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On-board optical television system for underwater vision across the air-sea interface

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This article examines the feasibility of developing an airborne optical television underwater vision system for detecting and recognizing underwater objects across the air-sea interface from a helicopter. The article analyzes the physical mechanisms of optical radiation attenuation in seawater, including absorption and scattering, as well as the influence of phytoplankton, organic, and inorganic impurities on the transparency of the aquatic environment. Passive and active-pulse optical television underwater vision systems are considered, substantiating the advantages of the active-pulse method, which reduces the influence of backscatter and increases the range and contrast of observation. The key elements of the system are described: a photodetector module based on a III+ generation image intensifier with a "blue" photocathode and a pulsed Nd:YAG laser. It is concluded that active-pulse optical television systems offer potential for obtaining high-quality visual information about underwater objects and expanding the capabilities of search and rescue operations.

Keywords: underwater vision, optical television system, active-pulse method, laser illumination, III+ generation image intensifier tube.

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Introduction

Recently, obtaining information about underwater objects has become increasingly important not only for their detection and localization, but also for their recognition and identification using images of these objects. In particular, such tasks arise when using special equipment installed on an aircraft, such as a helicopter, for searching, detecting, and identifying submerged objects, as well as for conducting search and rescue operations. At the same time, the search time for underwater objects from a helicopter's flight altitude is significantly

reduced due to the increased area of the covered observation region.

Attenuation of Radiation

The problem of using radars for these purposes arises from the fact that electromagnetic radiation in the entire radio frequency range used for terrestrial radio communications is unable to propagate in salt seawater, which is a good conductor of electric current. The depth of electromagnetic radiation penetration into seawater can be calculated using the following formula [1]:

$$h = \frac{1}{2 \cdot \pi \cdot f \cdot \mu \cdot \sigma}, \quad (1)$$

where f is the frequency of the electromagnetic radiation, μ is the magnetic permeability of seawater ($\mu = 4\pi \times 10^{-7}$ H/m), and σ is the electrical conductivity of seawater (from 1 to 4 S/m).

However, there is a range of radio waves that can propagate in salt seawater; these are very long radio waves in the extremely low frequency band (from 3 to 30 Hz) and the super-low frequency band (from 30 to 300 Hz). But operation with very long radio waves poses significant technical difficulties. The most difficult task is to create a transmit-receive antenna system due to the very large wavelength, which, for example, at a frequency of 82 Hz is 3658 km. Building an efficient antenna system with dimensions comparable to such a wave geometry is not feasible.

The use of sonar equipment for searching and recognizing underwater objects has fundamental drawbacks inherent to sonar systems: dependence on hydrological conditions, information delay caused by the low speed of sound propagation in water, low spatial resolution, vulnerability to noise, lower accuracy in determining the coordinates of underwater objects, as well as design complexity, increased weight and size characteristics, and high power consumption.

The potential advantages of optoelectronic systems for obtaining images of underwater objects through a disturbed air-seawater interface from a helicopter for detection and recognition purposes include: high spatial resolution, high sensitivity, a high signal-to-noise ratio, and high accuracy in determining the spatial coordinates and range to the detected underwater objects.

This gives rise to the task of considering the use of optical radiation to obtain images of underwater objects through a disturbed air-seawater interface from a helicopter (Fig. 1).

In this case, the processes of scattering and selective absorption of optical radiation in seawater have a significant influence on the image quality even at relatively short distances between the underwater objects and the helicopter-mounted observation system. This influence manifests itself in the decreased brightness and contrast of the image, its distorted

spatial structure, the loss of information about the object's color, a relatively increased noise component of the image, and, finally, in a limited visibility range determined mainly by the following factors. The first factor is associated with multiple scattering, which leads to the blurring of the underwater object's image, the second factor is due to the fluctuating distribution of underwater illumination caused by the random nature of optical radiation refraction at the disturbed surface.

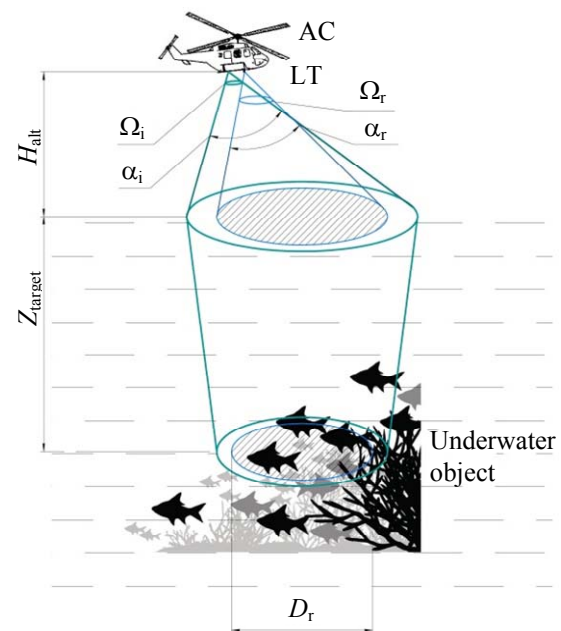


Fig. 1. Formation of images of underwater objects through the air-seawater interface from a helicopter

These fluctuations account for a fluctuation component in the signal, which is caused by wave motion, and the distortion of the image topology. Assuming that these factors are not mutually correlated, their influence on the image quality can be assessed separately. In addition, it is necessary to take into account the helicopter's speed and the multiple interactions with surfaces that the optical radiation undergoes when passing through the air, interacting with the water surface, propagating in the water, and then re-passing through the same surfaces. These interactions become even more complex when the scattering and absorbing substances present in the water have higher concentrations near the surface. All these difficulties together significantly reduce the overall return signal and thus limit the use of an

optoelectronic underwater vision system in shallow areas of the sea surface.

Taking into account the specific features of optical radiation propagation in the sea environment, this paper considers the use of high-resolution optoelectronic television systems to provide observation of the underwater space from a helicopter by recording the illuminating optical radiation reflected from underwater objects and forming an image of underwater objects on a monitor screen, which is used by the onboard operator for recognition of underwater objects under certain observation conditions.

Along the propagation path, the illuminating optical radiation undergoes several types of interactions with the medium (air and seawater) that attenuate its power, including scattering and absorption, which can be estimated using the Bouguer law [1]:

$$\Phi(r) = \Phi_0 \exp \left\{ - \int_0^r [\alpha(r) + \beta(r)] dr \right\}, \quad (2)$$

where $\Phi(r)$ and Φ_0 are the current and initial optical radiation fluxes, r is the thickness of the medium (air and seawater), $\alpha(r)$ is the absorption coefficient of the medium (air and seawater), $\beta(r)$ is the backscattering coefficient of the medium (air and seawater).

Absorption of optical radiation is the main attenuation mechanism that must be taken into account when optical radiation propagates in seawater. The optical radiation is absorbed when photons are absorbed by water molecules, increasing the electronic energy states of the molecules. Due to absorption, the attenuation of the laser radiation in seawater is influenced by a number of factors: the pure seawater itself, phytoplankton, decomposed plant material, and other inorganic particles.

For pure water, absorption of the optical radiation is quite low for wavelengths up to ~ 600 nm. As the wavelength of the probing optical radiation increases, stronger vibrational energy transitions cause a noticeable and significant increase in absorption intensity. The spectral characteristic of pure water absorption is shown in Fig. 2 [1].

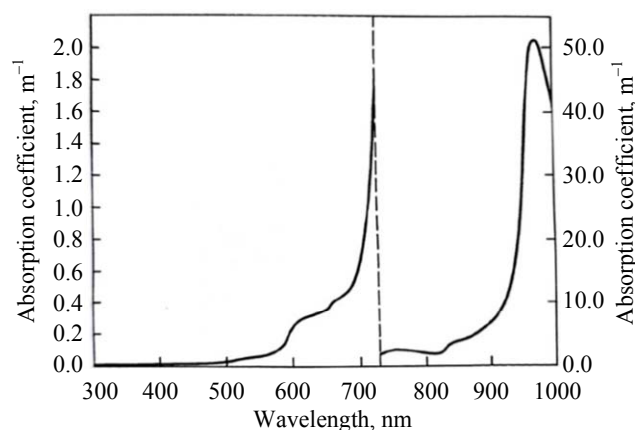


Fig. 2. Spectral characteristic of pure water absorption

The introduction of salt with concentrations typical only of seawater causes a very small increase in the absorption coefficient (on the order of 0.002 m^{-1}) in the wavelength range from 400 nm to 680 nm [3]. This is negligibly small compared to any other attenuating factor in the water medium. Therefore, seawater absorption for any given wavelength can be approximated by pure water absorption for the same given wavelength.

Phytoplankton and other photosynthesizing materials absorb the optical radiation significantly more strongly than pure seawater. The main absorbing component of photosynthesizing materials is chlorophyll, which exists in two types: chlorophyll *a* and chlorophyll *b*. Regardless of the type, chlorophyll has two main absorption bands – one in the “red” region of the visible spectrum, and the other in the “blue” region. Although this indicates that chlorophyll will absorb the optical radiation in these parts of the spectrum more readily, any wavelength of the optical radiation has a probability of being absorbed [1]. The level of optical radiation absorption by phytoplankton and other photosynthesizing materials depends on the location and concentration of chlorophyll in the water. In shallow areas, phytoplankton and photosynthetic materials can occupy the entire water column from the surface to the seabed. In deeper coastal waters or the open ocean, the concentration of photosynthetic materials depends on the intensity of ambient sunlight.

Thus, near the ocean surface, higher concentrations of chlorophyll-containing materials are observed, which partially extend into the water column until sunlight is completely absorbed, and, as the depth increases, the level of

optical radiation losses will be determined by absorption by the water medium. Therefore, the intensity of optical radiation absorption by chlorophyll-containing materials varies greatly depending on the location of the observation system's application. For example, there is no high concentration of these materials in the open ocean, and the absorption intensity caused by them is extremely low. However, in coastal waters, the absorption intensity from these materials can significantly increase the level of optical radiation losses.

In addition, the intensity of optical radiation absorption in seawater is affected by various non-photosynthesizing materials – such as decomposed plant materials known as colored dissolved organic matter, and other inorganic particles that absorb the optical radiation [1].

The spectral dependence of the optical radiation absorption intensity in the open ocean due to the aforementioned loss factors in seawater is shown in Fig. 3 [2].

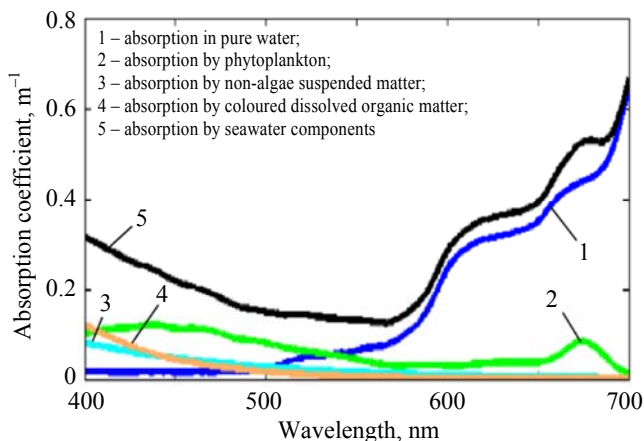


Fig. 3. Spectral dependence of the optical radiation absorption intensity in the open ocean

Optical radiation scattering is also a main attenuation mechanism that must be considered for the optical radiation propagating in seawater, and it takes two forms: elastic and inelastic. Elastic scattering does not result in a change in the wavelength and is often modeled in two different ways: Rayleigh scattering and Mie scattering. The model is chosen depending on the size of the scattering particles and the optical radiation wavelength. Considering that optical radiation absorption is minimal in the spectral range from 450 nm to 550 nm, and the diameter of water molecules is on the order of 0.3 nm,

Rayleigh scattering can be considered only for interaction with pure seawater.

The second elastic interaction of the optical radiation with the sea medium is Mie scattering, which occurs upon interaction with larger particles. The Mie scattering theory considers particles of any size suspended in seawater as a medium through which the optical radiation propagates, and it describes empirical data on the angular distribution of the scattered optical radiation in seawater quite accurately [1]. The angular distribution of the scattered optical radiation in various types of seawater is shown in Fig. 4 as a volume scattering function, which describes the distribution of the scattered radiation power from the incident flux among individual scattering angles [2].

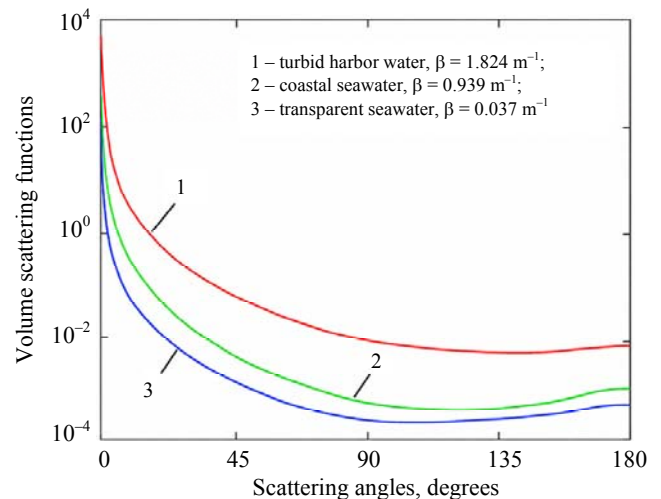


Fig. 4. Distribution of the scattered optical radiation power vs. scattering angles

The curves shown in Fig. 4 and plotted for laser radiation with a wavelength of 515 nm show the contribution of Mie scattering to the total attenuation of the optical radiation during propagation through various seawater types: turbid harbor water, coastal seawater and clear seawater [4]. The scattering values in the curves of Fig. 4 at angles of 0° represent the optical radiation that was either forward-scattered or not scattered at all, while at angles of 180° they show the level of optical radiation that was scattered in the backward direction. All other angles describe the distribution of the optical radiation scattered in any other direction. Analysis of the curves in Fig. 5 shows that most of the incident optical radiation continues to propagate in the forward

direction (~ 0 degrees), and only a small fraction propagates in the backward direction (near scattering angles of 180°). These curves are used to estimate the fraction of the scattered optical radiation in the forward and backward propagation of the optical radiation in various types of seawater.

Since the scattering and absorption characteristics of the optical radiation in seawater depend on the concentration of suspended substances in the water, the ocean depth is usually divided into three zones: the euphotic, dysphotic, and aphotic zones. The most interesting zone for the development of optoelectronic underwater vision systems (OUVS) is the euphotic zone – the region that absorbs 99% of the incident solar radiation at the ocean surface. Typically, the maximum depth for this zone is about 200 m, but it can vary depending on the availability of sunlight. The euphotic zone is the region with the maximum concentration of phytoplankton and other photosynthesizing substances; therefore, the attenuation of the optical radiation will be at its maximum here, and consequently, this region is the most important when designing optoelectronic underwater vision systems [1].

The concentration of phytoplankton and other photosynthesizing material decreases significantly from the ocean surface to the bottom of the euphotic zone, although in some regions of the world, a secondary maximum of the chlorophyll concentration exists at greater depths [2]. In coastal waters, there is a fairly high concentration of the dissolved organic matter throughout the water column, thus causing significant attenuation of the optical radiation. All this affects the perceived transparency of seawater and, consequently, the ability of the optical radiation to propagate through the aquatic environment. For example, most of the foreign impurities characteristic of coastal waters are absent in the open ocean, so the optical radiation losses during propagation in the seawater of the open ocean will be significantly lower than in coastal waters. A classification of the water medium that takes into account specific concentrations of chlorophyll and phytoplankton in seawater has been performed, which makes it possible to better predict how the probing optical radiation will be absorbed and scattered in seawater [5]. According to this classification,

seawater from the open ocean to coastal areas was divided into groups based on optical transmission. The stronger the attenuation of the optical radiation, the higher the number assigned to it. The spectral characteristics of seawater transmission based on the introduced classification are shown in Fig. 5.

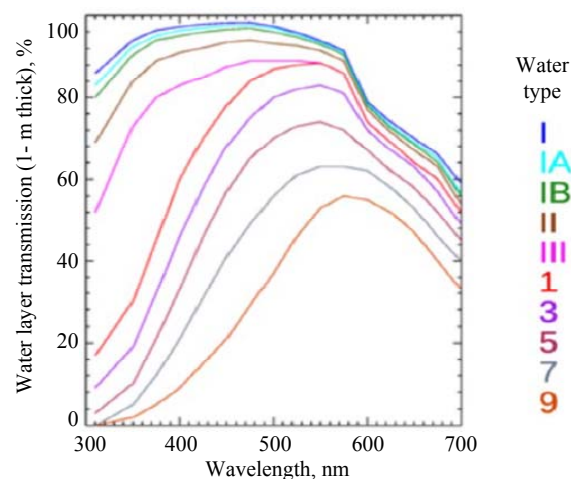


Fig. 5. Spectral transmission of seawater based on the introduced classification

The generalized spectral characteristic of optical radiation attenuation by seawater due to absorption and volume scattering is shown in Fig. 6. Analysis of the obtained characteristic shows that airborne OUVS should have maximum sensitivity in the spectral range of maximum seawater transparency (from 450 nm to 550 nm). Such systems can be divided into two large groups: passive and active-pulsed optoelectronic underwater vision systems.

In passive OUVS, the image is formed under natural (sunlight) illumination, although usually there is no illuminating solar radiation at great depths, or by using powerful searchlight illuminators for the continuous illumination of underwater targets.

The luminous flux is known to be attenuated significantly more strongly in seawater than in the atmosphere. The attenuation of the illuminating optical radiation can be compensated for by increasing the power of the optical radiation flux. However, this leads to increased brightness of the backscattering noise (hereinafter referred to as BSN), which reduces the image contrast. Experience in the operation of passive optoelectronic underwater vision systems shows that increasing the maximum range by 15–20% requires a tenfold increase in the searchlight light

source power [6]. Analysis of the results of operating Russian passive OUVS by specialists at FSUE SPMBM “Malachite” allows us to conclude that the capabilities of searchlight

illuminators to increase the underwater vision range have been practically exhausted. At the same time, their greatest advantage is their relatively low cost [6].

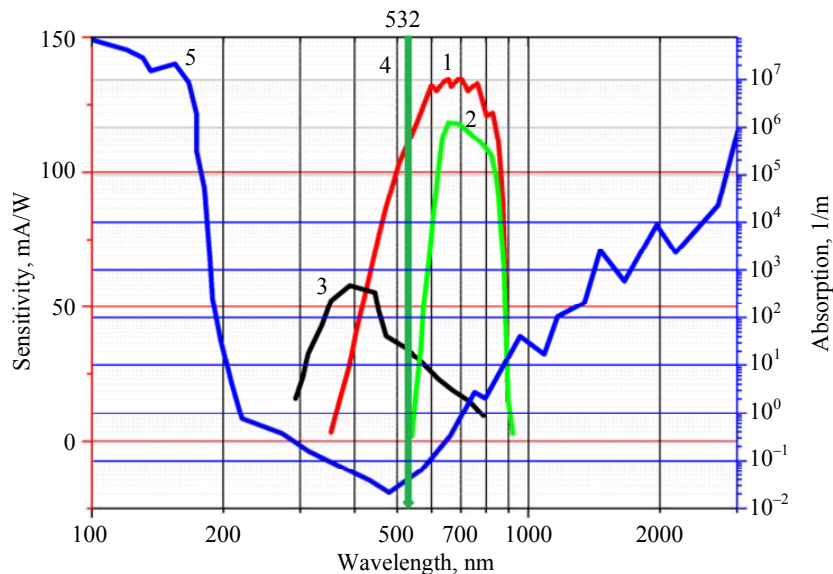


Fig. 6. Spectral characteristics of seawater transparency and the III+ generation image intensifier tube and Nd:YAG laser radiation: 1 – spectral photosensitivity of the III+ generation image intensifier tube with a “blue” photocathode; 2 – spectral photosensitivity of a standard III+ generation image intensifier tube with a GaAs photocathode; 3 – spectral photosensitivity of a II+ generation image intensifier tube; 4 – Nd:YAG laser radiation; 5 – spectral absorption characteristic of seawater

The use of the active-pulse method for forming underwater video images allows for the elimination of the “parasitic” effect of BSN caused by optical noise, such as scattering by seawater and phytoplankton, which is superimposed on the useful image of observed underwater objects, thereby reducing their contrast. The echo signal profile of an active-pulse OUVS located above the sea surface on board a helicopter is shown in Fig. 7.

Active-pulse optoelectronic underwater vision systems use artificial illumination in the spectral range of maximum seawater transparency ($\Delta\lambda = 450\div 550$ nm), which is generated by high-efficiency pulsed laser sources operating synchronously with a gated photodetector optoelectronic television channel sensitive in the same spectral range ($\Delta\lambda = 450\div 550$ nm), also operates in a pulsed mode.

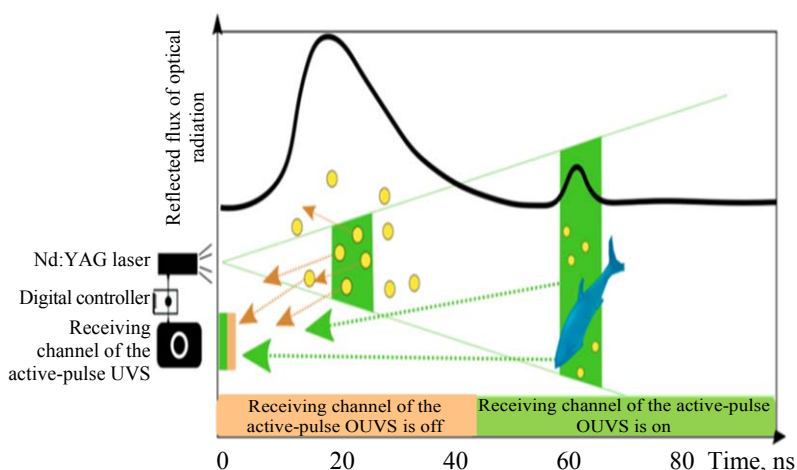


Fig. 7. Echo signal profile of an active-pulse OUVS: 1 – BSN of the marine environment, 2 – reflected signal from the underwater object

The key elements used to create high-efficiency laser active-pulse OUVS are a high-speed photodetector optoelectronic television channel, a high-efficiency pulsed laser, and a high-speed digital controller.

The high-speed photodetector optoelectronic television channel is based on a photodetector module of the FPM-5-1 type with a sensitive structure comprising a “III+ generation image intensifier tube and a programmable gated digital TV camera based on a large-format digital CMOS

array". The module structure uses a specially designed photodetector optoelectronic television channel featuring a negative-electron-affinity (NEA) photocathode with an extended spectral response into the blue-green region of the seawater transparency spectrum (Fig. 6), which is called a III+ generation image intensifier tube with a "blue" photocathode [7]. The developed III+ generation image intensifier tubes have a number of advantages compared to standard generation III+ image intensifier tubes, which have very low photosensitivity in the spectral range of seawater transparency (Fig. 6). Furthermore, generation II+, SuperII+, HyperII+ tubes have significantly lower photosensitivity in the spectral range of seawater transparency (Fig. 6), as well as very low photocathode resistivity, which does not allow for their gating with short pulses (down to a few nanoseconds).

The appearance of the optoelectronic television channel of the active-pulse OUVS based on the FPM-5-1 module type and developed by Joint Stock Company «RPC GEOFIZIKA-NV» is shown in Fig. 8, and its main parameters are given in Table 1.



Fig. 8. Appearance of the photodetector optoelectronic television channel of the active-pulse OUVS based on the FPM-5-1 type module

Table 1

Parameter name	Parameter values
Angular field, degrees	20
Spatial resolution across the field, TV lines	450
Diameter of the generation III+ image intensifier tube photocathode with a "blue" photocathode	18 mm
Spectral range of photosensitivity, μm	0.4÷0.8
Integral photosensitivity, $\mu\text{A/lm}$	2800
Spectral photosensitivity at $\lambda = 530 \text{ nm}$, mA/W	140
Type of digital TV camera based on a CMOS array	e2v EV76C560 ABT
TV camera format	1/1.8"
TV camera resolution, pixels	1282×1026
TV camera pixel size, μm	5.3×5.3
Frame rate, Hz	60
Power consumption, W	20
Weight, kg	1
Overall dimensions, mm	110×80×215

Another key element of the active-pulse OUVS is a high-efficiency pulsed laser, whose active medium is a Nd:YAG crystal. The laser active medium is pumped by diode bars, Q-switching is accomplished by an electro-optical switch, and the oscillation frequency is doubled by a KTP-crystal-based element to

achieve a wavelength of 527 nm, which ensures radiation in the spectral region of seawater transparency (Fig. 6). The appearance of the pulsed Nd:YAG laser of the N-R50-532 type, developed by the Institute of Physics of the National Academy of Sciences of Belarus (Republic of Belarus) as part of the active-pulse

OUVS, is shown in Fig. 9, and its main parameters are given in Table 2.



Fig. 9. Appearance of the pulsed Nd:YAG laser of the N-R50-532 type

To control the pulsed power supply of the generation III+ image intensifier tube with the “blue” photocathode, the digital CMOS array and the pulsed Nd: YAG laser, as well as for the primary processing of digital images of detected underwater objects, a high-speed digital controller is used. The adjustable time-gating control turns on the receiving channel of the active-pulse OUVS at a specific range, eliminates BSN, and provides observation of the underwater space through its depth in the absence of solar radiation.

Table 2

Parameter name	Parameter values
Radiation wavelength, nm	532 ± 5
Pulse energy, mJ	> 50
Fixed pulse repetition rate, Hz	20
Pulse duration, ns	< 10
Beam diameter, mm	< 5
Beam divergence, mrad	< 3
Power consumption, W	300
Weight, kg	2
Dimensions (without cooling system), mm	50×60×165

Conclusion

The implementation of active-pulse technology has led to the creation of optoelectronic television systems that provide observation of the underwater space from a helicopter by recording the illuminating optical radiation reflected from underwater objects and forming an image of objects on a monitor screen, which is used by the onboard operator for recognition of underwater objects under certain observation conditions.

The practical significance of the active-pulse mode consists in achieving a longer underwater vision range compared to other passive optical and optoelectronic devices, as well as high-frequency sector-scanning sonars operating under identical conditions. Changing to a qualitatively new level of obtaining visual information acquisition will expand the naturally limited capabilities of the human eye.

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