is at depth  $z_b$ , the contribution of multiple scattering along the path from the water surface to the bottom and back leads to an increase in the area on the water surface  $D_s$  through which the radiation reflected from the bottom exits and enters the receiver. As  $z_b$  increases, the contribution of multiple scattering grows. The size of the area  $D_s$  becomes larger than the size of the area entering the angular field of the receiver  $D_r$ . With increasing sounding altitude, the ratio of the diameters of the areas  $D_r/D_s$  decreases, leading to a reduction in the rate of decay of the lidar echo signal and, accordingly, an increase in the contribution of the function  $D(z)$ . Similar processes occur upon reflection from water layers located at a fixed depth.

Using Eq. (8), estimates were made of the dependence of the bottom-reflected echo signal power  $P_b$  on the lidar altitude above the water surface  $H$ , as well as the maximum possible flight altitudes for bathymetric surveys under these conditions. The results of these estimates are valid for the technical characteristics of the lidar available on the APL-3, as well as for the values of the hydrooptical characteristics of the water and the bottom reflectance coefficient typical of Bechevinskaya Bay.



**Fig. 13.** Values of the echo signal amplitude for the case of Fresnel reflection from the water surface  $P_F$ , as well as values of  $P_b$  for depths of 8, 12, 15, and 17 m. The blue dashed line indicates the approximation of the experimental data using equation (1), while the red line represents the approximation using equation (8) [50]

Figure 14 presents experimental values of  $P_b$  for depths of 10, 15 and 20 m, along with graph of the approximating function  $P_b(H)$ , whose form follows from the lidar Eq. (8). The dashed horizontal line indicates the minimum detectable signal level, determined by the average noise level. The dashed vertical lines denote the maximum possible flight altitude  $H_m$  for registering the bottom echo signal, where  $H_m$  strongly depends on  $z_b$ : for  $z_b=10$  m,  $H_m > 2500$  m; for  $z_b = 15$  m,  $H_m = 2250$  m; and for  $z_b=20$  m,  $H_m \approx 880$  m. The obtained estimates allow for refinement of the technical requirements imposed on bathymetric lidars and can be used in the development of next-generation lidar systems.

Laser bathymetry is advancing significantly more rapidly than other applications of lidar sensing. At the same time, issues regarding the influence of surface waves, the values and stratification of hydrooptical characteristics, and the contribution of the sounding path's length and condition remain insufficiently explored. Accounting for these factors and evaluating their impact on bathymetric survey results requires both *in situ* experimental research and numerical modeling. One of the critical tasks in lidar sensing remains the assessment of the feasibility of conducting bathymetric surveys in the coastal waters of Russian seas, which are characterized by relatively low water transparency.

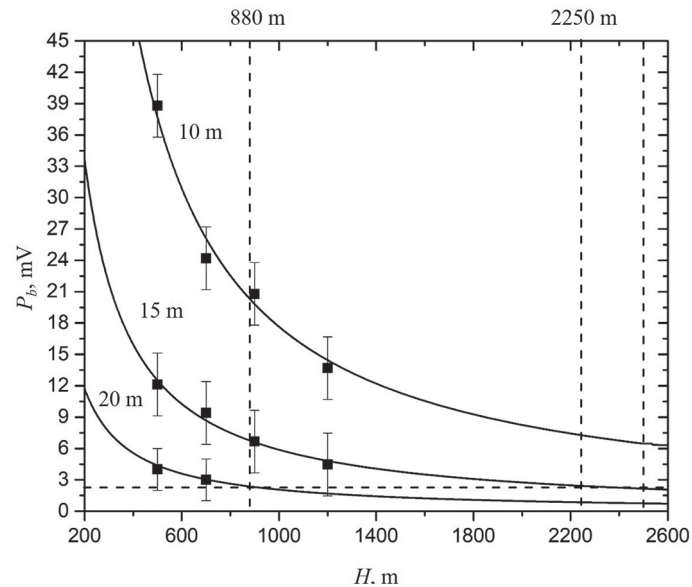


Fig. 14. Dependence of  $P_b(H)$  for different bottom depths [25]

#### 4. Conclusion

Methods for lidar sensing of marine environments are currently undergoing active advancement to address fundamental and applied problems in oceanology. In particular, lidars provide a unique capability, unavailable through other methods, to obtain a detailed three-dimensional representation of the spatial distributions of various seawater characteristics. Researchers at the Laboratory of Ocean and Atmosphere Optics of SPbB IO RAS, in collaboration with colleagues from the Laboratory of Ocean Optics of IO RAS, have utilized modern electronic components to design and manufacture several profiling lidars with diverse technical specifications, intended for shipborne and airborne platforms. Over the past decade, these lidars have been used to conduct field studies across Russian seas from both research vessels and laboratory aircraft.

Several key areas of research involving profiling lidars are of significant practical importance. One such area is the development of lidar methods for the remote sensing of the inherent optical properties of the upper ocean layer and their vertical distributions. Continuous measurements along a vessel's or aircraft's route enable the remote classification of World Ocean water masses, the rapid acquisition of data on the spatial distribution of hydrooptical characteristics, and the identification of various frontal zones.

Another practically significant area involves developing experimental lidar methods for detecting various dynamic processes in the upper ocean. The use of profiling lidars provides new insights into the variability of hydrooptical fields caused by internal waves, eddy processes in the surface layer, and small-scale turbulence. Future research will focus on assessing the feasibility of remote internal wave detection in relation to hydrological and hydrooptical parameters, as well as defining the optimal conditions for such observations.

Applied tasks include promising lidar applications in the fishing industry, as well as the development and implementation of bathymetric lidars. Of particular interest is the creation of Russian-made bathymetric lidar systems and the assessment of the feasibility of bathymetric surveys in the coastal waters of Russian seas, which are characterized by relatively low water transparency (in contrast to the coastal waters of the Pacific and Atlantic Oceans, where the vast majority of field studies have been conducted).

The development and deployment of autonomous marine lidars on unmanned aerial vehicles (UAVs), autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and moored or drifting hydrological buoys, as well as lidar sensing from high-altitude airborne platforms, represent highly promising directions for future research.

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## Conflict of interests

The authors declare no conflict of interests.

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