International Journal of Engineering & Technology, 7 (3.13) (2018) 17-21

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

The Single-Photon Model of Search of Pulse Signals for Telecommunication Systems

K.Y. Rumyantsev[1]*, L.A. Albogachieva[2], P.D. Linenko[3]

[1]*Southern Federal University, Rostov-on-Don, Russia, rke2004@mail.ru*
[2]*Grozny State Oil Technical University of Acad. M.D. Millionshtchikov, Grozny, Russia, lika5768@mail.ru*
[3]*Southern Federal University, Rostov-on-Don, Russia, LinenkoPD@yandex.ru*
**Corresponding author E-mail: rke2004@mail.ru*

Abstract

Detection of the optical pulse reception moment is a necessary condition for communication between moving correspondents. The search algorithm of pulse signals in a photons registration mode (single-photon pulses) is known. It is considered that in a reception complex the optical signals period is known. The photoreception channel consists of an single-photon dissector, the electron amplifier, and the amplitude discriminator. In the time frame which is equal to the optic pulse-repetition period, the moment of amplitude discrimination level equality fixed. The analysis of the threshold reason excess is made in a following frame. At repeated excess of a threshold it is considered, that useful radiation is revealed. Otherwise the decision on absence of a source radiation is passed. The system passes to the review of a new spatial element of decomposing in supervised spaces. At the second excess of a threshold it is considered, that useful radiation is revealed. Otherwise the system passes to the review of a new spatial element of decomposing in controllable space. The model is developed for check of algorithm efficiency, measurement of statistical characteristics of search system of radiation sources with detection of the reception moment of optical pulse. In system the single-photon dissector with the limited pass-band is used. By means of the developed simulation model working capacity is proved and algorithm efficiency is checked up, statistical characteristics of search system of radiation sources with detection of the occurrence moment of a signal are measured at use of an single-photon dissector with the limited pass-band.

Keywords: *model; search; single-photon pulse; single-photon dissector; static parameters.*

1. Introduction

Creation of laser communication systems with spacecrafts requires the solution of complex problems. Really, a high directivity of radiation of lasers requires mutual targeting of antennas of complexes. Detection of the moment of reception of optical pulse is a necessary condition of link establishment between removed and mobile correspondents [1-5]. The topicality of search and detection of a source of radiation is confirmed by the patented technical solutions [6-19].

At present, there is an equipment for establishment of two-way communication by means of an equipment of spatial search and detection of sources of optical radiation. However the question of optimization of characteristics of an equipment on the scanning single-photon photoemission instruments (single-photon photoemissive device, SPD) is still topicaly for the systems of distant space communication or quantum distribution of a key.

In [20], an algorithm for spatially-temporal search for pulsed signals in the single-photon pulse (SPP) registration mode is described. The proposed search algorithm is based on the fact that at the receiving end the optical signals repetition period T_s is known.

The photoreceiving channel consists of the one-photon dissector, the electronic amplifier and the amplitude discriminator (AD). During t time $[0, T_s]$ is fixed the moment of t_{AD} of the first exceeding of level of amplitude discrimination of U_{AD}. The reason of activation is analyzed in an interval $[T_s, 2T_s]$. In the waiting mode the channel does not react to a flow of photoelectrons and the dark current pulses (DCP) till the moment

$$t_{strob1}=t_{AD}-\tau_{delay1}+T_s-0{,}5\cdot\tau_{strob}. \qquad (1)$$

A repeated survey of the dissector is carried out in an interval $[t_{strob1},t_{strob2}]$. Here $t_{strob2}=t_{AD}-\tau_{delay1}+T_s+0{,}5\cdot\tau_{strob}$ corresponds to the moment of the end of action of pulse of gating during repeated survey.

The value of τ_{delay1} represents the delay time between the instant of operation of the AD t_{AD} and the instant of generation of a photoelectron t_{PE} (PE, primary electrons). The value of τ_{strob} corresponds to the duration of the gating pulse, during which photons can be recorded during reanalysis.

If the threshold level U_{AD} was again exceeded, then the decision on reception of the useful radiation in an analysable spatial element of expansion is made during time gating pulse action. Otherwise, a decision is made on the absence of radiation from the source. The system proceeds to a review of the next spatial element of the decomposition in the controlled space.

The decision on the absence of a signal is also made when is not exceeded the amplitude discrimination level during the time $t\in[0, T_s]$.

A patent was obtained on a single-photon receiver for search of optical pulse signals that implements the described algorithm [21].

In [22-24], quantitative relationships were established for describing the time and probabilistic parameters of the search complex for pulsed-radiation sources using a single-photon dissector with a limited bandwidth in the single-photon pulses registration mode. The expressions establishing connection of probabilities of false alarm and the correct detection with duration, the period and instability of repetition of optical pulses, dissector parameters (number of dynodes, bandpass range), the trigger level of amplitude discrimination, frequency of generation of SPP of background radiation and DCP are received.
However, in deriving the relations for describing the parameters of the search complex, a piecewise-polygonal (trapezoidal) approximation of the shape of the single-photon pulse was used. The actual form of SPP is described by the gamma function [25].
In addition, the previous analysis was carried out with the orientation toward the worst case of the temporary location of the SPP inside the optical pulse. The same conditions determine the choice of the duration and the moment of formation of the gating pulse in the analysis of the cause of the AD activation. Statistical time parameters were not taken into account.
The purpose of the research is to develop a model for testing the efficiency of the algorithm, measuring the statistical characteristics of the search system pulsed sources with the detection of an optical pulse using a single-photon dissector with a limited bandwidth, with the exception of the assumptions regarding the shape of the single-photon pulse and the time of the photon receiving inside the optical pulse.
Parameters of the optical pulse. The optical radiation source generates an ideal square pulse with a duration τ_s and a repetition period T_s. The instability of the optical pulse repetition period ΔT_s with respect to the repetition period of the optical pulses T_s is given by the coefficient k_T: $\Delta T_s = k_s T_s$.
Parameters of a single-photon dissector. A single-photon dissector has $N_d = 14$ dynodes. The average values of the secondary emission coefficients of the dynodes $m_{d.i}$, $i=\overline{1,N_d}$ are different. In the first and second dynodes, they are equally $m_{d1}=m_{d2}=5$. In all dynodes, from the third, the emission coefficients are $m_{d.i}=3$, $i=\overline{3,N_d}$.
The multiplication factor of the dissector G_{SPD} is calculated by the formula $G_{SPD}=\prod_{i=1}^{N_d} m_{d.i}$. At the dissector, the multiplication factor lies in the range 60 ... 80 dB. In this range, the calculated multiplier value is 71 dB.
The time of electrons flight between neighboring dynodes of a dissector is determined by the value of τ_d. This time constant is related to the bandwidth of the dissector Π_{SPD} at the level is 0.707 [5] by the relation $\Pi_{SPD}=b_{SPD}/\tau_d$. The proportionality coefficient b_{SPD} is determined only by the number of dynodes in the multiplication section of the dissector $b_{SPD}=\frac{1}{2\pi}\sqrt{\sqrt[N_d]{2}-1}$.
The quantum efficiency of the photocathode of the η_{SPD} dissector and pulse frequency of the dark current are determined after the amplitude discrimination ξ_{DCP}. It is believed that the DCP recorded by the equipment are due origin to the electrons from the photocathode of the dissector.
The active component of the load resistance of the dissector R_n is specified.
Form of SPP. The amplitude of the SPP on the load resistance R_l of a dissector having N_d identical dynodes and the multiplication factor G_{SPD} is calculated by the formula

$$U_{SPP.m}=\frac{e_{e1}\cdot G_{SPD}\cdot R_l}{N_d!\cdot\tau_d}\cdot {N_d}^{N_d}\cdot\exp(-N_d), \quad (2)$$

where $e_{e1}=1,6\cdot10^{-19}$ Kl – charge of the electron.
The form of the SPP on the load R_l of the dissector is described by the gamma function

$$u_{SPP}(t)=U_{SPP.m}\cdot\left(\frac{t}{N_d\cdot\tau_d}\right)^{N_d}\cdot\exp\left(N_d-\frac{t}{\tau_d}\right). \quad (3)$$

In the formula, the instant t = 0 corresponds to the instant of appearance of the photoelectron.
In [26] it is proposed a piecewise-polygonal approximation of the SPP form

$$u_{SPP}(t)=\begin{cases} 0,\ t\le 7\cdot\tau_d,\ t>23\cdot\tau_d; \\ U_{SPP.m}\cdot\frac{t-7\cdot\tau_d}{5,8\cdot\tau_d},\ 7\cdot\tau_d< t\le 12,8\cdot\tau_d; \\ U_{SPP.m},\ 12,8\cdot\tau_d< t\le 15,2\cdot\tau_d; \\ U_{SPP.m}\cdot\frac{23\cdot\tau_d-t}{7,8\cdot\tau_d},\ 15,2\cdot\tau_d< t\le 23\cdot\tau_d. \end{cases} \quad (4)$$

Here, at the instant t=0, the photocathode generated a photoelectron.
Parameters of the amplitude discriminator. To limit the supply of pulses of dark current from the anode of the dissector, amplitude discrimination with a level of U_{PHD} is applied. Using the approximation of the OFI form [27] allows us to obtain an approximate expression for finding the delay time τ_{delay1} between the arrival times of a single photoelectron t_{PE} and the activation of the amplitude discriminator t_{PHD} in the level U_{PHD}:

$$\tau_{delay1}=7\cdot\tau_d+5,8\cdot\tau_d\cdot U_{PHD}/U_{SPP.m}. \quad (5)$$

Accounting of background radiation. The frequency of generation of background photons ς_{bg} is given and the frequency of generation of background photoelectrons $\xi_{bg}=\eta_{SPD}\cdot\varsigma_{bg}$ is calculated.
Accounting for noise impact. Both single-photon pulses of background radiation and dark current pulses of the dissector are noise interference. Therefore, the concept of the frequency of generation of noise pulses is introduced into the model, the value of which is calculated by the formula $\xi_{noise}=\xi_{bg}+\xi_{DCP}$. The average number of noise pulses during the optical pulses repetition period T_s, $\overline{n_{noise.T}}=\xi_{noise}\cdot T_s$ is determined.
In the simulation of the statistical properties of the flux of noise pulses by Poisson's law, the probability of reception of n noise pulses (photoelectrons and SPP) during the optical pulses repetition period in the background element is

$$\Pr\{n|\overline{n_{noise.T}}\}=\frac{\overline{n_{noise.T}}^n}{n!}\exp\left(-\overline{n_{noise.T}}\right). \quad (6)$$

The probability of a zero event according to Poisson's law for the period of the following of optical pulses in the background element is

$$\Pr\{n=0|\overline{n_{noise.T}}\}=\Pr0_{noise.T}=\exp\left(-\overline{n_{noise.T}}\right). \quad (7)$$

Equipment parameters in the waiting mode. In the search system, a standby mode [28] is implemented, providing for the disconnection of the dissector itself immediately after the first activation of the AD until the time instant t_{strob1}.
The simulation calculates the duration of the gating pulse

$$\tau_{strob}=2\cdot\tau_s+2\cdot\Delta T_s+11,6\cdot\frac{b_{SPD}\cdot U_{PHD}}{\Pi_{SPD}\cdot U_{SPP.m}}. \quad (8)$$

The mathematical expectation and dispersion of the number of noise pulses for the duration of the gating pulse is calculated τ_{strob}:

$$\overline{n_{noise.strob}}=\sigma^2_{noise.strob}=\xi_{noise}\tau_{strob}. \quad (9)$$

The probability of receiving at least one photoelectron or DCP during the gating time in the background element will be

$$\Pr\{n=0|\overline{n_{noise.strob}}\}=\exp\left(-\overline{n_{noise.strob}}\right). \quad (10)$$

Design characteristics of system of search. The probability of false alarms belongs to probable characteristics of an search equipment of pulse signals in the mode of registration of single-photon pulses in background elements

$$P_{fa}=\left[1-\exp\left(-\overline{n_{noise.T}}\right)\right]\cdot\left[1-\exp\left(-\overline{n_{noise.strob}}\right)\right]. \qquad (11)$$

The temporal characteristics of the pulsed signal search equipment include the average time of observation of the background spatial decomposition element.

In the program realizing the proposed algorithm for searching for the source of optical radiation when receiving background radiation, the observation time of the decomposition element is:

- the period T_s in the absence of exceeding the discrimination level in the interval $[0, T_s]$;
- two periods $2T_s$ when the SPP or DCP are registered in the interval $[0, T_s-0{,}5\cdot\tau_{strob}]$, but in the absence of confirmation of the fact that the SPP of the useful radiation is recorded during the repeated analysis;
- three periods $3T_s$ in the absence of registration of the SPP or DCP in the interval $[0, T_s-0{,}5\cdot\tau_{strob}]$, the registration of at least one SPP or DCP on the interval $[T_s-0{,}5\cdot\tau_{strob}, T_s]$, but lack of registration during re-analysis.

In this case, the theoretical value of the average time of observation of the background spatial element is

$$M\{\tau_{cell}\}=\overline{\tau_{cell}}=T_s\cdot\exp\left(-\overline{n_{noise.T}}\right)+\rightarrow$$

$$+2T_s\left[1-\exp\left(-\overline{n_{noise.T}}+\frac{\overline{n_{noise.strob}}}{2}\right)\right]\exp\left(-\overline{n_{noise.T}}\right)+\rightarrow \qquad (12)$$

$$+3T_s\cdot\exp\left(-\overline{n_{noise.T}}+\frac{\overline{n_{noise.strob}}}{2}\right)\cdot\left[1-\exp\left(-\frac{\overline{n_{noise.strob}}}{2}\right)\right]\exp\left(-\overline{n_{noise.T}}\right).$$

Generation of noise pulses. When registering optical radiation, it becomes necessary to develop a time-saving statistical model that accurately reproduces the of noise pulse generation.

The process on the output of the dissector cathode represents a sequence of time countings corresponding to the moments of appearance of noise pulses. Moreover, the number of noise pulses N and the moments of their reception t_k are random values. Under these conditions, the modeling of the photoelectrons flux consists in the random distribution in the measurement interval $[0, \tau_{change}]$ of the events $t_k<\tau_{change}$, $k=\overline{1,N}$. Generation of noise pulses is performed in two stages: generation of the number of received noise pulses during the measurement time $t\in[0, \tau_{change}]$ and generation of the moments of their reception.

In the model, the generation of random numbers n that obey the Poisson distribution law is performed using the poissrnd(x) function from the MatLab catalog. Here, x represents the mathematical expectation of a random variable, which corresponds to $\overline{n_{noise.T}}$ in the first stage, and $\overline{n_{noise.strob}}$ during the second poll.

In the second stage, in the interval $[0, \tau_{change}]$, the moments of reception of noise pulses are determined. The moments t_k of reception of background photoelectrons and DCP are found from the relation $t_k=Z_k\cdot T_s$.. Here Z_k is a random variable uniformly distributed on the interval [0, 1]. To generate it, we used the function rand(1) from the MatLab catalog.

Note that the generated value of t_2 can be either larger or smaller than t_1. Consequently, the moments of the appearance of noise pulses $t_{noise1}, t_{noise2}, \ldots, t_{noiseN}$ must represent an ordered sequence of quantities $t_1, t_2, \ldots, t_N$. To do this, the simulation initially creates an array of data from n random numbers with the elements $xx(k)=Z_k$, $k=\overline{1, n}$. Then, using the sort(xx(1:n)) function from the MatLab directory, they are sorted in ascending order.

Thus, the process on the output of the photocathode of a single-photon dissector represents a sequence of time countings corresponding to the moments of appearance of photoelectrons of the background radiation, as well as dark current pulses.

Model of temporal search for optical pulses. Simulation modeling of noise pulses registration during preliminary search $t\in[0, T_s]$ consists in finding the number of noise pulses $n_{noise.T}$ with time moments of arrival $t_{noise.j}$, $j=\overline{1, n_{noise}}$ [29-30]. By noise pulses are understood as single-photon background radiation pulses, as well as the dark current pulses of the dissector.

To study the registering of noise pulses during the time $t\in[0, T_s]$, it is important to know a series of values (Fig. 1).

First, there are the moments of AD activation t_{AD1k}, $k\le n_{noise}$. Particular attention is paid to the measurement of the AD activation time t_{AD11} and the delay time between the moments of arrival of the noise pulse and the AD activation $\tau_{SPP.delay1}$. Secondly, the moments of the end of the pulse action on the output of the amplitude discriminator t_{AD2k}, $k\le n_{noise}$ are determined. Thirdly, the delay time $\tau_{SPP.delay.k}=t_{AD1k}-t_{noise.k}$, $k\le n_{noise}$ is measured between the arrival times of the noise pulse and the activation of the amplitude discriminator in the level U_{AD}. Finally, the duration of the pulse generated by the amplitude discriminator $\tau_{AD.k}=t_{AD2k}-t_{AD1k}$, $k\le n_{noise}$ is estimated.

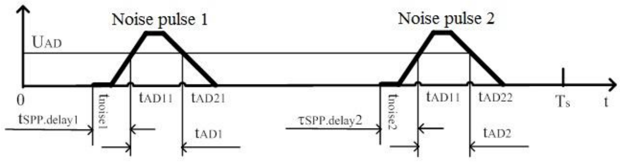

Fig. 1: Registration of noise pulses

Using the approximation of the SPP form, approximate expressions are obtained for finding the delay time $\tau_{SPP.delay}$ between the arrival times of a single noise pulse t_{noise} (the background photoelectron t_{PE} or DCP t_{DCP}) and the activation of the amplitude discriminator t_{AD1} in the level U_{AD}. The latter makes it possible to develop a sequence for determining the moment of the first activation of the amplitude discriminator by specifying the accuracy ε_u of determining the value of the reference u. The u value is considered found if $|1-u/U_{AD}|\le\varepsilon_u$.

When modeling the registering of noise pulses in the interval $[0, T_s]$, three values are given:

- the reception moment of the first noise pulse t_{noise1}, using the subprogramme of generation of noise pulses $\overline{n}=\overline{n_{n_{noise.T}}}$;
- achievement moment first noise pulse of peak value $t_{noise.m}=t_{noise1}+N_d\cdot\tau_d$;
- estimated a time delay $\tau_{noise.delay1}=7\cdot\tau_d+5{,}8\cdot\tau_d\cdot U_{AD}/U_{SPP.m}$ between the activation times AD t_{AD11} and the generation of the noise pulse t_{noise1} when only one background photoelectron or DCP is registered.

Three cells are assigned to the values x_{lower}, x_{mean}, x_{top}.

Step 1. Initially, the condition for generating at least one noise pulse in the interval $[0, T_s]$ is checked. If there are no pulses, then a decision is made about the absence of radiation from the source. The test is considered complete. If at least one pulse is received, then the lower limit for calculating the moment when the process reaches the level of amplitude discrimination U_{AD} is assigned the value $x_{lower}=t_{noise1}$, and the upper boundary – $x_{top}=t_{noise.m}$. The moment of voltage measurement from the output of a single-photon dissector $x_{mean}=0{,}5\cdot(x_{lower}+x_{top})$.

Step 2. The process count value is calculated u from the output of the dissector at the time x_{mean}. For this is given u=0 and $x=x_{mean}-t_{noise1}$. The level of the first SPP from the generated photoelectron or DCP is calculated at the time t_{noise1} and measured at the time x_{mean}

$$y=U_{SPP.m}\cdot\left(\frac{x}{N_d\cdot\tau_d}\right)^{N_d}\cdot\exp\left(N_d-\frac{x}{\tau_d}\right). \qquad (13)$$

The count value at the moment x_{mean} of the first SPP from the generated noise pulse at the time t_{noise1}: u=u+y is fixed.

Step 3. The condition of the influence of the response to the second PE or DCP at the time of taking the voltage reading is checked: $t_{noise2}<x_{mean}$. If the condition is met, then the values $x=x_{mean}-t_{noise2}$, y and u are computed. Here, the value of u represents the voltage counting at the time x_{mean} from the two photoelectrons. In the general case, at the j-th step, the condition for the influence of the response to the j-th noise pulse at the time of sampling is checked. If the condition is met, then the values $x=x_{mean}-t_{noise.j}$, y and u are computed. Here, the value of u represents the voltage reading at the moment x_{mean} from the 1st to the j-th photoelectron.

Step 4. In the absence of influence on the counting of the j-th photoelectron or DCP (the condition $t_{noise2}<x_{mean}$ is not fulfilled), the analysis of the obtained value u is carried out. The value of u is compared with the level of amplitude discrimination U_{AD}. If the condition $t_{noise2}<x_{mean}$ is satisfied, then the computation of the sampling time u is considered complete.

Step 5. If the condition $t_{noise.j}\geq x_{mean}$ is satisfied, then the condition $u<U_{AD}$ is checked. If the condition is met, x_{lower} is assigned the value x_{mean} $x_{lower}=x_{mean}$. Otherwise, x_{mean} is assigned to x_{top} $x_{top}=x_{mean}$. By the formula $x_{mean}=0{,}5\cdot(x_{lower}+x_{top})$ the moment of taking the count is specified. The transition to step 2 is carried out. The moment of the AD activation is fixed: $t_{AD11}=x_{mean}$.

Step 6. The delay time between the moments of arrival of the pulse and the AD activation in the level of U_{AD} is calculated: $\tau_{SPP.delay1}=t_{AD11}-t_{noise1}$.

The test is considered complete.

Results of statistical tests of an equipment of search of pulse signals. Using the developed model, one million statistical tests of the search complex in conditions of reception of background radiation are given.

The parameters of the optical pulse are set: duration 10 ns; the repetition period is 1000 ns; the instability of the repetition period is 0 ns.

Parameters of the single-photon dissector and its loading are set:

- quantum efficiency of the photocathode 0,20;
- number of dynodes in the dissector 14;
- secondary emission coefficient of the 1st and 2nd dynodes 5;
- secondary emission coefficients of the 3rd and subsequent dynodes 3;
- time constant of electron flight between dynodes 1 ns;
- appearance frequency of dark current pulses 10 kHz;
- load resistance of the dissector is 100 Ω.

The parameters of a single-photon dissector are calculated:

- multiplication factor (average value) is 71 dB;
- bandwidth is 36 MHz.

The parameters of a single-photon pulse are calculated:

- amplitude SPP on the dissector load is 22,5 mV;
- duration of SPP is 9,2 ns at level 0,5;
- the duration of the base of the SPP approximation is 16 ns;
- the duration of the SPP approximation peak is 2,4 ns.

The parameters of the amplitude discriminator are calculated:

- the normalized level of discrimination to the amplitude SPP is 0,5;
- level of amplitude discrimination is 11,3 mV;
- the delay time between the arrival of noise pulses and the AD activation is 9,9 ns.

At a given generation frequency of background photons of 10 MHz, the frequency of generation of background photoelectrons is 2 MHz is calculated.

The noise effect is taken into account by the following parameters:

- frequency of generation of noise pulses is 2,01 MHz;
- the average number of noise pulses during the optical pulses period repetition is 2,01;
- the probability of receiving noise pulses during the period repetition of optical pulses in the background element is 0,866.

The time, energy and probabilistic parameters of the equipment in the standby mode are specified:

- duration of the strobe pulse is 25,80 ns;
- average number of background photoelectrons and/or DCP during gating time is 0,0519;
- probability of receiving noise pulses during gating time is 0,051.

Calculation of parameter values of an equipment of search is made:

- the probability of false alarms is 0,044;
- the relation of the average analysis time of a background element to the optical pulses repetition period is 1,835.

The error in calculating the moment when the process reaches the amplitude discrimination level is set at 1%.

The results of statistical tests provide for the control of the energy and probabilistic parameters of the equipment at the first stage of the search for pulse signals and a comparison with the theoretical values:

- the average number of noise pulses during the optical pulse period repetition is 2,011 (The discrepancy with the theoretical value is 0,07%);
- dispersion of the number of noise pulses during the period repetition of optical pulses is 2,010 (The discrepancy with the theoretical value is 0,02%);
- the probability of a zero event during the pulse repetition period in the background element is 0.134 (The discrepancy with the theoretical value is 0.17%).

In the course of statistical tests, the average value is 0,353 and the dispersion is 0,069 of the AD activation times normalized to the pulse repetition period were determined. The normalized average delay between the moments of reception of noise pulses and the AD activation to the duration of the optical pulse is 0,984 (The discrepancy with the theoretical value is 0,60%). In this case, the normalized dispersion of the delay between the moment of reception of noise pulses and the moment of AD activation is $2{,}75\times10^{-5}$.

The average time of analysis of the background spatial resolution element normalized to the pulse repetition period is 1,308 (The discrepancy with the theoretical value is 28,70%), and the variance is 0,074.

In the process of statistical tests, the probability of false alarms is 0,044. (The discrepancy with the theoretical value is only 0,31%).

2. Conclusion

Using the developed model, the efficiency of the algorithm was proved, the statistical characteristics of the system of spatiotemporal search for pulsed radiation sources with detection of the moment of appearance of an optical pulse were measured using a scanning single-photon dissector with a limited bandwidth. The model excludes the assumptions regarding the shape of the single-photon pulse and the time moment of the photoelectron reception inside the optical pulse, adopted when establishing quantitative relationships for describing the parameters of the search complex.

Acknowledgement

The work was prepared with the support of the Russian Foundation for Basic Research, projects number 16-08-00752.

References

[1] Gagliardi R. M., Karp Sh. Optical Communications, John Wiley & Son, New York, 1976; translated to Russian, 1978; translated to Japanese, 1979. (Second Edition, 1995).

[2] Sheremetyev A. G., "Statistical theory of laser communication" Moscow: Communication, 1971. – 264 p.

[3] Sheremetev A. G., Tolparev R. G., "Laser communication" Moscow: Communication, 1974. 384 p. in Russian.

[4] Minaev I. V., Mordovin A. A., Sheremetev A. G., "Laser information systems of cosmic apparatus" Moscow: Mashinostroenie, 1981. 272 p. in Russian.

[5] Bichkov S. I., Rumyantsev K. E. "Scanning and detection of optical signals" // Monograph / Under edition of K. E. Rumyantsev. Moscow: Radio and communication, 2000. 282 p.

[6] Lang K. T., Lucy R. F. , Ratcliffe G. H. , "Acquisition and tracking laser communication system" – Patent 3566126 US. 23.02.1971. https://www.google.com/patents/US3566126.

[7] Smokier M. I. , Van Nuys, "Acquisition system" – Patent 3511998 US. 12.05.1970. https://www.google.com/patents/US3511998.

[8] Pizzurro, "Optical communication system" – Patent 3504182 US. 455/606. 31.03.1970. https://www.google.com/patents/US3504182.

[9] Michimasa Kunitsugu, "Optical alignment system" – Patent 4867560 US. – 19.09.1989. – http://www.google.com/patents/US4867560.

[10] Vyce Joseph Richard, "Alignment telescope" – Patent 3658426 US. 25.04.1972. https://www.google.com/patents/US3658426

[11] James C. Solinsky, La Jolla, "Alignment acquiring, optical beam communication link" – Patent 5060304 US. IPC H04B 10/00. 22.10.1991. http://www.google.com/patents/US5060304

[12] James C. Solinsky, La Jolla, "Method and apparatus for automatic acqusition and alignment of an optical beam communication link" – Patent 5142400 US. 25.08.1992. http://www.google.si/patents/US5142400.

[13] Stephany Joseph F, "Optical communication system" – Patent 3504979 US. – 7.04.1970. – http://www.google.com/patents/US3504979.

[14] Dennis A. Maier, "Self referencing retransmitting alignment sensor for a collimated light beam" – Patent 3942894 US. 9.03.1976. http://www.google.com/patents/US3942894.

[15] Martin Defour, Georges Coudrec, Remi Fertala, Benoist Grossmann, "System of optical communications between moving stations and corresponding communications method" – Patent 5282073 US. 25.01.1994. http://www.google.ch/patents/US5282073.

[16] Wissinger A. B., "Satellite communications system" – Patent 5475520 US. 12.12.1995. http://www.google.si/patents/US5475520.

[17] "Space optical communication line between two objects" – Patent 2106749 RU. 10.03.1998. http://www.freepatent.ru/patents/2106749.

[18] "System for space optical communication between cooperated object and correspondent object" – Patent 2275743 RU. 10.07.2005. http://www.freepatent.ru/images/patents/193/2275743/patent-2275743.pdf

[19] "Space optical system for communication between affiliated and sending objects" – Patent 2276836 RU. 10.07.2005. http://www.freepatent.ru/images/patents/192/2276836/patent-2276836.pdf

[20] Rumyantsev K. E.; Albogchieva L. A.; Bamatgireeva K. B., "Algorithm of existential search of pulse signals in a single-channel registration mode of single-photon pulses" // Electrical and data processing facilities and systems. 2012. № 4, V. 8. P. 3 – 11.

[21] Rumyantsev K. E.; Albogachiyeva L. A.; Bamatgireyeva K. B., "The single-photon receiver for spatiotemporal search of optical pulse signals" – Patent 2568939 RU. 23.10.2015.

[22] Rumyantsev K. E.; Albogachiyeva L. A., "Time characteristics algorithm single channel spatiotemporal search pulsed radiation" // XXI century: resumes of the past and challenges of the present plus. 2014. № 3 (19). P. 62 − 69.

[23] Rumyantsev K. E.; Bamatgireeva K. B., "Probabilistic characteristics algorithm spatiotemporal search pulsed radiation with single-channel information processing" // XXI century: resumes of the past and challenges of the present plus. 2014. № 3 (19). P. 70 − 77.

[24] Rumyantsev K. E.; Albogachiyeva L. A.; Bamatgireyeva K. B., "Requirements for single-channel equipment of space-time search of pulse radiation in the single-photon pulse recording mode" // Telekommunikatsii (Telecommunications). 2015. № 8. P. 6 − 11.

[25] Kovalyov V. V.; Subbotina F. M.; Shubnikov E. N., "Time of electron flight in FED" // Devices and technics of experiment. 1972. №1. P.158-159.

[26] Rumyantsev K. Y., "Single Electron Recording Reliability of Light-Flux" // Izvestiya Vysshikh Uchebnykh Zavedenii Radioelektronika. 1986. V. 29, № 12. P. 62–65. WOS:A1986F490800013. ISSN: 0021-3470.

[27] Rumyantsev K. E.; Khasambiyev I. V.; Albogachiyeva L. A.; Bamatgireyeva K. B., "Functioning features of equipment for time-space search of pulse radiation with single-channel data processing in standby mode" // Telekommunikatsii (Telecommunications). 2015. № 4. P. 2 − 9.

[28] K. E. Rumyantsev; I. V. Khasambiyev; L. A. Albogachiyeva,; K. B. Bamatgireyeva, "Functioning features of equipment for time-space search of pulse radiation with single-channel data processing in standby mode" // Telekommunikatsii (Telecommunications). 2015. № 4. P. 2 − 9.

[29] Albogchieva L. A.; Rumyantsev K. E., "Simulation of performance interference RX background radiation and the momentum of the dark current of single-photon dissector" // XXI century: resumes of the past and challenges of the present plus. 2016. № 3 (31). P. 28 − 36.

[30] Albogchieva L. A.; Rumyantsev K. E., "Modelling of search of pulse signals in a photons registration mode" // XXI century: resumes of the past and challenges of the present plus. 2016. № 3 (31). P. 36 − 45.