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An Application of Laser to Depth Sounding

Some selected phenomena determining light field in sea water have been discussed, and the principles of laser depth measurements presented. The effects of factors limiting the application of lasers to measurements performed in sea water have been evaluated by using a simplifed model of light transmission in sea.

1. Introduction

The ever increasing exploitation of sea waters requires a quick reconnaissance of the underwater regions. This holds particularly when detecting the shoals of fish, determining the sea pollution, measuring the fishery region depth, and studying the dynamics of changes in the bottom profile of the near-coast zone. Also in the case of inland waters a precise measurement to the depth of water reservoirs as well as an accurate determination of the river bed cross-sections, and changes in the water level of rivers are very important for the national economy as they form a basis for forecasting the flood emergency.

At present, depth gauges equipped with heads of high power laser enable a satisfactory — for practical purposes — solution of these tasks. Measurements made with laser probe may be performed on boards of any sailing units as well as of the aircraft. In the last case, the measurements may be made also via clouds and fog.

In the present paper, some factors forming the light field of the sea hydrosphere and the principles of the aerial depth measurement carried out by laser techniques are discussed. An attempt has been made to evaluate both the range of laser depth measurements and some limitations in the possibility of application of laser to the above measurements. The evaluations of the laser applicability have been based on a simplified one-dimensional two-parameter model of the sea reservoir.

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2. Fundamentals of the theory of laser radiation transmission in sea reservoirs

The fundamental equation in the theory of of laser light transmission in the sea water is that of energy transport. Taking into account the absorption and scattering of the radiation, this equation is obtained from the principle of energy conservation in the light field. The energy transport equation may be generally put into the following from [1–3]:

$$\frac{\mu}{c_w}\frac{\partial L(t,\boldsymbol{r},\varphi)}{\partial t}+\boldsymbol{\omega}\nabla L(t,\boldsymbol{r},\varphi)+ \varepsilon(\boldsymbol{r},\lambda)L(t,\boldsymbol{r},\varphi)-q(t,\boldsymbol{r},\boldsymbol{\omega}) = \frac{\sigma(\boldsymbol{r},\lambda)}{4\pi}\int\limits_{\Omega}\gamma(\psi)L(t,\boldsymbol{r},\varphi)d\boldsymbol{\omega}, \tag{1}$$

where: c_w — light velocity in water, α, φ and ψ — the directional angles, $\mu = \cos\alpha$, L — luminance, λ — light wavelengths, ε — attenuation coefficient σ — scattering coefficient, Ω — unit sphere, $\boldsymbol{\omega}$ — direction of spatial scattering, $\boldsymbol{r}$ — position vector, q — characteristic function of the radiation source, $\gamma(\psi)$ — indicatrix of scatte ring.

When investigating the laser light propagation in the sea water, the equation of the energy transport is usually reduced to the one-dimensional form as a function of depth and is represented as follows:

$$\frac{\mu}{c_w}\frac{\partial L(t,z,\varphi)}{\partial t}+\boldsymbol{\omega}\nabla L(t,z,\varphi)+ \varepsilon(z,\lambda)L(t,z,\varphi)-q(t,z,\boldsymbol{\omega}) = \frac{\sigma(z,\lambda)}{4\pi}\int\limits_{\Omega}\gamma(\psi)L(t,z,\varphi)d\boldsymbol{\omega}. \tag{2}$$

For specified hydrooptical parameters the solution of the energy transport equation depends on the knowledge of the function $q(t, \boldsymbol{r}, \omega)$. For a pulsed light source this function is equal to zero for all the time moments fulfilling the conditions $t < t_0 + \Delta t$, where t_0 denotes the moment of pulse ending, while Δt indicates the time interval between the two subsequent pulses. A general solution of the energy transport equation has not been found so far. In order to determine the coefficients appearing in the transport equation the empirical data are usually employed [1–10]. This leads to different particular cases of the equation. E.g. for monochromatic light it has the following form [5, 10]:

$$\mu \frac{dL(z, \mu, \varphi)}{dz} = -\varepsilon(z, \lambda) L(z, \mu, \varphi) + $$

$$+ \frac{\sigma(z, \lambda)}{4\pi} \int_0^{2\pi} \int_{-1}^{1} \gamma(\psi) L(z, \mu, \varphi) d\mu' d\varphi', \qquad (3)$$

where: μ' and φ' are the directional coordinates. In the equation (3) a number of phenomena important for light transmission in the water, like polarization of light, anisotropy of sea water, noise radiation and so on have not been included. However, even this case can be solved in a semi-empirical way only.

In the theoretical models of the hydrosphere light field some drastic simplifications are usually introduced. Thus, for instance, only single quantum processes are taken into account, nonlinear effects are neglected, the stratification of the water masses is assumed to be horizontal, and changes in radiation parameters are attributed to the depth only [3–7, 11–15]. Laboratory investigations may be considered as a source of empirical data enabling to construct theoretical models of laser light transmission in water, however, to a limited extent only. As a rule, difficulties in reconstructing the natural sea conditions in the laboratory restrict the examinations to the equilibrium states. In natural conditions, however, the factors determining a hydrooptical state in the see, i.e. salinity, density, temperature, chemical composition of the sea water etc. are subject to extraordinary dynamic changes [3, 4, 8, 10–19]. Some examples of interrelations between the basic factors determining the optical feature of the sea hydrosphere will be presented in further part of this section. One of the most important factors is the salinity; its value may differ considerably within a given sea region, the cyclic changes being typical are illustrated in Fig. 1 for the case of surface water of the Central Atlantic Ocean.

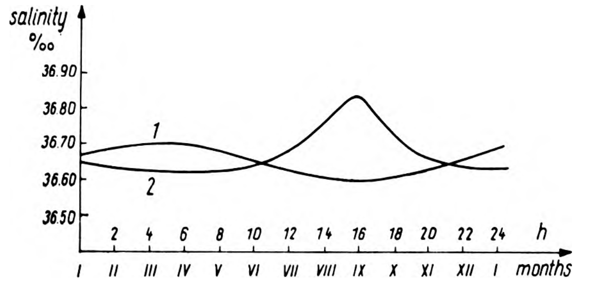

Fig. 1. Periodic changes in the salinity of the near-surface layer in the Central Atlantic waters
Curve *1* illustrates the annual changes in the salinity, while curve *2* shows the day and night changes of the surface water layer in the same region of the Atlantic Ocean

The salinity factor determines the value of the refractive index at the air-water boundary surface. The refractive coefficient has, in turn, a fundamental meaning for light transmission in a given optical medium. The value of the refractive index n_w in the sea water depends also on the wavelength of the light penetrating the water masses. Relationship between the refractive index, light wavelength, and salinity factor [10] is shown in Table 1. In the sea water the refractive index depends additionally on the water density which, in turn, is a function of the salinity and temperature of the water masses.

Table 1

Refractive index n_w as a function of the light wavelength λ and salinity S in the sea water

λ, nm \ S, ‰	0	10	20	35
447.2	1.33945	1.341138	1.34329	1.34616
501.6	1.33635	1.33824	1.34011	1.34193
587.6	1.33305	1.33491	1.33675	1.33951
667.8	1.33271	1.33271	1.33452	1.33726

Table 2 illustrates the dependence of the sea water density upon salinity S and temperature θ [17]. The last two parameters change with the depth and this relationship is presented in Fig. 2 [18].

Refractive index of the light n_w is also temperature-dependent. In the visual range,

Table 2

Sea water density ϱ in kg/m³ as a function of temperature θ and salinity S

θ °C \ S, ‰	25	30	35	40
0	1020.09	1024.11	1028.13	1032.17
5	1019.80	1023.75	1027.70	1031.67
10	1019.20	1023.08	1026.97	1030.88
20	1017.20	1020.99	1024.78	1029.85

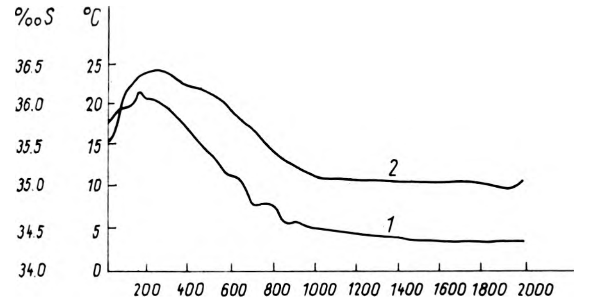

Fig. 2. Changes in temperature and salinity in the sea water as a function of the depth

Curve *1* shows the temperature changes, while curve *2* represents the sea water salinity versus the depth

the changes in the refractive index Δn_0 in the distilled water amount to about 0.02 for the temperature ranging within 10°–40°. Table 3 is an illustration of the phenomenon for selected wavelengths in the distilled water [18]. Similarly, the refractive index n_w in the sea water is also temperature-dependent. For a determined salinity of the sea water the changes in the refractive index associated with temperature variations do not exceed several thousandths. Table 4 presents the value of refractive index n_w for the yellow-green light as a function of water salinity S and temperature θ [17]. Density of sea water, its temperature, salinity and dynamics of water mass displacement are the factors determining morphological structure of suspended solids constituting the hydrosol. In a deep sea a horizontal stratification of the sea water masses is usually observed. However, this state may be subjected to serious perturbations due to various factors. Fig. 3 presents an illustration of this phenomenon [39].

Table 3

Refractive index n_0 in the distilled water as a function of the light wavelength λ and temperature θ

λ, nm \ θ, °C	10	20	30	40
447.2	1.340149	1.339423	1.338347	1.336984
501.6	1.337070	1.336353	1.335289	1.333939
587.6	1.333744	1.333041	1.331993	1.330662
667.8	1.331567	1.330876	1.329843	1.328528

Table 4

Light refractive index n_w as a function of temperature θ and salinity S in the sea water

θ, °C \ S, ‰	25	30	35	40
0	1.3390	1.3398	1.3407	1.3419
10	1.3384	1.3393	1.3401	1.3412
20	1.3375	1.3384	1.3393	1.3402

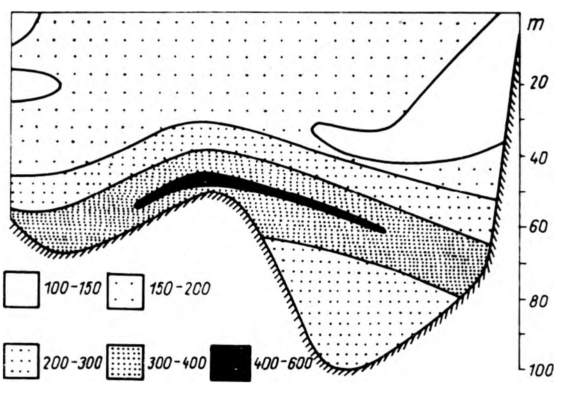

Fig. 3. Formation of stratified structure of the sea water as influenced by the water supply from the North Sea at the Kattegat Straits

Finally, it should be added that a given hydrooptical state depends also on the sea reservoir depth.

In the deep sea zone a decisive influence is exerted by a set of factors existing neither in the coast nor in the shallow sea. That is why particular sea zones differ significantly with respect to their optical parameters.

Due to the complexity of interrelations determining the light field in the sea hydrosphere construction possibilities of theoretical models of the light transmission in the sea water are seriously restricted. In the present state of scientific and technological development the experimental data in situ are insufficient.

3. Light attenuation in the sea water

Simplified models of the laser light transmission in the sea water take usually into account the dependence of the attenuation coefficient of light ε, on the duration of the laser action δt, position vector r of a definite point of the water masses and on the light wavelength λ.

The energy E of the laser radiation reaching a considered point of hydrosphere at a depth z may be determined for a vertical light beam (by neglecting the relation between the light attenuation coefficient and the local non-uniformities of the water masses) from the decay law [3, 4, 11, 21]:

$$E = E_0 \exp\left\{-\int_0^z \varepsilon(t, \lambda)\, dz\right\}, \tag{4}$$

where E_0 – energy of the beam penetrating the sea water. Assuming that the attenuation coefficient ε is constant (and this is approximately the case for a water layer of moderate thickness in the open sea) the law (4) may be restricted to the form:

$$E = E_0 \exp\{-\varepsilon z\}. \tag{5}$$

For relatively poor approximation [10] the attenuation coefficient appearing in formulae (4) and (5) is usually determined from the formula

$$\varepsilon = 4{,}4\left(\frac{E}{E_0}\right)^2. \tag{6}$$

The attenuation coefficient is used to determine a number of optical parameters of the light transmitting medium. One of these parameters much convenient, especially, for empirical investigations is the mean free path of a photon. It may be expressed by the reciprocal of the attenuation coefficient: $\delta = \varepsilon^{-1}$. This parameter (sometimes called attenuation length) renders possible to design the characteristics of the hydrooptical state of a definite sea region. A passage of a laser beam through a water layer of a thickness δ causes a loss amounting to 63% of the original energy. The knowledge of the value of the attenuation length δ allows to determine some physical magnitudes characteristic of its water. E.g. the visibility range in the sea water. It has been stated that at conventional light illumination of the objects submerged in the water the visibility range amounts to 4δ. if, however, laser light illumination is used the visibility increases up to 8δ. Similarly, the laser measurement range of the depth z as well as the laser light penetration range in the water are determined with the help of this parameter. At present the application of lasers of an appropriate power emitting the radiation turned to the optimal range of the light transmission in the sea water allows to perform the depth measurements in the open sea up to 20δ, while in the coast zone within 7δ–10δ. The detection of the laser radiation has been realized up to 50δ from the radiation source [3, 10, 22–23].

The light attenuation in the natural sea water depends on the optical properties of its components: pure water, dissolved matter, suspended solids, and the so-called yellow substance, i.e. decomposition product of the organic components of water [3–5, 11, 15, 33, 34]. The light attenuation coefficient ε_0 in the distilled water, expressed by the scattering factor σ_0 and absorption factors $\varkappa_0$ is given by the relation

$$\varepsilon_0(\lambda) = \sigma_0(\lambda) + \varkappa_0(\lambda). \tag{7}$$

The values of the light attenuation, scattering and absorption coefficients in the distilled water are influenced by the wavelength λ of the radiation penetrating the water. This relationship is illustrated in Fig. 4 [35].

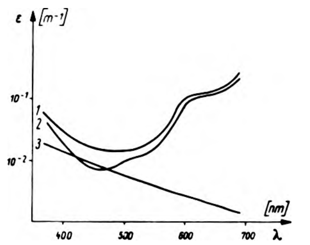

Fig. 4. Spectrum distribution in the distilled water for the following coefficients: 1 – light attenuation ε_0, 2 – light scattering σ_0, 3 – light absorption $\varkappa_0$

In the distilled water the influence of absorption on the light attenuation is relatively weak, the main part in this process being performed be the Rayleigh scattering. The values of the absorption coefficient of light for given wavelengths are listed in Table 5. The light attenuation of the sea water depends on attenuation of light in the pure water, its scattering and absorption on the hydrosol components and absorption in the yellow substance. In this case the attenuation coefficient for

Table 5

Absorption coefficient $\varkappa_0$ as a function of light wavelength λ in the distilled water

λ, nm	491	522	558	579
$\varkappa_0$	0.002	0.005	0.038	0.049

λ, nm	602	612	622	558
$\varkappa_0$	0.173	0.233	0.239	0.320

monochromatic light $\varepsilon(\lambda)$ may be determined from the relation [3, 4, 9]:

$$\varepsilon(\lambda) = \varepsilon_0(\lambda)+\sigma(\lambda)+\varkappa(\lambda)+\varkappa_y(\lambda), \tag{8}$$

where σ and $\varkappa$ denote, respectively, the scattering and absorption coefficients in the hydrosol components, while $\varkappa_y$ is an absorption coefficient in the yellow substance. For the scattering coefficient in hydrolysis the equality

$$\sigma = a\cdot\lambda^{-p} \tag{9}$$

is fulfilled [10], where $1.56\times 10^{-4}\leqslant a\leqslant 3\times 10^{-2}$ while a given value of a is determined by the average diameter 2d of the particles included by the hydrosol. Similarly, the exponent p occurring in (9) depends on the diameter of the light scattering particles. The corresponding data are presented in Table 6.

Table 6

Exponent p in the Eq. (9) versus diameter $2d$ of the light scattering hydrosol particles

$2d$, nm	70	100	150	230	300	350
p	4	3.5	3	2.5	2	1.5

The light scattering in the sea water is caused, first of all, by the hydrosol particles whose diameter is greater than the wavelength and the refractive index close to that of the water. That is why, e.g., 75% of the energy is scattered within the solid angle of 5° in cross-section, while the solid angle of 20° in cross-section contains as much as 75% of the total scattered light energy [5, 6, 9, 36–38]. The sea hydrosol consists of both organic particles. The majority of organic particles have a diameter of tens microns, while the prevailing number of inorganic particles have a diameter not exceeding a few microns. A typical distribution of particles in the sea hydrosol is given in Table 7.

Table 7

Per cent composition of the particles depending on the diameter $2d$ of the sea hydrosol

$2d$, μm	1–2.5	2.5–5	5–10	10–25	25–50	50
Organic particles, %	23.8	12.7	10.6	37.7	12.2	2.8
Inorganic particles, %	85.65	9.65	3.60	0.95	0.15	0

In particular sea reservoirs the light is attenuated to a different degree. The optimum light transmission range varies depending on the sea water composition. Fig. 5 shows the attenuation spectrum for the components of the Baltic Sea waters.

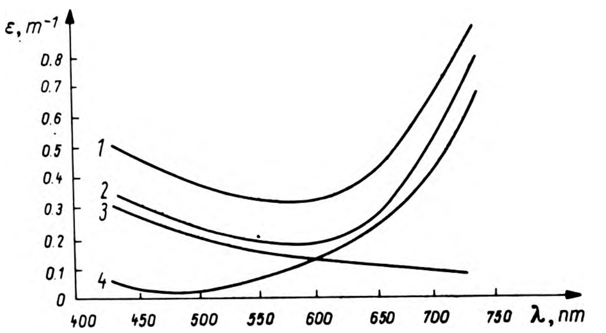

Fig. 5. Attenuation spectrum: *1* – in the natural Baltic Sea water, *2* – in the filtered Baltic Sea water, *3* – in the yellow substance, *4* – in the distilled water

Light penetrating the depths of separate sea regions suffers from attenuation caused by such factors as local difference in the sea hydrosol, sea water pollution, morphological structure of water masses, and so on. Analogically, the wavelength corresponding to the optimal light transmission is also subjected to some shifts, depending on the local hydrooptic conditions.

The value of the light attenuation in the sea depends also on the depth. In the deep sea three characteristic zones differing essentially in their optical parameters may be distinguished.

In the near-surface water zone light attenuation increases with the depth of sea water, due to the increasing concentration of living organisms within the intermediate undersurface region. In deeper layers of the sea water, the particle concentration in suspended matter diminishes, contributing to the decrease in the attenuation of light. However, in abyssal zone, which is usually characterized by an increased concentration of the hydrosol particles, another increment in the light attenuation factor is being observed. An example illustrating this phenomenon is presented in Fig. 6 (where changes of the light attenuation in the Baltic Sea waters are shown).

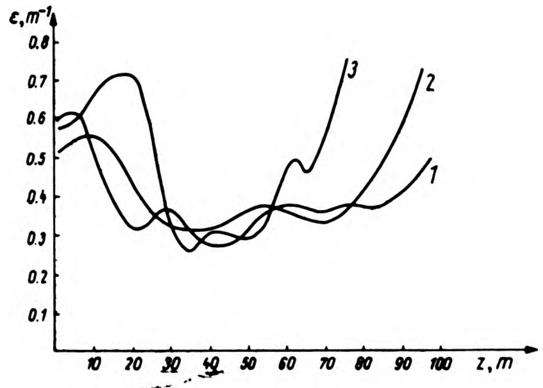

Fig. 6. Attenuation coefficient ε as a function of the depth z in the Baltic Sea for the light of wavelength $\lambda = 525$ nm: *1* – in the western part of the Central Baltic Sea, *2* – in the region of Bornholm, *3* – at the entrance to the Danish Straits, respectively

Another optical parameter, frequently applied in physical oceanography, is the transmittance T of the sea waters. This parameter is defined as a percentage value of the light energy transmitted through the layer of a thickness of 1 m. From the decay law in the form (5) and the said definition we obtain

$$T = 100\frac{E(z=1)}{E_0} = 100\exp\{-\varepsilon\}. \quad (10)$$

The sea water transmittance defined in terms of the above formula allows to characterize, in a simple way, the optical properties of the separate sea regions. Mean values of the basic optical parameters in different light transmitting media are listed in Table 8.

The determination of the water transmittance is relatively simple. In the oceanographic practice, the sea water is classified according to transmittance value. Spectral characteristics

Table 8

Average values of the transmittance T, the attenuation coefficient ε and the attenuation length δ for the light of wavelength $\lambda = 500$ nm in different optical media

Type of the medium	T, %	ε, m^{-1}	δ, m
Pure air	99.99	0.000029	34480
Mist	99.89	0.001	1000
Light fog	98.0	0.02	50
Distilled water	96.56	0.035	29
Densy clouds	95.1	0.05	20
Ocean water	86.9	0.14	7
Sea water	74.1	0.3	3
Vistula mouth		11	0.09

of transmittance performed for various types of sea water [4, 39] are presented in Fig. 7.

Because of a great diversity in the sea hydrosol composition, the optical parameters of the sea water in particular regions of the

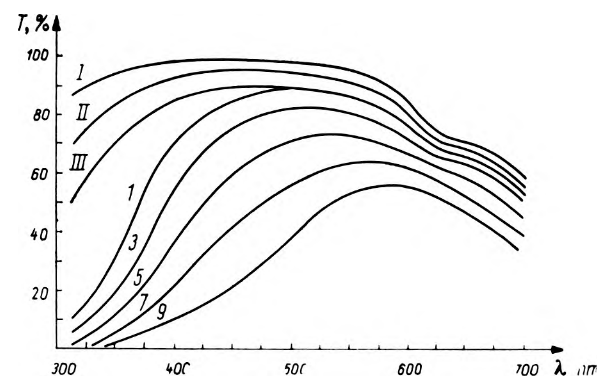

Fig. 7. Spectral characteristics of the ocean water transmittance of the types I, II and III as well as those of near-cost water of the types 1, 3, 5, 7 (after Jerlov)

oceans differ remarkably. An illustration is given in Table 9, where the mean values of the selected optical parameters in certain sea regions are presented.

Table 9

Average values of transmittance T, light attenuation coefficient ε, and attenuation length δ for the light of wavelength $\lambda = 500$ nm in the sea water

Sea region	T, %	ε, m^{-1}	δ, m
Saragossa Sea	96.94	0.031	32.3
Mediterranean Sea	87.81	0.13	7.7
Japanese Current	84.36	0.17	5.9
Atlantic Ocean	74.08	0.30	3.3
Baltic Sea	71,18	0.34	2.9

In view of the selective attenuation of light occurring in the sea water, the maximum range of the laser light penetration is defined for a specified light wavelength. In the distilled water the maximum penetration range is achieved for $\lambda = 475$ nm. In the natural waters a shift of the maximum range wavelength toward the red region of the spectrum is observed. In the sea water, the maximum penetration range is usually obtained for the yellow-green light from the 500–550 nm spectrum interval. However, in particular seas considerable deviations from this spectrum interval are observed. For instance, in certain regions of the Baltic Sea the seasonal maximum penetration range of the radiation occurs at the $\lambda =$ 580 nm light wavelength. An interesting anomaly in this respect shows the Crater Lake water where the maximum penetration range of the radiation occurs $\lambda = 425$ nm. As mentioned, the light penetration range in the sea water is usually expressed by the light attenuation length δ, which is the function of the wavelength of the light transmitted through the water. An example illustrating this phenomenon is given in Table 10, where the attenuation length δ is presented as a function of the light wavelength in the distilled water (see [10]).

Table 10

Values of δ_0 for some wavelength λ of the light penetrating the distilled water

λ, nm	400	440	480	520	560	600	560	700
δ_0, m	13	22	28	25	19	5.1	3.3	1.7

From the present-day investigations on the optical properties of the sea and ocean waters it is well known that for 90% of those waters the attenuation coefficient within the yellow-green part of the spectrum does not exceed 0.3.

Assuming that the limiting value of the laser range is as low as seven attenuation paths, the measurements can be performed up to the depth of 20 m. Hence, laser technique can be successfully applied to various underwater investigations.

4. Physical basis of laser depth measurement

To measure the depth z in the sea by means of a laser head it is necessary to determine the time interval Δt_z between the moments of the laser light pulse emission and the echo detection from the recognized surface. For the sounder located close to the water surface the following formula is valid

$$z = \tfrac{1}{2} c_w \Delta t_z, \tag{11}$$

where c_w denotes the light velocity in water. The depth gauge being located at some altitude over the water level the effect of the air layer separating the sounder from the water surface should be taken into account. In this case the time interval Δt between the moment of light pulse triggering and the echo detection from the surface to be recognized may be evaluated from the equation

$$\Delta t = 2\Delta t_a + 2\Delta t_w, \tag{12}$$

where Δt_a and Δt_a denote the time of light travel in air and water, respectively. From (11) and (12) we get the relation

$$z = \tfrac{1}{2}(\Delta t - 2\Delta t_a) c_w. \tag{13}$$

As a rule, the laser light beam is directed vertically onto the water surface, where in the case of a smooth surface about 2% of the light energy suffers from diffusion.

If, however, the sea is highly rough or polluted with an oil layer the diffusion of incident light energy ranges within 4–10% [40]. The deviation of the incident light beam from the normal incidence results in a rapidly increasing diffusion at the surface. The data for unpolluted water of a smooth surface are given in Table 11 [68].

Table 11

Per cent value of the laser beam energy scattered on a smooth nonpolluted water surface versus the beam incidence angle

Incidence angle of the light beam	0°	20°	40°	60°	70°	80°	90°
Percentage of the scattered energy	2.0	2.1	2.5	6.0	13.4	34.8	100.0

The light diffused at a water surface is the echo of this surface; this enables to determine the time elapse Δt_a. The times Δt_a and Δt, being known the altitude h_a of the measuring laser head position above the sea level, as well as the depth position of the object to be recognized can be determined by analogy to (11).

An ideological scheme of the laser depth measurement for the measuring head located over the sea surface is presented in Fig. 8.

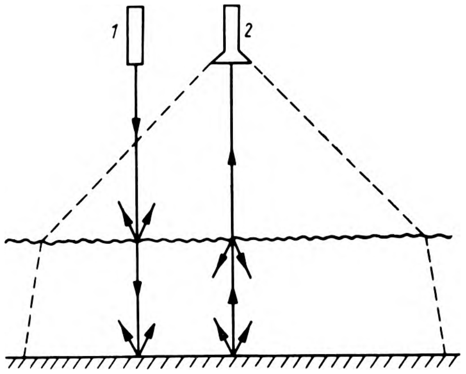

Fig. 8. Principle of both flight altitude and the diving depth measurements of recognized object from the sound with the help of laser:
1 — laser, *2* — echo detector

The useful range of the laser depth measurement in the sea is proportional to the radiation output of the laser. For this reason the pulsed lasers of great power are used in the depth gauges. The laser action rating as well as the horizontal velocity of the measuring head exert a decisive effect on the resolving power of the depth gauge. The corresponding data are given in Table 12.

Table 12

Relationship between the horizontal shift of the depth sounding process, the measuring head velocity v and the laser action rating f

f, Hz / v, km/h	1	20	60	300
5	1.25 m	0.05 m	0.023 m	0.005 m
20	5.0 m	0.25 m	0.08 m	0.018 m
35	10.0 m	0.5 m	0.17 m	0.034 m
60	16.0 m	0.8 m	0.22 m	0.044 m
90	24.0 m	1.2 m	0.42 m	0.08 m

First attempts of exploiting the laser light to illuminate the object submerged in the sea water were made in the early sixties. At the initial stage of investigations the pulsed ruby lasers were used. The radiation ($\lambda = 694.3$ nm) produced in the $Al_2O_3 + Cr^{3+}$ ruby crystal by $^2E - ^4A_2$ transition is strongly attenuated in the sea water [41–43]. For this reason at present neodymium lasers are usually employed. In prevailing sea waters the second harmonic radiation of lasers at the wavelength $\lambda = 532.4$nm is relatively well tuned to the interval of optimum light transmission. For the laser pulse duration of order of tens of nanoseconds and the conversion efficiency of several per cent the achieved useful power of radiation amounts to a few megawats. The values of basic optical parameters for different laser light sources in the distilled water are given in Table 13.

Table 13

Values of some optical parameters of the distilled water for different laser light sources

Light source	λ, nm	T_0, %	ε_0, m^{-1}	δ_0, m
YAG type Laser	1064.8	0.002	11.0	0.09
Ruby Laser	693.4	58.4	0.537	1.9
He-Ne Laser	632.8	78.4	0.243	4.1
YAG second harmonics	532.4	95.3	0.049	20.4
Argon Laser	514.5	96.3	0.038	26.3
Argon Laser	488.0	97.3	0.027	37.0
Cadmium Laser	411.6	96.2	0.039	25.6
Second harmonic Ruby Laser	346.7	95.4	0.047	21.3

If the considerations are restricted to the single-quantum processes the intensity of the echo originating at the unknown surface submerged in the water may be evaluated on the basis of the decay law (5). Taking account of the laser light attenuation, both in the air and in the water, we obtain:

$$I_d = RI_0 \exp\{-2(\varepsilon_a h_a - \varepsilon_w z)\}, \qquad (14)$$

where I_d and I_0 denote the intensity of the light reaching the detector and light emerging from the laser, respectively.

The value R appears in formula (14) as a function of the form $R = R(R_{aw}, R_b, R_{wa})$, where R_{aw}, R_b and R_{wa} are coefficients of light reflection at the air-water boundary, from the bottom, and at the water-air boundary, respectively. If the influence of the air layer on the measurement results is neglected the relation (14) may be reduced to the form:

$$I_d = RI_0 \exp\{-2\varepsilon_w z\}. \qquad (15)$$

This equation allows to estimate the maximum depth which can be determined by the aid of a laser of output power P_0. Denoting by $S(z)$ the noise equivalent power reaching the detector from the water layer of a thickness

z, and by k a threshold detectivity coefficient of the signal, the maximal depth z_{max} is given by the formula

$$z_{\max} = \frac{1}{2}\delta_w \ln \frac{RP_0}{kS(z)}. \tag{16}$$

It is usually assumed that the value of a threshold detectivity of the signal is $k = 3$ [20, 45].

However, the possibility of producing the very high output powers of the laser light are limited in an obvious way by the strength of the materials used as the laser rods. Similarly, in the sea water the critical power density of the laser beam (which is of the order of 10^{13} $\mathrm{Wcm^{-2}}$) being exceeded a number of effects disadvantageous for the measurement occur as a result of the interaction of the radiation with the water components. These effects are: the boiling, ionization, dissociation of the molecules, etc. They all limit the applicability of the laser light radiation for the depth measurements [46–50]. Taking account of those disadvantageous effects, the limiting power $P_{\lim}$ of the laser beam is determined from the following relation [29]:

$$P_{\lim} = \frac{\varrho A \Delta\theta}{\delta t}, \tag{17}$$

where ϱ is the specific heat of the sea water, A denotes the beam cross-section, $\Delta\theta$ is the admissible temperature increment in the sea water, and δt indicates the laser pulse duration. From formulae (16) and (17) we get the formula for the limiting laser measurement range in the sea

$$z_{\lim} = \frac{1}{2}\delta_w \ln\left(\frac{R}{kS(z)} \times \frac{\varrho S \Delta\theta}{\delta t}\right). \tag{18}$$

In the lasers used nowadays the radiation power output does not reach the critical values. However, a momental excession of the critical density value due to self-focusing of laser beam in the water, being possible also in the beam of subcritical power, may cause some measurement perturbations.

Under real sea conditions the laser beam suffers from rather intensive spreading due to diffusion and multiple photon scattering. At the distance from the source exceeding 50 m, on the average, the laser beam looses gradually its natural collimation. An increase in the noisy background, produced by multi-quantum processes and light diffusion [10], is simultaneously observed. The influence of light diffusion of laser beam on its propagation in the sea water is schematically presented in Fig. 9.

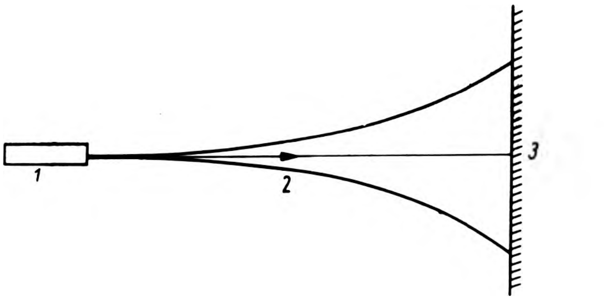

Fig. 9. Laser light beam diffusion in the sea water: *1* – laser, *2* – diffusive speeding off the beam, *3* – light reflecting surface

The noisy signals, generated in the sea water due to multi-quantum processes and backscattering, diminish to some extent the resolving power of the laser depth gauge and partly reduce the depth measurement range. On the other hand, the loss of the laser beam power caused by single-quantum scattering is considerably compensated by the multiple scattering occuring in the sea water, since a considerable number of photons scattered secondarily reenter the signal beam. For instance, the numerical ratio of scattered photons, existing in the signal beam, to the unscattered photons amounts to about 10^3 at a $10\delta_w$ distance from the laser radiation source, while at a distance of $40\delta_w$ it increases up to 10^9 [28]. It is worth noticing that the laser beam spreading, caused by multiple scattering, though a disadvantageous phenomenon is, however, not much harmful for the depth gauge. The effect of the single- and multiple quantum processes on the light attenuation in the sea water is presented in Fig. 10.

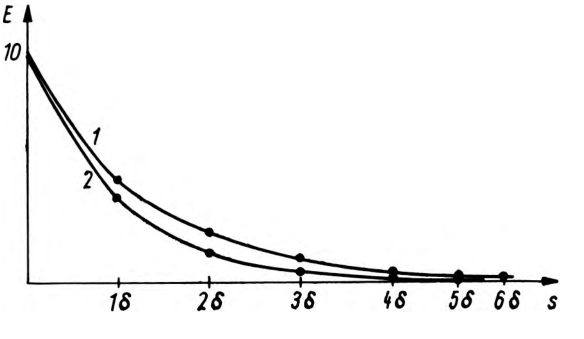

Fig. 10. Light attenuation of the laser beam in the sea water resulting from
1 – multiple scattering, *2* – single-photon scattering

In order to evaluate the depth measurement range in the sea water, it is necessary to know the reflectivity R_s of the surface to be recognized. In general, for a defined material the values of this coefficient in air and water are different.

The values of reflection coefficients for some metals in the air and in the water are given in Table 14 [7].

Table 14

Reflection coefficient for some metals in the air: a) for a pure metal surface, b) for a metal surface covered with a fat layer of $n = 1.45$ and for the same metal in water, c) for a pure metal surface, and d) for a metal deposited with a fat layer of $n = 1.45$

Case / Metal	a	b	c	d
Silver	95.0	95.2	95.0	95.2
Magnesium	92.9	90.6	91.3	90.6
Sold	85.1	81.1	84.0	80.9
Mercury	73.3	67.9	71.0	67.6
Copper	70.1	67.4	68.4	67.0
Nickel	62.0	52.4	53.8	51.7

The presented maximally simplified model of depth measurements in water reservoirs and of diving objects made by laser technique allows a rough estimation of the depth measurement range. The number of optical parameters exerting an essential influence on the light propagation in the sea are not considered. Despite these shortcomings the model can be used to estimate the different difficulties met in construction of theoretical models of the laser light propagation in the sea water. It can be also applied to the evaluation of the sea depth measurements. The depth measurement range for a laser system is usually determined empirically. At present there are numerous empirical formulae, by which the laser depth measurement range under specified hydrooptical conditions can be estimated in the degree satisfying the demands of the oceanographic practice [7, 20, 45, 51–54].

5. Depth measurement in the sea carried out by means of a laser sound

Due to successful solution of basic research and design problems the interest in laser technique applications to various measurements in the sea water [23–25, 56–58] has risen considerably. In the laser sounds used now, an analog and digital depth determination is usually made. Consequently it is necessary to equip the depth gauge system with a relatively complex electronic data-processing block. A block diagram of a typical laser depth gauge presented in Fig. 11 is designed for operating from a helicopter.

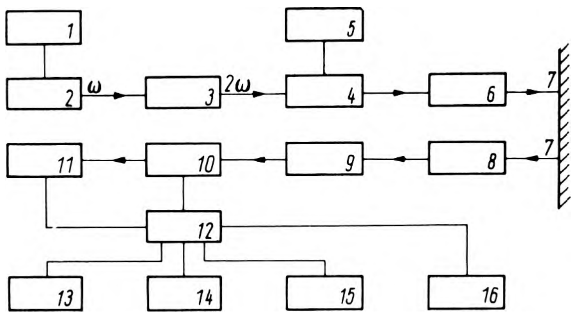

Fig. 11. Laser depth gauge diagram
1 – power supply, *2* – laser, *3* – optical frequency converter, *4* – modulator, *5* – high frequency generator, *6* – optical system of the emitter, *7* – the test-surface, *8* – optical system of the detector, *9* – discriminator, *10* – photomultiplier, *11* – timer, *12* – data processing block, *13* – analog indicator, *14* – digital indicator of the flight altitude, *15* – digital indicator of the depth, *16* – recorder

An experimentally used laser depth gauge assures a relatively high measurement accuracy. For example, if the draught of the recognized object does not exceed the value $1/3z_{\lim}$ the measurement error is not greater than 0.5% of the measured depth. Such an accuracy of the depth measurement in the sea becomes unavailable, when applying conventional measurement methods. As a rule, light modulation, electronic gating and other methods are usually employed in the laser depth gauge to reduce the influence of noise. Those methods enable to effectively extract the information signal from the background [7, 20, 54]. The characteristic quantities of the experimental laser depth gauge (reported by many authors [23–25, 59–64]) are listed in Table 15.

The divergencies in the data presented in Table 15, and the lack of proportionality between the range and the installed laser power, in particular, are caused by local differences in the hydrooptical conditions of the sea regions, where the investigations were made in situ. Thus, the results obtained cannot be compared, the more that the authors restricted their measurement data to absolute values, without determinig the fundamental optical parameters of the sea water the sounding was performed.

Table 15

Characteristic parameters in contemporary experiments with laser depth gauge

λ, nm	P_0, MW	t, ns	f, Hz	Z, m
530.0	0.01	—	0.2	26 – 300
530.0	0.5	—	30	70
530.0	2	10	2	100
530.0	0.5	10	—	50
530.0	0.8	10	60	30
532.4	3	10	30	15 – 200
540.1	0.08	5	300	120

At present, the works conducted by the Raytheon on the construction of a model of laser sound of the PLADS system (Pulse Laser Airborne Sounding) are realtively advanced. The sound is equipped with a laser head of the neodymium laser of YAG type and a system of radiation frequency processing. For radiation conversion efficiency, which in this model amounts to about 1% the effective power of a beam radiation in the second harmonic is several MW. The depth gauge is designed to operate from a SH-3 helicopter whose horizontal flight velocity during measurement performance does not exceed 90 km/h. For pulse repetition equal to 30 Hz the flight altitude above the water surface can be determined with the accuracy of ±30 cm, and the diving depth of the recognized surface with the accuracy of ±50 cm.

The sound of the PLADS system consists of laser head, detecting system, and electronic block for data processing. The optics of the sound consists of a long-focal-length objective and selective narrow band filters. Schematic representation of the optical system for the PLADS type sound is given in Fig. 12.

In the light of experience achieved by using the PLADS type sound it may be stated that the laser depth gauge can be applied to profile determination of the coast zone bottom as well as for measuring the depth in bays and docks with relatively highly polluted water down to the 15 m depth. In typical near-coast water it is possible to measure the depth down to 35 m, while in the open sea diving depth measurements can be performed down to 70 m. Finally, in the pure ocean waters the laser depth gauge may be applied to measure the diving depth of the objects to be recognized down to 200 m. According to some optimistic forecasts, due to the development of new de-

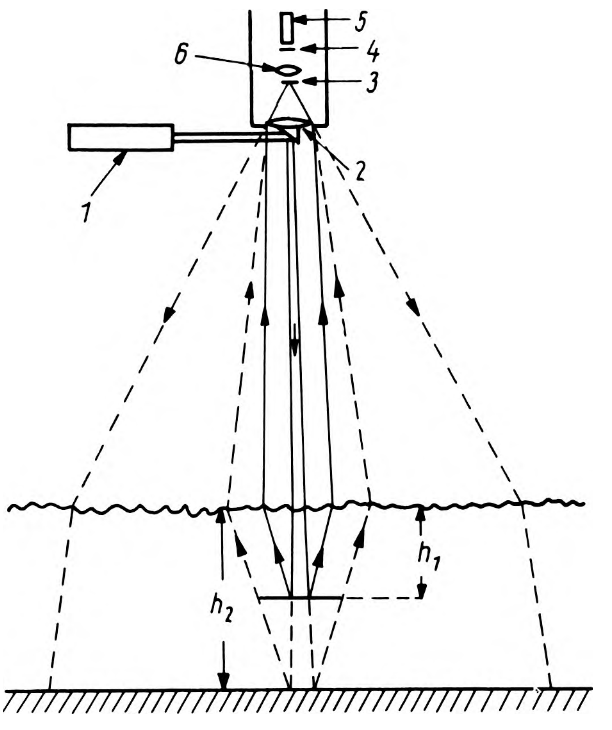

Fig. 12. Schematic representation of the optical system of the PLADS type sound:
1 – laser, *2* – objective, *3* – polarizing filter, *4* – narrow band filter, *5* – photodetector, *6* – focusing system, h_1 – diving depth of the object under test, h_2 – depth of the water reservoir

tecting systems as well as of selective detecting systems, these ranges in the nearest decade will be enlarged even by one order of magnitude. Laser sound, sounds allow to recognize the sea bottom and to detect the fish shoal, as well as to determine the water mass velocity, turbulence, turbidity and pollution level [65-67].

The experimental data of the PLADS sound verified in the Mexico Bay and other sea regions, as well as the results obtained by using otherless advanced-experimental models of laser depth gauge have allowed to state that devices of this kind can be used both in oceanographic research and economic development of the sea. Therefore, it may be hoped that in a relatively near future the laser depth gauge will find broader applications to various types of measurements made in the sea hydrophere.

Sur l'utilisation du laser pour la mesure de profondeur

L'ouvrage présente certains phénomènes formant le champ lumineux dans la mer, les principes de mesure par le laser de la profondeur dans la mer; on a également évalue l'influence de facteurs limitant l'utilisation

des lasers dans la mer. Les estimations sur la possibilité de l'utilisation des lasers pour mesurer la profondeur ont été fait sur un modèle simplifié de la transmission de lumière dans la mer.

О применении лазера для измерения глубины

Обсуждены некоторые явления, формирующие световое поле в море, и изложены принципы лазерного измерения глубины моря. Делаются попытки опеределения влияния факторов, ограничивающих применение лазерое в море. Оценка применимости лазеров для измерения глубины произведена на упрощенной модели пропускания света в море.

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