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OPTICAL COMMUNICATION ON SCATTERED OR REFLECTED LASER RADIATION

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ABSTRACT

Results of theoretical and experimental research of NLOS (Non-Line of Sight) communication systems in the atmosphere, under water, and in mixed media based on publications of authors from China, Canada, Greece, the USA, Great Britain, Russia, and other countries are discussed in the present work. The theory of radiation transfer and the linear systems theory provide the basis for theoretical research. The radiation transfer equation is solved by the Monte–Carlo method in the single-scattering approximation. It is demonstrated that approximate methods are applicable when the average scattering multiplicity in open communication channels does not exceed 1.

The Monte Carlo method is used to study the influence of optical-geometric parameters of schemes of communication channels on the probabilities of communication errors, signal/noise ratios, limiting base lengths, attenuation of information-carrying signals, and their superposition leading to communication errors.

Examples of communications in the atmosphere in the UV range at distances up to 1300 m, in the visible range up to70 km, and under water up to 20 m are given.

Search for optimal methods of signal modulation, development of software and hardware complexes for numerical simulation of the transfer properties of communication channels, refinement of analytical models of impulse transfer characteristics of non-coplanar schemes of bistatic optoelectronic communication systems (OECS), and research of the effect of wind-driven sea waves and processes of radiation scattering in water are planned to study the efficiency of operation of the communication systems and to expand ranges of variations of the input NLOS and OECS parameters in the experiments carried out in natural water reservoirs.

Keywords: optical communication systems in the atmosphere and under water, Monte Carlo method, single scattering

1. INTRODUCTION

Essential progress in the development of modern high-quality communication and control systems through atmospheric channels is connected with application of radio waves for these purposes. Communication in radio range is all-weather and accessible practically to everyone.

Historically, the optical range was first used for high-rate message transfer. Though the exact date of the beginning of optical communication is unknown, it is possible to suggest that it goes in depth of centuries, when alarm fires, torches, and so forth were used for message transfer. Nowadays this communication technology is used to transmit signs of the telegraph Morse code using directional devices (for example, ISNP-250M).

Centuries later, new technologies based on applications of laser radiation sources and fibre optic channels have replaced these simplest methods of information transfer. Integration of possibilities of radio and optical communication systems of this type has culminated, in particular, in the development of the worldwide communication network – the Internet.

Does it make sense to create new optical communication systems and whether the conditions exist at which control signals or information flows cannot be transferred in radio range through the air or in acoustic range through water? Yes, because there is the impossibility or undesirability of application of radio-waves or low rates of data transfer by low rate of data transmission by acoustic devices underwater.

Therefore, the next branch of optical communication systems based on application of open communication channels in vacuum, atmospheric, and water media has been developed that allows line-of-sight information flows to be transmitted and received. Communication systems of this type are more often called *LOS* (*Line-of-Sight*) systems abroad. The useful signal in them is unscattered optical radiation. Extensive theoretical investigations devoted to the feasibility of realization of the LOS systems, estimation of their range of action in air, water, and mixed (water-air or air-water) media are performed. Results of these and experimental investigations have already been published in numerous works and continue to be published intensively (for example, see [1–10]). There are commercially available optoelectronic communication systems (OECS). A PAVLight ET-4000 optical modem can serve as an example.

This review presents results of theoretical and experimental investigations of the OECS, in which useful signal is scattered or reflected optical radiation. These OECS in Russia are called over-the-horizon or bistatic communication systems and abroad they are more often called *Non-Line-of-Sight (NLOS*) communication systems. Despite that the feasibility of realization of such communication was reported in scientific publications in the last century (for example, see [11]), intensive theoretical and then experimental studies in this direction have been started more than 15 years ago and remain relevant nowadays.

The main advantage of line-of-sight communication is high rate of data transfer. However, it can be interrupted because of interference on the radiation propagation path and beam wandering over the receiver aperture plane caused by turbulent pulsations of optical characteristics in open communication channels. Non-line-of-site optical communication has no such disadvantages. Advantages of the *NLOS* communication in comparison with *LOS* communication are that it can be realized at much larger distances when there are barriers between the receiver and the transmitter and that it is multiuser one.

Below we limit our consideration by the communication systems based on pulsed radiation sources considering that they have essential advantages at least in the range of action (and we are interested in over-the-horizon communication) over the systems with cw radiation sources.

In the review we do not consider all results of investigations in this scientific and technical area. This does not mean that the works that are not included in References of the present review have contained no new results by the moment of their

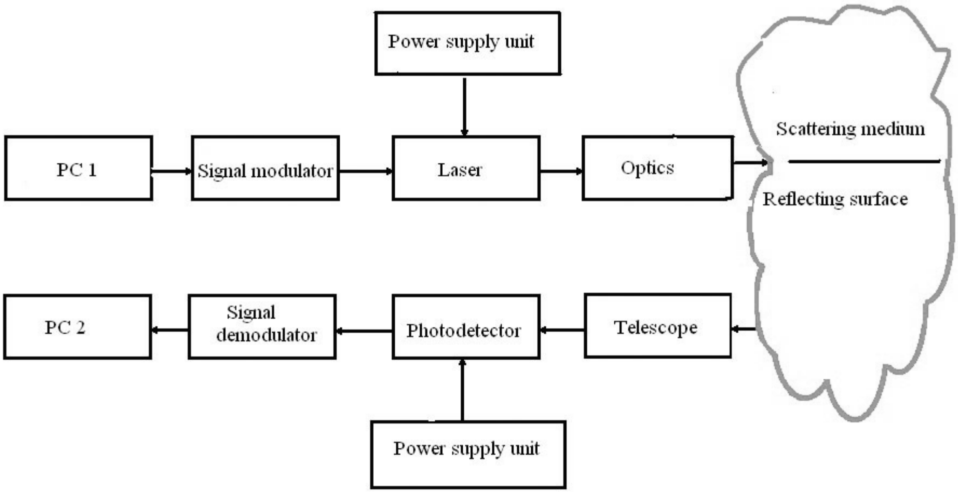

Fig. 1. General block diagram of an over-the-horizon OECS

publication; this is due to the fact that hundreds of works have already been published in reviewed journals, proceedings, and materials of conferences and symposiums.

2. PURPOSES OF RESEARCH AND PROBLEM FORMULATION

Let us describe the bistatic OECS by a set of the following parameters (we call them input ones). The radiation source: wavelength λ, polarization type, angular beam divergence ν_s, outer radius of the initial beam cross section r_s, orientation of the optical axis $\boldsymbol{\omega}_s(\theta_s, \varphi_s)$, and average power P_s. Receiving optoelectronic system: field-of-view angle ν_d, radius of the entrance pupil r_d, orientation of the optical axis $\boldsymbol{\omega}_d(\theta_d, \varphi_d)$, spectral sensitivity of the photodetector and level of its noise N. The blocks of electronic modulation and demodulation of transmitted and received radiation are compound multi-component elements of any communication system, including bistatic one. The base distance between the source and the receiver L_d is the main external OECS parameter. Fig. 1 shows the block diagram of the bistatic OECS.

In Fig. 1 we have used the following designations: PC1 denotes the control computer, PC2 denotes the receiving computer to record the obtained information and, for example, to estimate the quality characteristics of the communication channel, etc. Modulator is intended for input of information into the laser beam, and Demodulator is intended for decoding of the received scattered or reflected laser radiation. In the unit Optics, laser radiation with required divergence is formed; radiation with wavelength λ_1 can be converted into radiation with wavelength λ_2, etc. We note that in literature, bistatic OECS are sometimes called Direct NLOS if the useful signal is reflected from a surface (a building, an aircraft, a ship bottom, an air-water interface, etc.) and Non-Direct NLOS if radiation is scattered in water or in air medium.

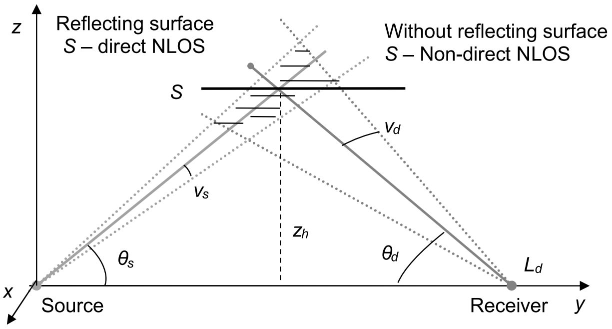

Fig. 2. Geometrical scheme of forming external channels of over-the-horizon communications

The general geometrical scheme of forming a bistatic communication channel is illustrated in Fig. 2. To simplify the figure, a coplanar OECS is shown with optical axes of the laser beam and receiving optical system located in the *XoY* plane and orientation of the axes determined by the elevation angles θ_s and θ_d.

To the main (called *output*) OECS characteristics as a whole, we refer the error probabilities *p*, their standard deviation (SD) σ, and the rate of symbol transfer *s*. Each of these characteristics depends on the parameters of transceiving systems and geometrical parameters of the schemes of external channels of the bistatic OECS.

Therefore, the main goals of theoretical and experimental investigations of the bistatic communication or control systems consist in the determination of these characteristics depending on the entire set of the parameters determining the concrete OECS type or on some part of these parameters as well as on the optical conditions in the external channels of radiation propagation from the source to the receiver. In addition, experimental investigations can be aimed at confirmation or disapproval of theoretical conclusions on the feasibility of realization and characteristics of these or other OECS. Thus, for example, in [11] the feasibility of realization of over-the-horizon communication in the UV wavelength range was predicted in 1997 at base distances up to 200 km. So far, this conclusion has neither been confirmed, nor denied.

3. ATMOSPHERIC OVER-THE-HORIZON COMMUNICATION SYSTEMS

From the viewpoint of the system analysis, any of the OECS shown in Fig. 1 can be subdivided into two parts: transceiving system and external communication channel. For fixed characteristics of optoelectronic blocks in Fig. 2, the output OECS characteristics will depend on the optical state of the channel of radiation propagation from the source to the receiver. Both in the atmosphere and in the water medium these conditions can greatly change [12–15]. Therefore, attention in [16–40] was focused on an analysis of the influence of the input OECS parameters, including the optical properties of the atmosphere, on the communication quality.

For all other conditions remaining the same, the optical properties of the communication channel can limit the working range of the OECS, increase the probability of errors, and, as for one of the means of overcoming these limitations, to a forced decrease in the rate of information signal transfer.

Theoretical research of the transfer properties of the bistatic OESS channels are carried out within in the context of the theory of short-wave radiation transfer in scattering and absorbing media (namely, in the atmosphere and water media) and of the theory of analysis of linear systems.

The radiation transfer equation (RTE) establishes a relationship between the light field intensity at the given point in a preset direction in the medium and its optical characteristics. In the integro-differential form, it is written as

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

where $I = I(\lambda \boldsymbol{r}, \omega)$ is the radiation intensity at the point $\boldsymbol{r}$ in the direction ω, c is the velocity of light, $\beta_{ext}(\lambda \boldsymbol{r})$ is the extinction coefficient at the point $\boldsymbol{r}$, $\beta_{sc}(\lambda \boldsymbol{r})$ is the scattering coefficient at the point $\boldsymbol{r}$, $g(\lambda \boldsymbol{r}, \omega\omega')$ is the normalized scattering phase function at the point $\boldsymbol{r}$ in the direction ω, ω' specifies the direction of radiation propagation before scattering, and Φ_0 is the source function at the point $\boldsymbol{r}$ in the direction ω.

Equation (1) is linear for the intensity; therefore, it is expedient to analyze the transfer properties of the bistatic communication channel in the context of the linear systems theory, that is, to investigate the channel response $h(t)$ to the input $\delta(t)$ pulse depending on the input OECS parameters.

Equation (1) has no general analytical solution. For communication with the NLOS systems, different algorithms of the Monte Carlo method (from direct simulation algorithms [19] to double local estimate modifications [20]) are often used. The single scattering approximation for the determination of impulse response h (t), pulse broadening, etc. has obvious limitations of its application field. This is illustrated in Fig. 3.

The time interval [t_1, t_2] indicated in Fig. 3 corresponds to the intersection of the laser beam divergence angle with the field-of-view angle of the receiving system in Fig. 2 (hatched region). The function h (t) for t lying beyond this interval is determined by radiation with scattering multiplicity higher than 1. This means that the leading and trailing edges of the impulse response $h(t)$ in Fig 3 can be determined by solving RTE (1) taking into account scattering multiplicity no lower than 2.

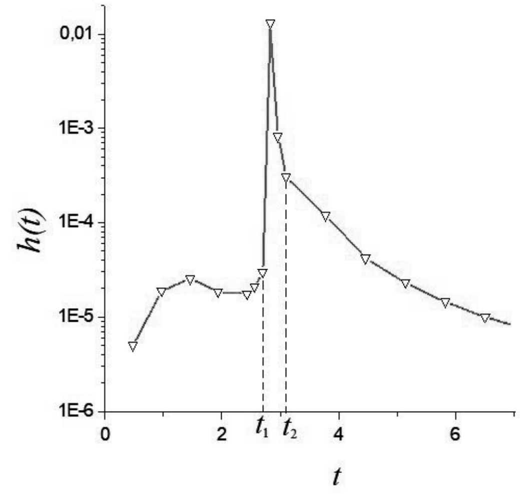

Fig. 3. Example of the impulse response simulated in [18] by the Monte Carlo method

The atmospheric OECS have a wider spectral range of characteristics of laser sources – from UV to IR ranges; for the underwater systems, this choice is limited by the visible range (*green* and *dark blue* ranges).

What are reasons for interruptions or infeasibility of bistatic communication? Obviously, to record informative signal, its power must be greater than the power P_f of the intrinsic photodetector noise. Communication errors arise if this condition is not satisfied from time to time. This can be caused by the presence of turbulent fluctuations of the optical characteristics in the communication channel or when local scattering or absorbing optically denser formations (fragments of smoke plumes, cloudy media, etc.) fall within the receiver field-of-view. The power of the received informative signal can exceed that of noise, but nevertheless, communication can be impossible. This occurs when the impulse response at $t < t_1$ and $t \to t_1$ or at $t < t_2$ and $t \to t_2$ becomes close or equal to max h (t) in its central part.

Let us try, proceeding from this general knowledge of interaction of optical radiation with scattering and absorbing media, to estimate the influence of some optical-geometrical parameters of bistatic OECS, for example, on the range of action. We now perform a number of the following thought experiments. We fix all geometrical and optical parameters and the photodetector characteristics. Let the laser radiation beam divergence v_s be zero. And let the range of action reaches L_d. We will increase v_s to $\pi/2$. It is obvious that L_d will monotonically decrease since the radiation flux density in the region of intersection of cones of the beam divergence and of the field of view of the receiving optical system will monotonically decrease (Fig. 2). The increase in v_s will also result in the increased impulse response at $t < t_1$ and $t \to t_1$ or at $t < t_2$ and $t \to t_2$, thereby increasing the probability of errors, which can be decreased by decreasing the pulse transfer rate.

Let all optical-geometrical parameters of the OECS scheme be fixed (Fig. 2), except the field-of-view angle of the receiving optical system v_d, which we will monotonically increase starting from zero value. We assume that at $v_d = 0$ the range of OECS action is equal to L_d. It can be easily demonstrated that with increasing v_d, the power of the fronts of the impulse response $h\ (t)$ will increase together with the interval $[t_1, t_2]$, but max $h\ (t)$ will not increase. Both these factors can lead to an increase in the communication errors, that is starting from some critical v_d values the maximum base L_d will decrease.

It is sufficiently simply to predict the dependence of L_d on the variations of some optical properties of the medium in which the external channel of the OESS in Fig. 2 is formed. Let the optical characteristics of the medium be homogeneous. We fix values of the remaining OECS parameters. Let the scattering properties of the medium be absent. Then obviously, the base $L_d = 0$, the probabilities of errors $p = 0$, and the rate of symbol transfer $s = 0$. Let the scattering coefficient $\beta_{sc} \to \infty$; then it is obvious that $L_d \to 0$, the probabilities of errors $p \to 0$, and the rate of symbol transfer $s \to 0$. Hence, for each concrete β_{sc} value, there exist nonzero values L_d, p and s. This means that for each set of the input OECS parameters, there exists such optical state of the medium at which a maximum L_d value can be realized.

This suggests that optimal conditions for communication (at least, from the viewpoint of max $h(t)$) can be obtained by variations of the orientation angles θ_s and θ_d of the transmitter and receiver axes (given that all other OECS parameters remain the same), when θ_s and $\theta_d \to 0°$. This conclusion remains the same if vertical optical inhomogeneity of the atmosphere is considered with its scattering properties decreasing with increasing altitude above the Earth surface. In this case, exotic cases when the scattering properties near the Earth surface $\beta_{sc} \to \infty$ were disregarded. It is obvious that an increase in the average or peak laser radiation power will lead to the increase of the maximum L_d values.

As to the atmospheric OECS, much greater number of theoretical and experimental works was devoted to the UV NLOS systems. A fairly good review on the history of the development of UV signal transmission and registration is suggested in [16]. The lamps and flash lamps mentioned in this work were previously used as light sources in communication systems. All these devices, as a rule, are bulky, and consume significant power. Semiconductor optical sources have low cost, small size, low power consumption, and high reliability. Therefore, modern commercial light-emitting diodes and photodetectors (including avalanche ones) are accessible and are widely used in the bistatic UV communication systems. Nevertheless, there are examples of application of solid-state UV lasers [21] and of transformation of output radiation of the visible range lasers into the UV range [56].

The overwhelming majority of experimental investigations in [16–40] consider UV OECS with application to small bases L_d. In [56] a bistatic communication was operated in this spectral range in the daytime at the base distance equal to 1300 m.

We emphasize that the number of works on the OECS in the visible and IR spectral ranges is significantly less than of works on the OESC in the UV range. Works [2] (an infrared LOS OECS) and [53] (a visible range NLOS OECS) can be mentioned here as examples. Interest to the UV communication systems is understandable. In the solar-blind range they can be employed round the clock in the absence of artificial UV noise sources.

The main methods of research of the transmission properties of NLOS channels are the Monte Carlo method [18–20,23,29,30,32,33,34,39,50–52] and the single scattering approximation [11,17,22,38]. In [17–19] results of theoretical and experimental investigations of the influence of the geometrical parameters on the probabilities of errors and range of action of the bistatic OECS were presented. In [30] it was shown that the single scattering approximation cannot be used to solve the RTE to explain exhaustively the results obtained in experiments. In [30] the widths of the impulse response determined for concrete input parameters of the OECS schemes by the Monte Carlo method and in the single scattering approximation were compared. It was shown that the single scattering approximation is applicable to estimate *h* (*t*) if the medium is transparent and the multiplicity of scattering in the atmospheric channel does not exceed 1. In model experiment with the average number of collisions in the channel equal to 3.85, the duration of *h* (*t*) was 8 μs, whereas in the single scattering approximation it was practically absent.

The common feature of [16,17,19,21–36,38,39] was that they presented results of theoretical and-or experimental investigations devoted in some extent to an analysis of the influence of the input OECS parameters on the communication quality (probability of errors) and range of action (not exceeding 100 m in the experiments) on the rate of data transfer and the protection against noise.

In [54] an example of simulation by the Monte Carlo method of the impulse response was given, and with its help ranges of action and data transfer rates were estimated taking into account the characteristics of a FEU-17a photodetector. Statistical experiments were performed for the OECS comprising the laser radiation source at a wavelength $\lambda = 0.5$ μm. A dependence of the communication quality on the temperature regime of the receiver operation was considered in [6, 57].

An important place in theoretical and experimental investigations of experts on the bistatic OECS was occupied by the methods of increasing the stability of their operation. The choice of the methods of radiation modulation and their comparison was considered, for example, in [26]. In [23, 25] different types of the OESS radiation receivers were discussed.

4. UNDERWATER BISTATIC COMMUNICATION SYSTEMS

Works [41–51, 55] were devoted to theoretical and experimental investigations of underwater communication systems. Among them, attention is drawn to work [44] in which extensive review of studies was presented devoted to the LOS systems, but including some aspects of the communication NLOS Systems. It contains 232 references to publications of authors from the USA, Canada, China etc. Let us complement it by a short analysis of other works.

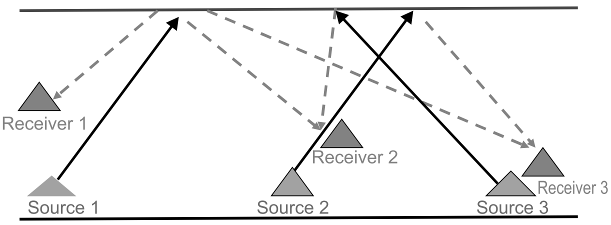

Fig. 4. Geometrical scheme of underwater communication based on radiation reflection from the water-atmosphere interface

In Fig. 4, one of such problem formulations considered in [46, 51] is shown. This communication scheme was called Direct NLOS (see Fig. 2). Interest in these investigations is caused by the application of networks of intellectual robots for solving problems of monitoring of states of underwater objects, exploration of natural resources, etc. In [46, 51] numerical experiments were performed, and not only flat, but also wavy water surface was considered; however, radiation scattering in water was not taken into account.

In publication [42], results of experimental laboratory research performed for small base distances not exceeding several meters were discussed. Conclusions from these experiments are reduced to that the range of action of LOS and Direct and Non Direct NLOS communication systems depends on the water turbidity whose increase leads to the decrease of their range of action and data transmission rate.

The overwhelming number of publications of the results of theoretical investigations of the bistatic underwater OECS are based on the application of the Monte Carlo method for solving the radiation transfer equation. Here we refer only to [43,47–51] publications. The transfer properties of the underwater bistatic communication channels were described in the context of the linear systems theory using the influence functions *h* (*t*) ([47] reference can serve as an example). In [48], possibilities of the LOS and NLOS systems were compared. Numerical experiments demonstrated that the rate of symbol transfer in the LOS communication systems can reach 100 MHz in a turbid medium and is much greater in a clear medium. For NLOS systems, this rate is limited by 20 MHz in clear water. These results were obtained by numerical experiments with base distances up to 20 m. For simulation by the Monte Carlo method of the process of optical radiation propagation in a water medium, the Henyey–Greenstein model of the scattering phase function was used in [48]. The probabilities of communication errors caused by the pulse interference, that is, superposition of the leading edge of the current pulse on the trailing edge of the previous pulse (see Fig. 3) were estimated in [48].

Let us pay attention to papers [45, 55] in which results of experiments on optical communication through mixed media were presented. In [45], results of laboratory experiments were discussed with the LOS scheme of communication on air-water paths (the receiver was placed in water) and on water-air paths (the receiver was placed in air). In [55], results of field experiments in a natural water reservoir were presented. In particular, the probabilities of communication and their standard deviations were given for communication through ice.

5. CONCLUSIONS

The urgency of research on the problems of optical communication based on scattered or reflected radiation is confirmed by abundance of previous and continuing publications (there are examples of works published in 2018). The countries in which scientific groups carrying out study in this direction are sufficiently widespread all over the world: China (the greatest number of publications), Canada, the USA, Greece, Great Britain etc. There are some examples of international teams.

The main conclusions based on the above-discussed publications can be formulated as follows. Results of simulations by the Monte Carlo method of the informative signal transfer through atmospheric bistatic channels [54] in the visible wavelength range have allowed us to conclude that at small base distances (2–3 km), the power of the received informative pulse is maximum for radiation in the UV range ($\lambda \approx 0.3$ μm) given that the remaining conditions remain the same. For large base distances and low turbidity of the medium (meteorological visibility range $S_M \approx 50$ km), it is observed at $\lambda \approx 0.5$ μm. At high atmospheric turbidity ($S_M \approx 10$ km), depending on the base distances and the orientation of the receiving plane, it can be obtained at $\lambda \approx 0.5$ μm and $\lambda \approx 0.9$ μm. In the same work, it was also shown that the limiting frequencies of pulses transmission in a bistatic optoelectronic communication system, depending on the optical conditions in the atmosphere and geometrical parameters of the schemes of communication channels, lie within the limits from 4×10^3 to 2×10^7 Hz (for ideal characteristics of the receiving and transmitting systems).

The implementation of the bistatic communication in the atmosphere in the visible wavelength range for base distances up to 70 km was reported in [53]; in [56] the communication in the UV range was realized for base distances up to 1300 m; and the underwater communication in a natural water reservoir for base distances up to 40 m was reported in [58].

In [28] based on investigations on the network applications of the NLOS systems, it was established that the optical communication systems intended for short (up to 100 m) base distances with semiconductor sources are significantly cheaper and have smaller overall dimensions. Experiments in [28] were carried out at a radiation wavelength of 0.34 μm.

Software for investigation of the transfer properties of non-coplanar communication systems (for example, see [23, 33]) has been developed. Theoretical results obtained in [24] were confirmed by experiments.

In [31] the possibility of application of network technologies for monitoring of biosystems, detection of fires, control of atmospheric pollution, and communication in the UV range of wavelengths 0.200–0.280 μm was analyzed. On the basis of analytical relationships derived in the single scattering approximation for small base distances, the influence of optical-geometric conditions of observations and radiation power on the probability of errors, the signal/noise ratio, and some other characteristics of the examined OECS was investigated.

In publications, different types of laser sources used in bistatic OECS were reported. There are examples of application of CW (continuous wave) radiation with its subsequent transformation into pulsed radiation [40]. The OESS can include solid-state lasers in the UV range and gas-discharge lasers with radiation in the visible range that can be transformed, if necessary, into UV radiation using nonlinear BBO crystals.

Attention of researchers was also focused on the problem of application of polarization properties of light to improve the noise protection of the OECS operating on scattered laser radiation. In [34], the development of the Monte Carlo program-algorithmic complex was reported intended for simulation of propagation and reception of polarized radiation in the NLOS communication channels. It was shown that the reception of the polarized signal makes it possible to decrease the probability of errors by decreasing the influence of multiple scattering on the formation of the leading and trailing pulse edges.

One of the factors that influence the quality of bistatic OECS performance is turbulence. It can decrease the useful signal power and interrupt the communication. In [35], the influence of the number of receivers on the communication errors was analyzed.

The important OECS components are photodetectors. In the literature discussed above, Hamamatsu solid-state photodetectors, avalanche photodiodes, domestic FEU142 and 17a, and modern photoelectronic multipliers UFK-4G-4, UFK-4G-3, and UFK-4G-2 (manufactured by the "KATOD" LLC) were used.

In [52, 53], the procedure of estimating in real time of the probabilities of communication errors and their SD was described for OECS testing in the atmosphere, water, and mixed media.

In [51], the Monte Carlo method was used to perform numerical experiments on underwater communication taking into account the wavy water surface for schemes of Direct NLOS, and the rate of data transmission in clear and turbid water was estimated.

Future investigations will be aimed at the search for optimal methods of signal modulation, the development of means for numerical simulations of transfer properties of the NLOS communication channels, the development of analytical models of the impulse response in non-coplanar schemes of the bistatic OECS, the study of the influence of waves on the water surface and scattering processes in water on the overall performance of the communication systems on scattered laser radiation, and expansion of the range of variations of the input parameters of NLOS OECS for carrying out experiments in natural water reservoirs.

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