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# OPTOELECTRONIC COMMUNICATION IN THE ATMOSPHERE USING DIFFUSE LASER RADIATION: EXPERIMENTS IN THE FIELD

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**ABSTRACT**

This article presents results of field experiments with bistatic optoelectronic communication systems (OECS) in the atmosphere using diffuse laser radiation. The work was performed in 2013–2016. The experiments were carried out in order to estimate communication quality (based on the control of probabilities and errors, as well as their root mean square deviations) and allow deriving the following conclusion: it is possible to create bistatic OECSs, which operate effectively in the atmosphere with hundreds of metres in UV and hundreds of kilometres in visible intervals of wave lengths, with orientation of the receiver axis both in a hemisphere containing the direction to the source and in a hemisphere containing the direction of propagation of non-diffused laser radiation.

**Keywords:** optoelectronic conmmunication, laser radiation scattering in atmosphere, time- pulse modulation, error probability

## 1. INTRODUCTION

The main questions associated with developing bistatic (over the horizon) optoelectronic communication systems (OECS) using diffuse laser radiation are discussed in [1] and a Monte-Carlo method choice was substantiated for the simulation of transmission characteristics of atmospheric bistatic channels. Published in the same journal in 2012, were a description of laboratory implementation of the experimental installation and an example of its test under real atmospheric conditions.

In 2013–2016, a series of field experiments was performed during the summer and autumn seasons to evaluate the possibility and quality of receiving information using bistatic optical communication channels under various atmospheric conditions and when changing the geometric parameters of the send-receive OECS circuit.

The work reproduces new and previous results of these studies performed at atmospheric routes in Tomskaya region.

## 2. EQUIPMENT, OPTICAL AND GEOMETRICAL CONDITIONS OF THE EXPERIMENTS

A flow chart of the bistatic OECS laboratory model, which is described in detail in [1], is given in Fig. 1.

Copper bromide vapour lasers [2] were used as a radiation source. They were developed in the IOA of the Siberian Branch of the Russian Academy of Science. They had the following characteristics: radiation wave length $\lambda$ = 510.6 nm, pulse frequency repetition of (11–14) kHz, pulse duration $\Delta t$ = 30 ns, average power $P$ = (4–14) W, beam diameter on entering the atmosphere $\varnothing$ = 15 mm; radiation divergence $\Delta v$ = 0.06 mrd.

The visual field angle of the receiving telescope was $FOV$ = 2°. As a photodetector, a photoelectric multiplier (PEM) ФЭУ-84 was used. The op-

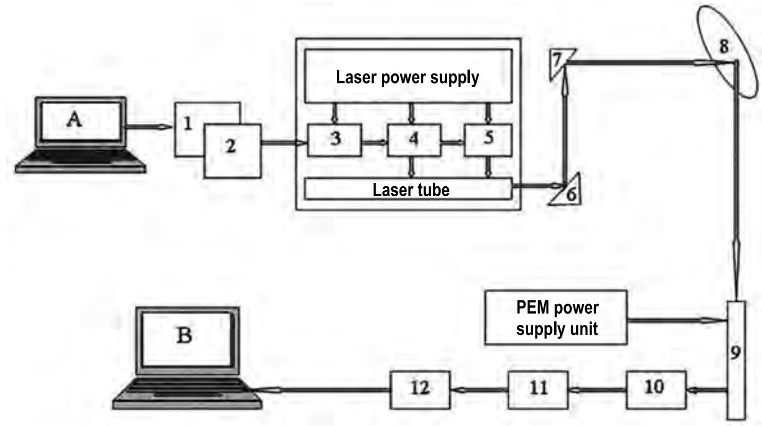


Fig. 1. A flow chart of the laboratory model of the communication system bistatic laser. Labels: A – "transmitting" computer, 1 – interface, 2 – data coding device, 3 – master generator of the laser, 4 – modulator, 5 – laser thyratron, 6 and 7 – alignment units, 8 – diffusing volume, surface, 9 – telescope + photoelectronic multiplier (PEM), 10 – signal amplifier, 11 – decoding device, 12 – interface, B – "receiving" computer

tical axis of the receiving telescope crossed the optical axis of the laser beam, and its inclination relative to the horizontal plane was set by $\alpha$ angle. The transmitting OECS was placed in the northern tower of the IOA building A at the height $h_0$ = 13 m from the ground surface, or 173 m above sea level. The direction of the laser beam axis was determined by altitude angle $5^o < \theta < 15^o$ and by azimuth angle $-10^o < \varphi +10^o$ in the horizontal plane from the direction to the receiving OECS. During experiments in 2013, the average power of the laser source was equal to 4 or 6 W, in 2016 it was equal to 8.5 or 14 W.

The laser beam passed (depending on the receiving optical system location) over the city of Tomsk and the Tom River (Fig. 2, direction 1), over Tomsk, Tom River and a suburb area (Fig. 2, direction 2), over Tomsk, Tom River and the town of Beryozkino (Fig. 2, direction 3), and over Tomsk, Tom River, forest areas, Ob River and fragments of the Ob swamp (Fig. 2, direction 4).

During the experiments, the time interval between the radiated laser pulse and clock pulse was measured. This modulation type of the radiation (pulse-time) exactly is used in the laboratory model of the bistatic OECS. During the experiments, by means of the Zond M active-and-pulse highly sensitive OECS [3] operating in a passive mode, the ray's diffuse trace in the atmosphere was recorded on video, selectively. Fig. 3 shows examples of these images.

A mobile OECS receiving office could be placed in any point accessible for vehicle transport. The first successful field experiments were made in 2013 when the OECS receiving office was placed at a distance of 9.9 km from the laser radiation source and the receiver height above sea level was 79 m. The main experiments were performed in 2013 when the receiving system was placed in a field behind the Tom River in the radiation direction 2 in Fig. 1. The source-receiver base was 8.77 km, the receiver height above sea level was 77 m. The maximum length of line sections from the source to the re-


Fig. 2. A scheme of laser ray directions to the points of placing the receiving OECS (green arrows) in 2013–2016

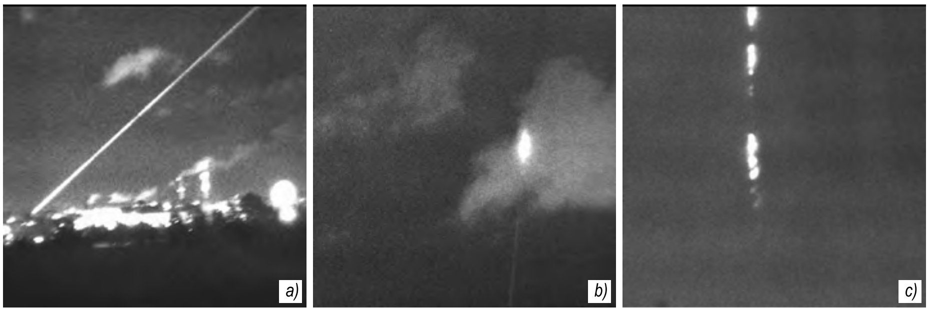


Fig. 3. Videos frames: (a) – of information laser ray diffused along a cloudless route in atmosphere, (b) – of diffused radiation passing a cloudy formation, and (c) – of radiation diffused on aerosol non-uniformities

ceiver through the intersection point of optical axes of the receiver and of the laser beam was 11 km (we name this distance the communication line length).

The experiments were made from August to October 2013 in a dark time under cloudy atmosphic conditions (separate cloud formations and solid cloud cover), as well as in a cloudless atmosphere and with precipitation. The information which was transmitted along the atmospheric bistatic channel for an evaluation of communication quality, was an image of graphic test signal in the form of a periodic triangular structure (without a horizontal leg).

Each experiment was carried out according to layout presented in (Fig. 4). One of two orientations of the transmitting laser beam with an altitude angle $\alpha \approx 5°$ and 15° was recorded at azimuth angle $\varphi \approx 0°$. The receiving telescope was orientedted in the directions corresponding to the $\alpha$ angles (15–85)°. To control the communication operation, an additional transmitting laser beam orientation, corresponding to $\varphi \approx \pm 10°$, was carried out. Duration of each communication session at the stable experiment geometry depended on atmospheric conditions and was equal to between 7 and 30 min. Information (a graphic test signal) containing between 7,000 and 40,000 symbols was transmitted and registered in a computer. Each experiment lasted between one and three hours.

The control of the bistatic atmospheric communication channel under field conditions cannot be achieved completely. Therefore, to analyse the influence of weather and optical conditions on the quality of the OECS's work the following parameters were applied:

– Meteorological visibility range $S_M$, which was measured with an interval of 1 hour within the territory of the basic experimental complex of the IAO [4] located at a distance of 12 km from point S

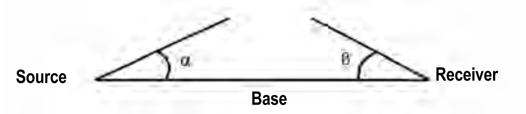


Fig. 4. Geometric experiment layout

(Fig. 2). The $S_M$ measurement interval was limited from the top by $S_M$ value equal to 30 km.

– Aerosol pressure, humidity and concentration (with particle size greater than 0.3 μ), which were measured on the TOP-station [5] placed at the High-rise station of the IAO (located at a distance of 400 m from the radiator of the bistatic OECS).

– Coefficient of atmosphic aerosol extinction $\beta^{a}_{ext}$ at wavelength $\lambda = 0.5$ μ, which was determined along a horizontal route (coming from the building, where the OECS transmitting laser was placed) using the equipment and the technique described in [6–8].

## 3. RESULTS OF THE EXPERIMENTS

In order to estimate the quality of the communication, probability $p$ and its root mean square deviation (RMSD) $\sigma$ were used during communication sessions, when all geometrical parametres of the experiment setup were recorded. An algorithm of the real-time statistical characteristic calculation (i.e. at the time of carrying out the experiment) is described in detail [18].

It is clear from the information about the statistical characteristics of transmission quality that both atmospheric distortions, and changes of characteristics and send-receive optoelectronic units can be reasons for error, (for example, laser radiation power, photoelectronic multiplier (PEM) noise, etc.).

The error probability and error RMSD analysis has shown that some communication sessions have an ideal communication quality, i.e. $p = 0$ and $\sigma = 0$

**Table 1. Selective values of communication error probabilities and their RMSD in the experiments of 10/1/2013.**

| Time | *P* | *σ* | Time | *P* | *σ* | Time | *P* | *σ* |
|---|---|---|---|---|---|---|---|---|
| 8:35 p.m. | 0.538 | 0.565 | 8:55 p.m. | 0.053 | 0.065 | 9:08 p.m. | 0.043 | 0.060 |
| 8:36 p.m. | 0.277 | 0.308 | 8:56 p.m. | 0.046 | 0.059 | 9:09 p.m. | 0.035 | 0.069 |
| 8:37 p.m. | 0.221 | 0.252 | 8:57 p.m. | 0.054 | 0.065 | 9:11 p.m. | 0.030 | 0.041 |
| 8:38 p.m. | 0.143 | 0.163 | 8:58 p.m. | 0.089 | 0.103 | 9:12 p.m. | 0.041 | 0.054 |
| 8:39 p.m. | 0.114 | 0.135 | 8:59 p.m. | 0.103 | 0.120 | 9:13 p.m. | 0.033 | 0.051 |
| 8:48 p.m. | 0.043 | 0.061 | 9:02 p.m. | 0.064 | 0.082 | 9:14 p.m. | 0.026 | 0.035 |
| 8:49 p.m. | 0.060 | 0.079 | 9:03 p.m. | 0.055 | 0.063 | 9:15 p.m. | 0.026 | 0.039 |
| 8:50 p.m. | 0.068 | 0.086 | 9:04 p.m. | 0.041 | 0.054 | 9:16 p.m. | 0.029 | 0.043 |
| 8:51 p.m. | 0.083 | 0.106 | 9:05 p.m. | 0.039 | 0.060 | 9:17 p.m. | 0.031 | 0.049 |
| 8:53 p.m. | 0.069 | 0.081 | 9:06 p.m. | 0.040 | 0.054 | 9:18 p.m. | 0.030 | 0.047 |
| 8:54 p.m. | 0.039 | 0.054 | 9:07 p.m. | 0.035 | 0.046 | 9:20 p.m. | 0.024 | 0.040 |

(for example, on September 4th), or close to it (for example, on September 11th). In other situations, $p$ and σ values reached 0.8 and 0.9 respectively (for example, on September 29th).

To find out the reason for th variation in error probability $p$, aerosol concentration, transmittance coefficient, meteorological visibility range, temperature, humidity and atmospheric pressure were monitored.

The physical basis of bistatic communication is the diffusion effect, and both aerosol, and molecular components of atmosphere play their part. Therefore, we should first determine which of these processes affects communication quality more, or whether their influence is equal. With this end in sight, molecular diffusion coefficient $\beta^m_{sct}$ values and aerosol diffusion $\beta^a_{sct}$ values were compared. Aerosol scattering coefficients were determined using the *LOWTRAN-7* package [9], and molecular diffusion coefficients were calculated by the formulae given in [10] using the temperature and pressure data measured at the TOR-station [5].

It follows from this data comparison that aerosol diffusion coefficients considerably (almost by an order of magnitude) exceed molecular diffusion coefficients, i.e. one can assume that along cloudless routes, the aerosol component directly determines information transmission quality in bistatic OECS, at least, for a 510.6 nm wave length. The analysis has shown that there was no stable correlated relationship between error probabilitiy values and optical and meteorological atmospheric characteristics near the transmitting OECS.

As already mentioned, other sources of error in information transmission via atmospheric communication channels can be parameter change in the equipment of separate units. With the selected method of information modulation (pulse-time), the quality of information received is primarily influenced by the laser radiation power $P$, which in the experiments was changed within an interval of 4–6 W. When reducing $P$, we can expect a deterioration in communication quality, i.e. increase of error probability $p$. This is confirmed, for example, by a comparison of $p$ values obtained diring experiments performed on September 16th ($P$ = 6 W) and on September 25$^{th}$, 2013 ($P$ = 2 W). In these experiments, $p$ equalled 0.01 and 0.572 respectively, air temperature was + 14.7 °C on September 25th, and – 4.3 °C on September 16th, meteorological visibility range $S_M$ on September 16th and 25th exceeded 30 and 7 km respectively, and aerosol extinction coefficient $\beta^a_{ext}$ restored from the 9 p.m. measurements was equal to 0.102 km$^{-1}$ on September 16th and to 0.260 km$^{-1}$ on September 25th.

Therefore, before specifying the main reason of the abrupt change in $p$ errors (temperature, laser radiation power, or aerosol extinction), we will consider the influence of PEM temperature on the communication quality.

The results are presented in Table 1, where $p$ and σ values are given depending on the time of the

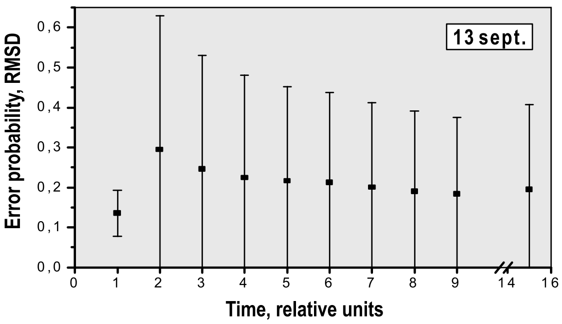


Fig. 5. Error probabilities and their root mean square deviations (RMSD) in the experiments of September 13th, 2016

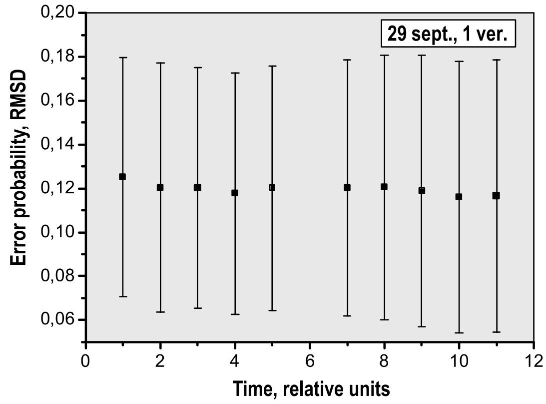


Fig. 6. Error probabilities and their RMSD in the experiments of September 29th, 2016

communication sessions in 2013. The first session was held without PEM forced cooling (beginning of the session was at 8:35 p.m.), and PEM temperature $T$ corresponded to the ambient temperature, i.e. $T = + 6.7$ °C. The second and the next sessions were held with a switched-on cooling installation, which gradually cooled the PEM to a temperature of – 17C° over 30 minutes. As it can be seen, PEM temperature significantly influences the communication quality, and its change from + 6.7 °C to –17 °C leads to a reduction in communication errors by almost by an order of magnitude. This result confirms the known result of the influence of temperature conditions on PEM operation quality [11].

The first series of experiments in 2016 was performed at a laser source average power of 8.5 W and with the location of the receiving telescope near Berezkino settlement at a distance of 26 km from the laser radiation source (Fig. 2, direction 3, communication line length was equal to 26.12 km). The experiments were carried out under a cloudless firmament (along the laser beam propagation line). The angle of altitude of the telescope optical axis and altitude angle of the laser radiation axis were $\alpha \approx 5°$ and $\beta \approx 10°$ respectively. Fig. 5 shows an example of the real-time result evaluation of error probabilities $p$ and $\sigma$ in this experimental series.

On September 29$^{th}$, 2016, an optoelectronic communication over the horizon, with diffuse laser radiation from 69.5 km and the length of the communication line at 69.83 km was carried out. The averaged power of the laser radiation source was 14 W. The receiver was placed in close proximity from the Tomsk-Novosibirsk road between Nashchekovo and Desyatovo settlements (Fig. 2, direction 4). The receiver captured the radiation, which was distributed over Tomsk, Tom River, Ob River, Ob swamp and forest area between the swamp and the road. The angles of altitude of the receiver optical axis and radiation axis were $\alpha \approx 10°$ and $\beta \approx 7°$ respectively.

In Fig. 6, results probability error evaluations and their RMSD for this experiment are given. The absence of results for the 5–7 time intervals in Fig. 6 is due to the fact that at this exact time interval a vehicle convoy drove the road with brigh headlamps, which diffused the radiation (there were no cutoff filters) and was registered by the PEM.

External limiting factors, such as the OECS's applicability area are noises connected with natural and artificial radiation sources in this wave length interval. Therefore, their use along atmospheric routes can be especially difficult in day time, or in night time if used close to intensive artificial sources (see Fig. 6, time interval 5–7).

This problem can be solved or rendered less significant, with the use of UV interval wave lengths lasers and, primarily, solar-blind wave length interval lasers as OECS radiation sources. This is evident from a growing body of theoretical research [12–15], which has expanded during the last decade.

In the experiments of 2016, a hardware implementation of the bistatic OECS was used as the baseline, which was tested in the visible wave lengths interval and was described in detail in [16–18]. A stationary copper bromide laser (wave length $\lambda$ = 510.6 nm, of 10 W average power) was used as the primary source, the radiation of which was transformed to the radiation with wave lengths of $\lambda$= 255.3; 272.1 and 289.1 nm. A nonlinear transformation based on a *BBO* ($BaB_2O_4$) optical crystal was used. In the experiments considered below, radiation with wavelength 289.1 nm was used (0.3 W average power, 14 kHz frequency repetition pulses, 30 ns pulse duration). The beam cross section at the point of entry to the atmosphere was a square

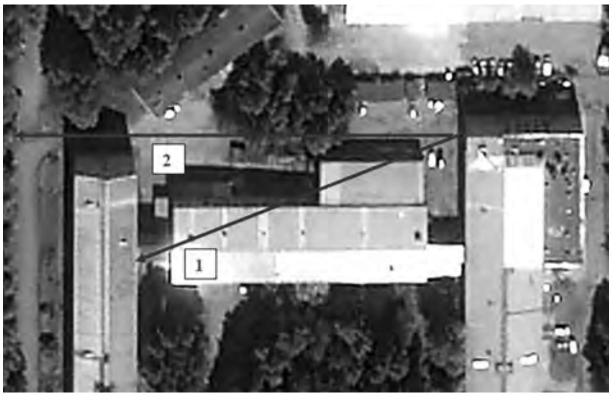


Fig. 7. A satellite picture of IAO cases of the Siberian Branch of the Russian Academy of Science and directions of radiation of a stationary laser UV source (arrow 1, 2)

of 2 mm side with full angular divergence by the sides equal to 2.5°. This wave length was selected based on the analysis of diffusing and absorbing atmosphere properties in the bottom layer. The receiving optical system was assembled using a refractor telescope scheme. Some its characteristics are as follows: the diameter of the light lens is 94 mm, the glass material is quartz glass КУ-1, uniformity class is 1, and focal length is equal to 300 mm. The field of vision of the receiving system is 2°. As a converter of optical radiation into the electric signal, PEM PhEM 142 was used. The experiments were made along routes 1 and 2, represented by a satellite photo of the IAO buildings given in Fig. 7. A stationary laser source was placed on the third floor of building A – north tower of the Institute (on the right in Fig. 7). In the first series of experiments, radiation was directed towards a receiver placed in the main building of the Institute (direction 1 in Fig. 8). Arrows 1 and 2 in Fig. 7 are horizontal plane projections of optical axes of the laser beams used in the experiments.

Fig. 8 shows geometrical schemes of three series of these experiments (side view). A receiving telescope was placed in a room on the second floor of the IAO building and was directed to the radiation source. The radiation was directed sequentially to points 1, 2 and 3. Point 1 corresponded to **n1** direction vector and was at a distance of 3 m over the receiver. The **n2** and **n3** direction vectors corresponded to points 2 and 3, and they were located at a distance of 4 and 8 m from point 1 respectively. This geometry excluded entering a non-diffused radiation into the lens of the receiving telescope. The length of the communication lines was equal to 96.2; 96.26 and 96.5 m.

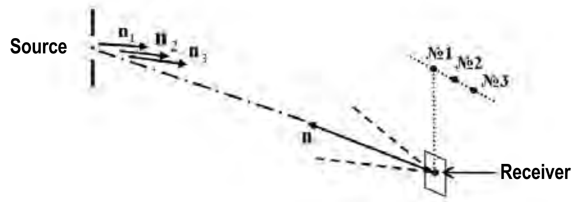


Fig. 8. Geometric diagrams of the first experiments

The second series of experiments was performed, where the laser radiation was directed into free atmosphere over the IAO main building at an angle of 2° to the horizon. The receiving telescope was placed on a site behind the main Institute building under ray 2 in Fig. 7. The receiver's optical axis was directed at angles between 15° to 110° to the horizon relative the source direction. The length of communication lines in these experiments was changed from 100 to 108 m.

In Fig. 9 as an example of error probabilities and their RMSD dependencies on the experiment series number are given. The experiments were performed on May 20th, 2016 according to the diagram in Fig. 8 for points 1 and 3. The squares and triangles designate the error probabilities, and horizontal intervals of different size designate upper and lower RMSD boundaries for points 1 and 2 respectively.

Probabilities and their RMSD corresponding to point 2 in Fig. 8 for all experimental series are between the values for points 1 and 3. It follows from a comparison of these results that the communication quality decreases with increasing communication line length (a sequential transition from point 1 to point 3). This conclusion is rather obvious, if we take into account that during the two hours, when the experiments were performed, optical conditions in near the ground atmosphere according to the TOR-station [5] did not change significantly.

Levels of communication error probabilities obtained in the experiments and their RMSD for the laser radiation propagation direction 2 in Fig. 7 are presented in Fig. 10. To illustrate the results obtained in these experiments, two situations were selected: (a): optical axis of the receiving system is directed to the hemisphere of directions from the source at an angle of 45° to the horizon, and (b): this axis is oriented into the hemisphere of directions from the source at an angle of 135° to the horizon. In Fig. 10, along the abscissa axis, relative time corresponding to the experiment series number for situations (a) and (b) is given.

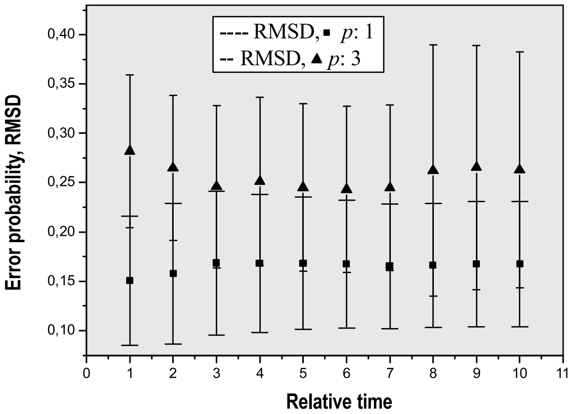


Fig. 9. An example of the estimated results of communication quality in the experiments according to the Fig. 8 diagram for points 1 and 3

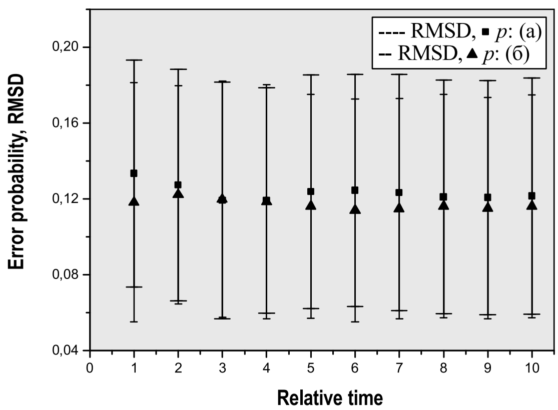


Fig. 10. An example of the evaluation results output of communication quality in the experiments for the laser radiation direction 2 in Fig. 7

The following conclusions can be drawn from the error probabilities and their RMSD comparison in Fig. 9 and 10. The values of these parameters in situations (a) and (b) are rather close. This can be explained by the fact that the prevailing radiation diffusion source at a wavelength of $\lambda$ = 289.1 nm is molecular but not an aerosol atmosphere component, for which the diffusing indicatrix is symmetric relative to the directions of the front and to the back hemispheres. This leads to the fact that when the geometrical parameters of the communication lines correspond to situations (a) and (b), the fluxes diffused by air molecules become comparable.

A possible reason of this could be the fact that the experiments performed for series (b) were conducted 1.5 h later. All experiments were undertaken between 9 and 11 pm local time. We can assume that aerosol concentration decreased during this time, and since the moment of carrying out the experiment series for situation (a), it remained almost constant, and this is confirmed by the TOR-station data [5]. Therefore, error probabilities value variations as well and their RMSD in Fig. 10 (curve b) are somewhat lower. In particular, probability $p$ variations in situation (a) did not exceed 0.014141, RMSD module – 0.01829, and in situation (b) $p$ variations did not exceed 0.008889, RMSD module – 0.005541.

It is interesting to compare the quality of communication in visible and UV wavelength intervals. For this purpose we refer to [16], where examples of the evaluating error probabilities and their RMSD are given. These data were obtained in field experiments using a laboratory model of the bistatic OECS with diffuse laser radiation in the visible wavelength interval ($\lambda$ = 510.6 nm) at communication line length of more than 10 km. This comparison shows that communication quality in the visible interval is significantly higher than in the UV interval. It would seem that the UV interval is preferable for high-quality communications, because solar radiation noise in this case is significantly lower.

However, if we remember that the experiments were conducted in twilight time and that the visible interval laser radiation power was higher than the UV interval power by more than 15 times, and that various PEMs were applied, then the comparison results are practically assured.

## 4. CONCLUSIONS

The field experiments conducted in 2013–2016 in order to evaluate the possibility and quality of information transmission along bistatic OECS using a diffuse laser radiation, allow formulating the following general and particular conclusions.

1. A high-quality bistatic optoelectronic communication in the visible wavelength interval can be implemented under both cloudy and cloudless atmospheric conditions.

2. In the case of a a cloudy sky, the communication can be accomplished via intromission and diffusion areas of laser radiation on the lower boundary of the solid cloud cover, or on the bottom and a side boundary of individual clouds.

3. Statistical characteristics of the quality if information transimission using bistatic atmospheric channels (error probabilities and their root mean square deviations) depend on laser radiation pow-

er (decreasing in proportion with its growth) and on PEM sensitivity. Cooling of the PEM (ФЭУ 84) used in the experiments from + 6.7 to – 17 °C led to a reduction of error probability almost by an order of magnitude.

4. An analysis of the influence of the optical and meteorological state of the atmosphere on statistical characteristics of communication quality at a wave length of 510.6 nm has showed that in the case of bistatic communication, when laser ray interception is accomplished by the receiving system in the surface layer of the atmosphere, it is determined by radiation diffusion, which generally depends on atmospheric aerosol concentration and on the fact that a maximum base, with which a stable communication with error probability at a level of 0.1, can exceed 70 km.

5. To exclude or reduce the influence of hardware failure during operation of an over the horizon OECS, field experiment carrying out conditions should provide for a guaranteed power stability of the radiation transmitter and constant temperature of the PEM.

6. The field experiments affirmed the possibility of developing and operating at a high level of quality bistatic multiple-address OECS in UV wavelength interval with an operating range exceeding hundreds of metres.

7. At basic distances up to hundreds of metres and more, optoelectronic UV interval communication is possible both with the receiving system optical axis orientation in the direction to the source of horizon angles at more than 10°, and in the direction from the source to the receiving system optical axis tilt angles to the horizon up to 30–40°.

8. The results presented by this research require a further replication and correction as part of subsequent pilot and theoretical studies in order to determine the main influences on communication quality and long-range operation areas of bistatic OECS according to their optical and geometric characteristics and parameters of their implementation versions.

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