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BISTATIC UNDERWATER OPTICAL-ELECTRONIC COMMUNICATION: FIELD EXPERIMENTS OF 2017–2018

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ABSTRACT

The article describes the results of experiments with underwater bistatic optoelectronic communication systems with scattered laser radiation as the source of information and the valid signal. The information reception distance of up to 40 m was gained in field conditions of lake water.

Keywords: natural water medium, bistatic optical communication, scattering, probabilities and SD of communication errors, photoelectronic multipliers

1. INTRODUCTION

The works [1–3] review capabilities and variants of development of underwater bistatic optoelectronic communication systems (OECS), which use scattered or reflected optical radiation (in particular, laser radiation) as the source of information and the valid signal[1].

Theoretical studies of transmitting properties of bistatic channels of OECS are being conducted within the frameworks of the theory of short-wave radiative transfer in scattering and dissipative media (such as the atmosphere and water media) and the theory of linear system analysis. The relation between radiance in a given point and in the given direction in a medium with the optical characteristics of the medium is determined by the radiative transfer equation which has the following integro-differential form:

$$\frac{1}{c}\frac{\partial I}{\partial t}+\left(\omega, grad\ I\right)= \\ =-\beta_{\text{ext}}I+\beta_{\text{sc}}\int_{\Omega} I\left(r,\omega'\right)g\left(r,\omega,\omega'\right)d\omega'+\Phi_0\left(r,\omega\right),$$

where $I = I(\lambda, r, \omega)$ is the radiance at a wavelength λ in point r in the direction ω; c is the light speed; $\beta_{\text{ext}}(\lambda, r)$ is the extinction coefficient at λ in point r; $\beta_{\text{sc}}(\lambda, r)$ is the scattering index at λ in point r; $g(\lambda, r, \omega, \omega')$ is the scattering indicatrix at the wavelength λ in point r in the direction ω; ω' is the direction of radiation before scattering; Φ_0 is the source function in point r in the direction ω.

This equation: *a*) is linear in relation to l, therefore the analysis of transfer properties of the bistatic communication channels is practicable to be performed within the framework of the linear systems theory, i.e. to study the channel reaction $h(t)$ for the input $\delta(t)$ impulse depending on the input parameters of OECS; *b*) does not have a general analytical solution, therefore different algorithms of the Monte Carlo method (from the forward modelling algorithms [4] to modifications of double local estimates [5]) are used for its solution for applications related to communicative underwater bistatic OECS.

The publications [6–10] overview the modelling results of impulse reactions of underwater

[1] Bistatic OECS are more often called *Non Los of Sight (NLOS)* OECS in literature, and sometimes those using reflected radiation as a valid signal are called *Direct NLOS* OECS, whereas those using scattered radiation are called *Non Direct NLOS* OECS

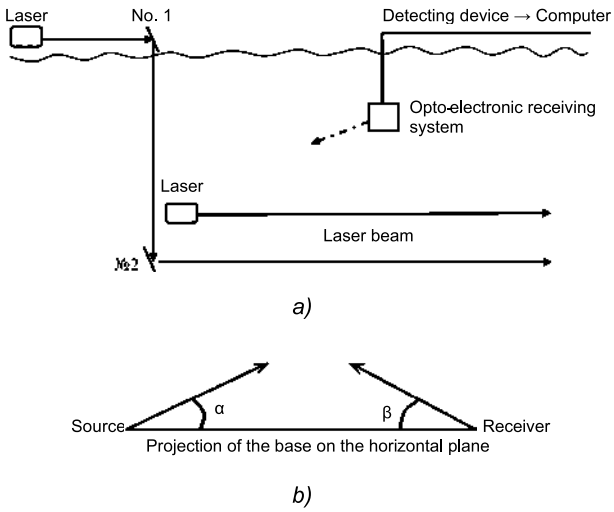

Fig. 1 Schemes of the experiments: *a* – side view: "green" laser on the lakeshore and "blue" laser in the water; *b* – plan view: direction of optical axes of the radiator and the receiving system

communication channels by means of the Monte Carlo method, with the help of which the maximum ranges of coverage of specific variants of underwater *Direct NLOS* OECSs were evaluated. Those were ranging between 5 and 100 m depending on the varied parameters of OECS and optical condition of the water medium. In [10], the impact of random wave tilts on the air-water interface on the OECS coverage range was taken into consideration, whereas in [9], the impact of optical-geometric conditions of bistatic channels formation on probabilities of communication errors was assessed.

The article [11] proposes an analytical model of the received bistatic signal, described the results of pool experiments with the distances between the source and the receiver (called basic) L of up to 50 m. Comparison of theoretical estimations of signal strength loss has shown that the proposed model is rather consistent with experimental measurements with L ranging between 10 and 50 m. On these routes, the signal loses its strength at (6–10) dB depending on the optical condition of water and orientation directions of the source and the receiver optical axes. The same work contains the results of experiments in the *Woods Hole Oceanographic Institution*, the USA, in the course of which underwater optical communication was performed in puddled water at distances of up to 40 m. The article [12] discusses the results of our first experiments with bistatic OECS[2] in the *natural water medium*.

2. EQUIPMENT, SCHEMATICS, AND THE RESULTS OF EXPERIMENTS

The goal of this work was to compare the range of coverage and quality of underwater communication (based on communication errors and standard deviation (SD)) on the basis of the field experiments of 2017–2018 conducted during tests of underwater bistatic OECS with various-spectra radiation sources and various average power in a *natural* water basin. Since these characteristics depend on the optical condition of water medium, it was of interest to compare them during tests in different periods of the year (in winter, when the water is less puddled and in spring, when the lake receives aerosol from the atmosphere and wastes from the surrounding territory.

A detailed description of the methodology of the experiments of 2017–2018 and the equipment used for them is given in [14]. Let us briefly repeat it. As impulse radiation sources, a "green" laser based on the vapours of cupric bromide (peak λ = 510.6 nm) developed by IAO SB RAS and a "blue" laser module *B2000* (peak λ = 445.0 nm) switched to impulse mode were used. Real-time probing of communication channels quality was performed based on estimations of sample average values and SD of communication errors. For this purpose, a test periodical graphic signal was transferred via the communication channels. The experiments of 2015–2016 were conducted both in water medium and through the ice into and out of the water [12].

The average power of the impulse "green" laser during the 2017–2018 experiments was equal to (4–6) W and that of the "blue" one was equal to (13–20) mW, laser beam divergence did not exceed 1° and 2° within the field of sight of the receiving system.

The orientation schematics of receivers and sources of radiation implemented during the experiments are shown in Fig. 1.

The place of the experiment was the Boyarskoye lake near Tomsk. According to [16, 17], it may be proposed that the Boyarskoye lake is eutrophic with optical characteristics close to those of the water of the Lapa lake in Altai Krai. Like the Boyarskoye lake, it is a closed lake, a dead stream branch located in the vicinity of the city. The experiments with the "green" laser were conducted in Febru-

[2] Field studies of bistatic OECS in the atmosphere are described, for instance, in [13–15].

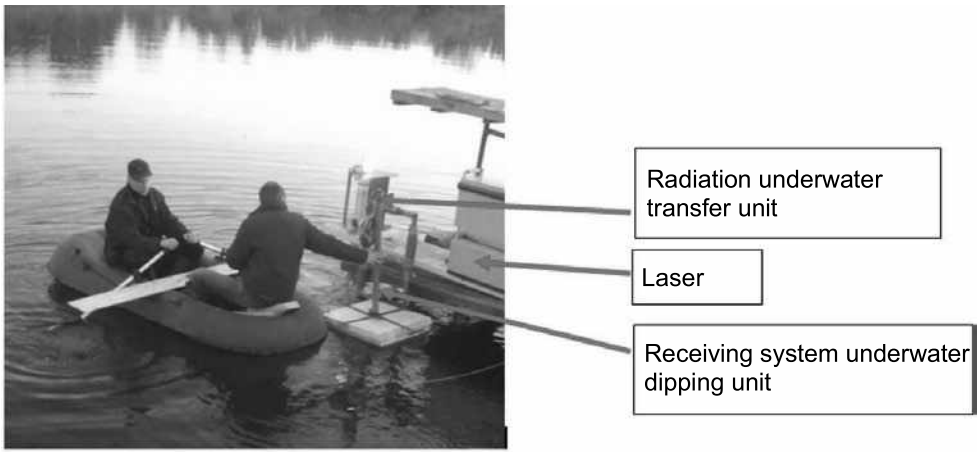

Fig. 2. Photo of the experiment participants moving the receiving unit across the lake and main units of the OECS laboratory set

ary and May, 2017. Input of the "green" laser radiation in winter was performed by means of two mirrors, No. 1 and No. 2 (Fig. 1, *a*) through a hole in the ice (the ice thickness reached 50 cm, the depth of the lake in the experimental areas is 6 m). The impulse frequency of the laser radiation was 11 kHz, their duration was (20–40) ns. In 2017, the receiving unit included an FEU-84 photoelectronic multiplier. The receiving unit was dipped in the water through the hole in the ice to the distance of up to 70 cm from the lower ice border. The results were obtained for L ranging between 5 and 25 m and are discussed in [13]. The distinction of the geometrical scheme of the underwater experiments (i.e. not through the ice layer) was that dipping depths of the receiving unit and the laser beam were different. Such schemes of communication arrangement are called noncoplanar. The optical axes of the radiator and the receiving system were parallel to the lower border of the ice, did not cross each other, and the distance between them was 20 cm. The average radiant power of the laser on the first mirror did not exceed 4 W.

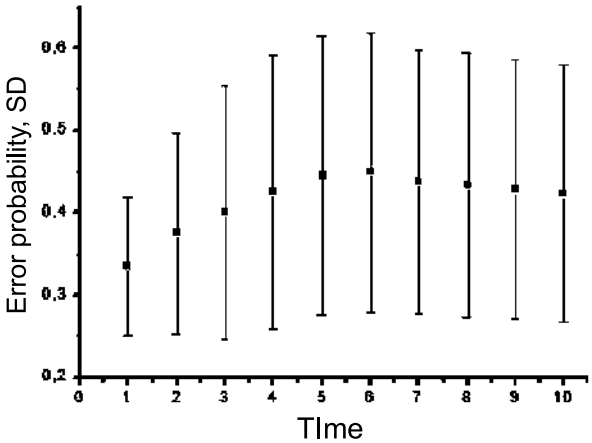

Fig. 3. Dependencies of single values of error probability and SD intervals (vertical lines) on the period of underwater channel quality probing (for communication conditions, see the text)

Let us describe the results of summer (May) tests of the same year, which were conducted using the same laboratory set and scheme of communication channel arrangement as in February (Fig. 1) but with laser radiant power of 6 W. The receiving unit and the laser source were dipped at a depth of 1 m from the water surface. The photo (Fig. 2) shows the main units of the OECS laboratory set and the participants of the experiments. One of the main goals of these experiments was to determine the maximum L with fixed characteristics and parameters of the radiator and the receiving unit. In the course of the experiments, for each value L, the angle α was fixed and the angle θ was changed (Fig. 1, *b*). Probability of communication errors and their SD were estimated in real time. 7,000 to 90,000 symbols were transmitted during each communication session with a duration varying between 7 to 30 min. The duration of each experiment was 1 to 3 h. L was increased with the step of 5 m starting from 5 m. Maximum L was equal to 40 m. This result is close to that previously obtained in artificial and natural water basins [11].

Fig. 3 shows one of the results of quality probing of the underwater channel with $L = 40$ m. Quality criteria: sample average and SD of communication errors (y-axis in Fig. 3) and conditioned time (x-axis). The values of angles α and β (Fig. 1, *b*) were 8.5 and 75.0° respectively.

Unlike the results obtained in winter (February), with $L = 25$ m [12] and close to the said values of α and β, the quality of the summer (May) communication channel was significantly worse than that of the winter one. This may be explained by the fact that

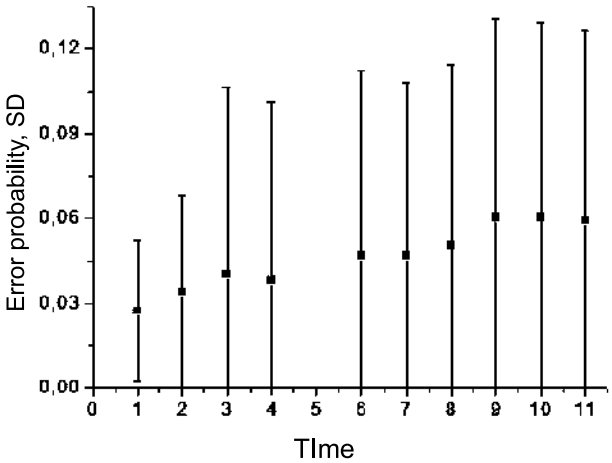

Fig. 4. Similar to Fig. 3. The "blue" laser and the receiver are in the water on the level of 10 cm from the lower border of ice. L = 10 m, α = 3°, and β = 2°

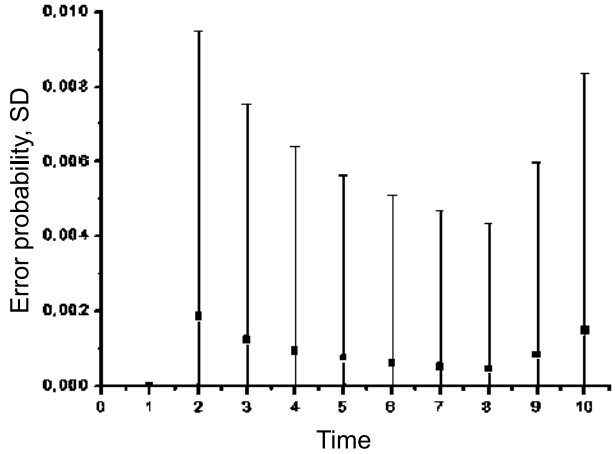

Fig. 5. Similar to Fig. 3 and 4. The "blue" laser and the receiver are in the water on the level of 43 cm from the lower border of ice. L = 10 m, α = 31°, and β = 25°

increasing of L causes decreasing of fluence on the entry gap of the receiving system which is not compensated by increasing of laser radiant power from 4 to 6 W in these experiments. Another reason of deterioration of quality of the underwater communication channel is that water turbidity is higher in summer than in winter when the water basin is covered with ice and is not being filled with substances increasing its turbidity (see, for instance, [16, 17]).

In 2018, the laboratory setting of the bistatic OECS was modified: FEU-84 was replaced by UFK-4G-2 photomultiplier (manufactured by OOO Katod, Novosibirsk), the optical unit of the receiving system was supplemented by *Semrock FF01–442/42–25* filter, and a semiconductor laser on the basis of the *B2000* module was used as a radiator with the average impulse mode power of 20 mW (peak λ = 445.0 nm). In February 2018, using this (modified) OECS set, the experiments similar to those conducted in 2015 using the "blue" laser were conducted with the average power of 13 mW and the same value of L (Fig. 1). Let us compare the quality of underwater bistatic communication channels for two variants of receiving systems. The example of the estimation results of probabilities and SD of communication errors in the "blue" underwater winter channel taken from [12] is shown in Fig. 4.

Fig. 5 shows one of the quality estimation results of the "blue" underwater bistatic OECS channel during the experiments in February 2018. As we can see, the quality of the 2018 "blue" channel is an order of magnitude higher than that of the 2015 one. If we check the geometrical characteristics of the communication channel formation schemes, we can see that they were more optimal in 2018 than in 2015. In the first case, the angles α and β complied with the situation when the receiver was oriented towards the source; in the second case, the receiver was oriented towards the section of the laser beam distant from the source. The average laser ra-

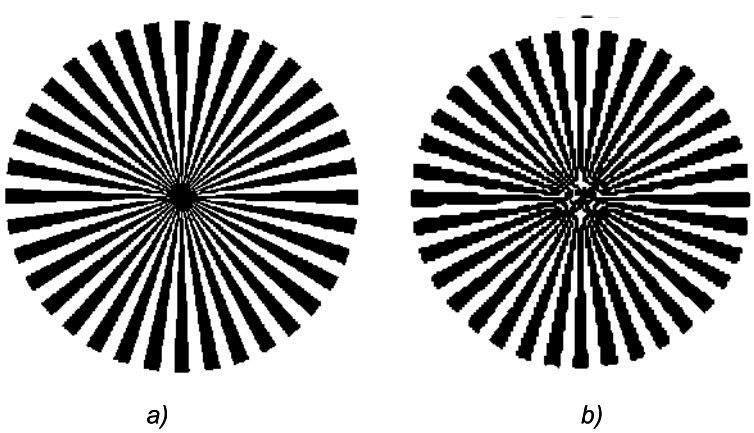

Fig. 6. Original sectorial target (*a*) and received image of the same (*b*)

diant power is 1.5 times higher in the second case than in the first one, but does not provide an increase of the communication channel quality by an order of magnitude. Therefore, the communication quality significantly increased in 2018 due to application of UFK-4G-2 photomultiplier.

In 2018, experimental transfers of images of a flat test object (sectorial target) were conducted. Fig. 6 contains the images of this object for communication conditions compliant with Fig. 5.

3. CONCLUSION

Possibility to develop operational optoelectronic systems of bistatic underwater communication based on scattered laser radiation in the visible range of wavelengths in lake water with base distances between the source and the receiver L of up to 40 m was experimentally confirmed, which is consistent with the results of [11].

There are reasons to propose that the range of coverage of such OECSs may reach hundreds of metres by applying laser sources with significantly higher output and more sensitive photodetectors. We also proved that the application of contemporary UFK-4G-2 photomultipliers instead of FEU-84 increases the quality of communication by an order of magnitude.

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