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ESTIMATION OF LIDAR RETURN SIGNAL LEVELS IN TWO-BEAM HYDROOPTICAL LASER SENSING

V. S. Shamanaev UDC 551.46.07

In the present paper, the feasibility is demonstrated of application in hydrooptics of the method that has long been developed for atmospheric sensing and undecervedly forgotten. The range of lidar return signal variations is calculated versus the water turbidity. Upgrade of the equipment allows a hypothesis about vertical homogeneity of water depth to be abandoned.

Hydrooptical sensing has been used for sea studies at the Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences for more than 20 years. The canonical experimental configuration is used with one laser beam falling within the field of view of one receiving telescope. The equipment has been significantly improved, and interesting scientific results have been obtained. A lidar was most often placed in the cabin of the AN-30 aircraft-laboratory, and sea water sensing was carried out in the nadir through a photohatch (fabricated from optical glass) initially intended for aerophotography [1, 2].

The lidar was placed on board scientific-research vessels *Akademician Keldysh* and *G. Yu. Vereshchagin*; it was mounted in one of the laboratory rooms (in a cabin). Outside of the cabin window, a flat tilted mirror was mounted which directed transmitted laser radiation into water and reflected laser radiation at the receiver [3]. The distance to the water surface was a few tens of meters, and the experimental conditions were similar to those for lidar operation on board a helicopter flying at low altitudes.

In addition, in winter the lidar was placed in a trailer on the ice surface of Lake Baikal; laser radiation reflected from a tilted mirror was transmitted into water through an ice-hole – the so-called maina [1]. (Problems of electric power supply, earthing, water protection from freezing, etc. are not considered here.) The situation was also similar to airborne sensing, but the lidar did not move here, and no waves creating certain problems were present on the water surface.

Results of remote investigations into the spatial distribution of optical water properties have been published, for example, in [2–4]. However, as indicated above, all of them are based on the conventional sensing geometry, when the laser beam fell within the receiving field of view of one telescope. Lidar return signals were then processed using these or other algorithms each with its own advantages and limitations. We have no universal method of signal processing. Nowadays, the conventional method of logarithmic lidar return signal derivative (for example, see [4]) is most often used from other analytical methods of airborne hydrooptical laser sensing to solve the inverse problem. Its limitations are strict enough: approximation of single light scattering and the assumption that the medium being sensed – water – is vertically homogeneous. The method of logarithmic derivative is simple for practical realization, and this predetermined its wide application.

However, as early as 1968, Kano (Japan) [1] suggested a method of atmospheric laser sensing simultaneously in two directions of the upper hemisphere. In this case, two different optical thicknesses correspond to the same distances from the lidar; exactly this circumstance provides the basis for the construction of an algorithm of solving the inverse problem for the vertical extinction coefficient profile of the atmosphere. The limitations here are the following. The medium being sensed must be horizontally homogeneous, and only single scattering of laser radiation is taken into account.

Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences, e-mail: shvs@iao.ru. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, No. 12, pp. 9–13, December, 2007. Original article submitted September 19, 2007.

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Thus, we have the relatively simple Kano formula for sensing of vertically inhomogeneous atmosphere with horizontally stratified homogeneous layers. As already indicated above, this formula was derived for sensing of the upper troposphere. It describes the vertical profile of the atmospheric transparency $T(h)$ which by definition is written as

$$T(h) = \exp\left[-\int_0^h \alpha(x)dx\right]. \tag{1}$$

Here h is the distance from the lidar (or the altitude above it), and $\alpha(h)$ is the vertical profile of the extinction coefficient above the lidar. By its physical meaning, $T(h)$ is a smooth function monotonically decreasing with distance h. Exactly for this reason, the vertical profile of the extinction coefficient $\alpha(h)$ can be calculated by its numerical differentiation stable enough from the viewpoint of errors. The methods of stabilizing the calculated values of derivatives of the form $\alpha(h) = dT(h)/dh$ have well been developed and are not discussed here.

For the atmosphere, the main Kano working formula has the following form:

$$T(h) = \left[\frac{S_1(h)}{S_2(h)}\right]^{\frac{\cos\varphi_1 \cos\varphi_2}{2(\cos\varphi_2 - \cos\varphi_1)}}. \tag{2}$$

Here φ_1 and φ_2 are zenith angles for the 1st and 2nd sensing directions (we consider the 1st direction to be basic one). The experimentally measured lidar S-functions, that is, lidar return signal powers corrected for squared distance h, are written as

$$S_1(h) = A\gamma_\pi(h)\alpha(h)\exp\left[-\frac{2}{\cos\varphi_1}\int_0^h \alpha(x)dx\right],$$

$$S_2(h) = A\gamma_\pi(h)\alpha(h)\exp\left[-\frac{2}{\cos\varphi_2}\int_0^h \alpha(x)dx\right], \tag{3}$$

$$S_{1,2}(h) = F_{1,2}(h)\cdot h^2.$$

Here A is the lidar instrumental function, $\gamma_\pi(h)$ is the lidar ratio for the medium being sensed at altitude h, $\alpha(h)$ is the vertical profile of the extinction coefficient, and $F_{1,2}(h)$ are experimentally measured powers of both lidar return signals.

Formula (2) was derived from Eq. (3) by division of S_1 into S_2 and subsequent extraction of the expression under the exponent sign. We note that the medium being sensed here (the atmosphere) is considered homogeneous in the refractive index of the material, that is, in the lidar ratio.

The natural logic of the experiment makes it desirable to orient the first sensing beam vertically (in the zenith or nadir), that is, $\varphi_1 = 0$ and $\cos\varphi_1 = 1$.

In sensing of the upper sea layer, the medium is already inhomogeneous in the refractive index n, which for the atmosphere-water interface is equal to 1.33. We designate the altitude of the lidar placed onboard an aircraft or on the deck of a vessel above water by H_0. The general sensing geometry of the suggested two-beam sensing method is shown in Fig. 1. Here the angle of beam incidence on the water surface φ_2 obeys the well-known Snell's refraction law, and in water the beam propagates at the angle φ_3.

For this hydrooptical experiment, the vertical profile of water transparency assumes the form

$$T(z) = \left[\frac{S_1(z)}{S_2(z)}\right]^{\frac{\cos\varphi_3}{2(\cos\varphi_3 - 1)}},$$

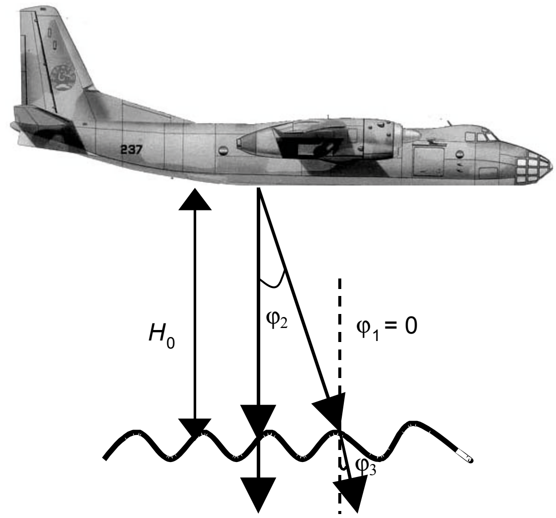

Fig. 1. Geometry of the suggested two-beam sensing method.

$$S_1(z) = F_1(z)\left[H_0 + \frac{z}{n}\right]^2, \tag{4}$$

$$S_2(z) = F_2(z)\left[\frac{H_0}{\cos\varphi_2} + \frac{z}{n\cos\varphi_3}\right]^2.$$

Here H_0 is the lidar altitude above the water surface, z is the depth in water counted from the water surface, $S_1(z)$ and $S_2(z)$ are the left sides of Eq. (3), and $F_i(z)$ are lidar return signal powers for the 1st and 2nd sensing directions.

Since the extinction coefficient α in Eq. (1) is under the exponent and integral signs, taking logarithm of Eq. (1) and differentiating this expression with respect to z, we obtain that

$$\alpha(z) = -\frac{1}{T(z)}\frac{dT(z)}{dz}. \tag{5}$$

We note that Eq. (5) describes exactly the procedure of numerical differentiation of the experimental functional. Therefore, in the initial step of our study it makes no sense to construct its analytical expression and then to analyze it.

We now estimate the applicability of the suggested method from the viewpoint of the influence of horizontal inhomogeneities in the radiation extinction coefficient (turbidity) of water (and this is one of the conditions of its applicability). First, what is the influence of the exponent $\cos\varphi_3 / 2(\cos\varphi_3 - 1)$ in Eq. (4)? It has no optimal value, since formally the given parameter decreases by a hyperbolic law with increasing angle φ_2 (and hence φ_3). We will proceed from physical and technical substantiations. In addition, for too large incidence angle φ_2, the Fresnel component, describing the signal component reflected into the atmosphere, sharply increases, and the component penetrating into water decreases (by the way, this peculiarity is not observed for atmospheric sensing).

The sizes of the bottom hatch of the AN-30 aircraft-laboratory allow the two working lidar beam directional patterns to be separated up to $\varphi_2 = 30^\circ$ for the above-mentioned sensing geometry. (In this case, the underwater angle φ_3 will be 22.8° for the flat water surface.) However, the flat water surface is seldom encountered; therefore, the influence of sea waves should be estimated even preliminary. In classical monograph [5], different types of sea waves were considered. The influence of capillary waves having wavelengths from a few millimeters to a few centimeters will be considered automatically in the process of averaging over the diameter of the laser radiation spot on the water surface. For conventional divergence of the collimated laser beam of 1 mrad and the chosen lidar altitude, this beam diameter is about 20 cm. Ripples have the least influence on the error among the energy-carrying waves. The wavelengths of these waves are a few hundred meters, and they are deterministic by their nature. The angle φ_3 for them will vary by ±0.5°. The maximum errors are expected when laser beams pass through wind-driven waves with wavelengths from a few fractions of a meter to a few meters. They have a significant stochastic component that calls for further special consideration. Nevertheless, based on an analysis of tilt angles of regular side slopes of these waves, we can calculate that deviations of the angle φ_3 will be as great as ±2.5°. Here the procedure of preliminary selection of "good" lidar return signals we have already used for sea water sensing from a board of a vessel [3] can be recommended.

Let us now analyze the physical limitation of the method caused by horizontal optical inhomogeneities of water areas.

In our previous experiments on airborne lidar sensing of sea water areas, we investigated paths from 10 km to several hundred kilometers [6]. The inhomogeneities of the water extinction coefficient α of different scales were studied. It was found that far from coastal lines and river mouths, the water areas with linear sizes of about 500 m and greater can be considered homogeneous. Therefore, to obtain reliable estimates, we can take a linear distance of 200 m between the points laser beams enter water. In this case, with allowance for the value of tan30°, the allowable flight altitude should not exceed 350 m. It can be added that the flight altitude $H_0 \approx 200$ m was chosen historically, since it was the typical height of the lower cloud boundary above the northern and far-eastern seas of Russia.

We now estimate the amplitude difference for the pair of lidar return signals, that is, consider whether they can be registered by registration systems of a unified design or photomultipliers and analog-to-digital converters with different working characteristics must be used. In the first stage, we use a model of water homogeneous with depth, that is, with a constant extinction coefficient and scattering phase function.

We perform our calculations from formulas that follow from Eqs. (3) and (4). The received lidar signal powers $F_1(h)$ and $F_2(h)$ in relative but common units can be written as

$$F_1(z) \approx \frac{A\alpha(z)}{(H_0 + \frac{z}{n})^2} \exp\left[-2 \int_{H_0}^{H_0+\frac{z}{n}} \alpha(x)\,dx\right], \tag{6}$$

$$F_2(z) \approx \frac{A\alpha(z)}{\left(H_0 + \frac{z}{n\cos\varphi_3}\right)^2} \exp\left[-2 \int_{H_0}^{H_0+\frac{z}{n}} \alpha(x)\,dx\right].$$

Recall once again that the single-scattering approximation is used here disregarding the influence of wind-driven sea waves. Figure 2 shows the relationship between signals $F_1(z)$ and $F_2(z)$ received from two directions for very pure water with the extinction coefficient $\alpha = 0.15$ m^{-1} and for pure but already much less transparent water with $\alpha = 0.30$ m^{-1}. We note that in the first case, the depth of visibility of a standard white disc under water (the Secchi depth) is 40–50 m, and in the second case, it is 20–25 m.

From the depth profiles of lidar return signal power it can be seen that for each pair of signals, they differ by about two times. Fortunately, this is not orders of magnitude, which allows us to use a unified two-channel system of signal registration. This means that the engineering solution for practical implementation of the suggested method can be significantly simplified. This is the main result of the present study.

Further research will be devoted to an optical scheme of the experiment and estimation on the statistical basis of the influence of energy-carrying and capillary waves.

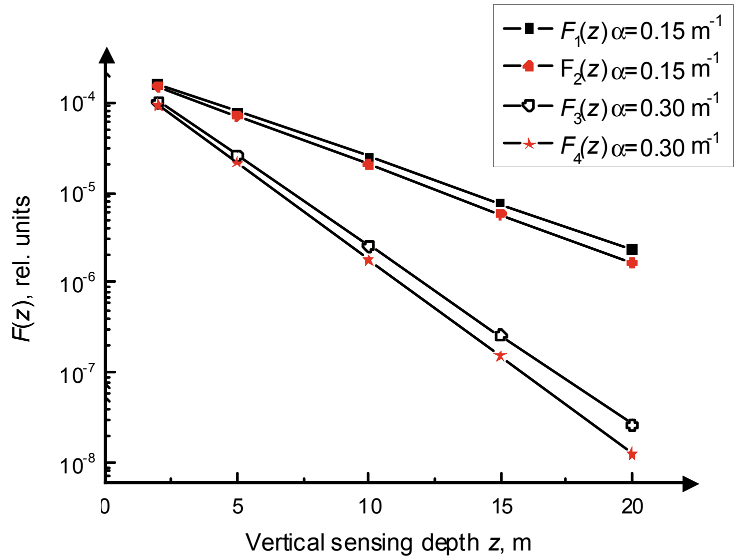

Fig. 2. Relationship between lidar return signal powers for two pairs of lidar return signals and the indicated values of water turbidity.

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