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Active electro-optical system of targets detection with dynamic spectral processing of optical radiation

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Abstract. The issues discussed in this paper provide for further development of studies in the sphere of imaging spectroscopy and laser vision. In terms of forming the information fields (radiation fields), the electro-optical systems are subdivided into the passive and active ones. Passive electro-optical systems use the information fields formed by natural radiation sources, whereas the active ones suggest using artificial sources. Comparative analysis of mathematical and physical issues of designing the electro-optical systems with dynamic spectral processing of optical radiation of the passive and active types has been performed. It has been shown that the controlled dynamic spectral processing of optical radiation can be implemented within the passive and active electro-optical systems on the basis of the same algorithm that represents operation of the optical processor performing the mathematical operation of dot product. The authors have developed the block diagram of an active electro-optical system with dynamic spectral processing. The algorithm for optimal detection of optical signals has been developed using basics of the signal detection theory. Mathematical modeling of target detection against an inhomogeneous background has been performed. It has been shown that the optimal dynamic spectral processing of optical radiation in active electro-optical system enables to separate the desired optical signal by suppressing the background signal.

Keywords: active electro-optical system, dynamic spectral processing, optimal detection, laser vision.

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1. Introduction

In terms of forming the information fields (radiation fields), all the electro-optical systems can be subdivided into the passive and active ones. The passive electro-optical systems use the information fields formed by natural radiation in the space of targets. The method of designing the active electro-optical systems suggests creation of an information field by using artificial sources of radiation.

Our analysis of publications devoted to the development of active electro-optical systems has shown that this area of optoelectronics is currently developing rapidly, and the active systems are becoming a widespread alternative to the passive electro-optical sensors [1]. Active spectral imaging, which uses lasers as radiation sources, has attracted growing interest in recent decades. It has been shown in [2, 3] that this, in particular, is facilitated by the development of tunable (frequency-agile) and broadband (supercontinuum) lasers, as well as array photodetectors. These technologies provide spectral images with high spectral and spatial resolution.

To record the spectral characteristics of targets in active spectral imaging systems, there can be used either a combination of a supercontinuous laser emitter with a hyperspectral sensor [4], or a combination of a tunable [5] as well as a multi-wavelength [6] laser radiation source with a polychromatic sensor.

The paper [7] related to active spectral imaging systems provides the explanation of advantages of active electro-optical systems as compared with the passive ones. The input signal of the passive electro-optical system, in a particular case, is provided by the solar radiation reflected from the observed area of the Earth surface. It is known that radiation accepted by the receiver depends on the image formation pattern, in particular, on angular position of the Sun, position of the target and the receiver system. Therefore, when using the passive systems there exists a mismatch between the input signals and *a priori* information about them, which results in worsening the output characteristics. The active electro-optical systems that use a fixed position of eigen radiation sources with the possibility of controlling their radiant flux are partially free from the aforementioned drawbacks. Also, the active electro-optical sensors can operate at night or at low light levels.

In conclusion to the review of publications devoted to the development of active spectral imaging systems, it should be noted that all known systems of this class are characterized by post-detector image processing. It means that the received radiation is converted into an electrical signal and digitized, and then processing is performed, for example, in the interests of targets detection and recognition [2, 8].

When discussing the advantages of pre-detector spectral filtration of optical signals and images, it seems obvious to rely on the fundamental advantages offered by the optical processing. If the processing is performed within the optical bandwidth without transformation of the signals into the electric ones, it allows excluding the errors occurring at transformation and opening the opportunity of a parallel processing of large volumes of information. Therefore, the studies related to further improvement of electro-optical systems with dynamic spectral processing of optical signals, are of great importance.

The paper [9] provides the basics for developing the passive electro-optical devices with dynamic spectral filtration. The dynamic spectral filtration represents a further development of the imaging spectroscopy. Unlike the imaging spectrometers, the electro-optical systems with dynamic spectral filtration apply realization of controlled spectral filtration of optical signals within the pre-detection domain [10].

Within the passive systems with dynamic spectral filtration [9] the selective device performs two functions – firstly, it provides decomposition of the received radiation into the spectral components, and secondly, on the basis of the *a priori* data, it changes the transmittance for each of spectral components in order to provide maximum suppression of the background radiation spectral components at a minimum attenuation of the optical signal from the target. The acousto-optical filter is used as the selective device, and it assures variation of the amplitude and spectral composition of the received optical signal [10].

The papers [11] show the possibility to design active systems with dynamic spectral processing for contrast enhancement of target image. The source of multi-spectral radiation in the suggested active electro-optical system (AEOS) is represented by a set of laser emitters. *A priori* data about spectral characteristics of the target and background are used in order to increase the target image contrast. According to this *a priori* information, the radiance from the system of laser emitters is varied in order to decrease the values of spectral components of the signal reflected from the surface of the background with a minimum intensity attenuation of the signal reflected from the target.

The objective of this paper is to develop the basics for designing the active electro-optical system with dynamic spectral processing of optical radiation that provides detection of target signals.

2. Basics of dynamic spectral processing of optical radiation in the active electro-optical systems

When developing the principles of designing the active electro-optical systems with dynamic spectral processing of optical signals, it turned out to be reasonable to perform a comparative estimation of the properties of active and passive electro-optical systems, as well as of mathematical and physical aspects of their construction.

The electro-optical systems with dynamic spectral processing of optical radiation of both passive and active types are represented by analog optical computing devices, in which the algorithm of forming the control signals is identical, while the difference between the systems is only in their technical realization.

It is known that main mathematical operations with non-coherent optical signals in the analog optical processors are represented by addition and multiplication [12]. The operation of addition is realized by means of convergence of several light beams in one point (it also can be made using the lens). The operation of multiplication is realized either by optical elements with a controlled transparency T (Fig. 1a), or the elements with the controlled reflectance factor R (Fig. 1b).

In the passive systems with dynamic spectral filtration, the operation of multiplication is realized using the optical elements with the controlled transparency, while in the active electro-optical ones – by means of varying the intensities of spectral components in the irradiating light flux at known values of spectral reflectance of the observed surface.

Let us further consider that an active electro-optical system comprises the transmitting and receiving parts, and spectral processing of optical radiation within this system is realized as the result of performing the following operations:

- first, the directed light flux is formed by source of optical radiation that consists of a set of elementary monochromatic emitters different by their spectra;
- second, an independent variation of the radiation intensities for each of the monochromatic emitters is provided according to *a priori* information about spectral characteristics of the target and background;
- third, sensing the observed surface is performed by the multi-spectral laser signal;
- fourth, measuring the reflected optical signal is performed using the non-selective radiation receiver.

Let us imagine that the signal received by the radiation detector of the active electro-optical system represents a dot product of two vectors. For that purpose let's determine the radiant flux Φ_e, which arrives at the radiation detector of the receiving end of AEOS.

Let the transmitting part of AEOS include the radiation source possessing the spectral radiance $L_{\Sigma e}(\lambda)$. The radiation source directs the light beam onto the target located at the distance l_l from the electro-optical system. A part of the flux, which is reflected from the target, falls onto the entrance pupil of the receiving end in the electro-optical system located at the distance l_2 from the target. When the equality $l_1 = l_2 = l$ is valid, and one deals with the round-shaped exit and entrance pupils of the transmitting and receiving parts of AEOS, as well as under the diffusive mode of reflection from the surface of the target, it follows [13]:

$$\Phi_e = \frac{\pi D_{out}^2 S_2}{16 l^2} \cdot \left(\frac{D_{in}}{f'} \right)^2 \int_{\lambda_{\min}}^{\lambda_{\max}} L_{\Sigma e}(\lambda) \tau_{o1}(\lambda) \tau_m^2(\lambda) \rho(\lambda) \tau_{o2}(\lambda) d\lambda \qquad (1)$$

where S_2 is the radiation receiver area; D_{out} – diameter of exit pupil in the transmitting part of AEOS; D_{in} – diameter of entrance pupil in the receiving part of AEOS; f' – focal length of the optical subsystem in the receiving part; $\tau_m(\lambda)$ – spectral transmittance of the medium [3]; $\tau_{o1}(\lambda)$ – spectral transmittance of the optical subsystem in the transmitting part; $\tau_{o2}(\lambda)$ – spectral transmittance of the optical subsystem in the receiving part; $\rho(\lambda)$ – spectral reflectance of the observed surface.

Let the spectral radiance of radiation source for the transmitting part $L_{\Sigma e}(\lambda)$ be formed as the sum of m monochromatic emitters with the values of spectral radiance $L_{ek}(\lambda)$:

$$L_{\Sigma e}(\lambda) = \sum_{k=1}^{m} L_{ek}(\lambda) = \sum_{k=1}^{m} A_k \varphi_{ek}(\lambda), \qquad (2)$$

where $\varphi_{ek}(\lambda)$ is the relative spectral radiance of the k-th source; A_k – maximum value of spectral radiance of the k-th source of radiation.

By substituting (2) into (1) and considering that the spectral radiance in (2) is a sum of a finite number of monochromatic components, we obtain

$$\Phi_e = q \sum_{k=1}^{m} A_k \int_{\lambda_{\min}}^{\lambda_{\max}} \varphi_{ek}(\lambda) \tau_{o1}(\lambda) \tau_m^2(\lambda) \rho(\lambda) \tau_{o2}(\lambda) d\lambda =$$

$$= q \sum_{k=1}^{m} f_k x_k \cong \vec{F}^T \vec{X}, \qquad (3)$$

where $q = \frac{\pi D_{out}^2 S_2}{16 l^2} \cdot \left(\frac{D_{in}}{f'} \right)^2$ is the component dependent upon the distance to observed surface and the structural parameters of AEOS; $\vec{F} = [f_1, \ldots f_k, \ldots f_m]^{\mathrm{T}}$ – vector of the instrumental function of the transmitting part of AEOS (the weight vector of processing), the coordinates of which mean maximum values of intensity for each of the monochromatic components of the radiation source, $f_k = A_k$; $\vec{X} = [x_1, \ldots x_k, \ldots x_m]^{\mathrm{T}}$ – vector of the input optical signal, the coordinates of which correspond

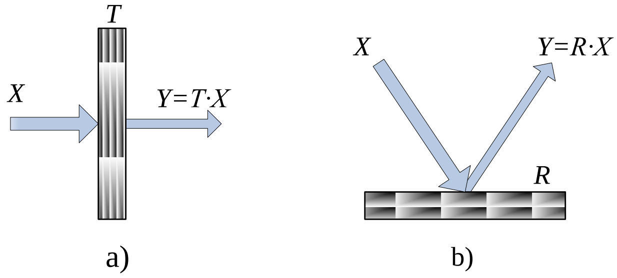

Fig. 1. Fundamental analog optical operations: a) multiplication based on the effect of light transmission; b) multiplication based on the effect of light reflection.

to the radiant fluxes arriving at the input of the receiver for each of the monochromatic components of the source:

$$x_k = \int_{\lambda_{\min}}^{\lambda_{\max}} \varphi_{ek}(\lambda) \tau_{o1}(\lambda) \tau_m^2(\lambda) \rho(\lambda) \tau_{o2}(\lambda) d\lambda . \qquad (4)$$

Therefore, the radiant flux Φ_e, arriving at the input of the radiation receiver in AEOS with the dynamic spectral processing, will be determined by a dot product of the vector $\vec{X}$ corresponding to the radiation flux reflected from the target, and the vector of the instrumental function (the weight vector) $\vec{F}$ of the transmitting part of AEOS.

Considering that dynamic processing of radiation assumes performance of linear transforms with regards to the field intensity, it follows that the only operations with positive values of the field can be performed in AEOS. With account that the light radiance intensity may have only positive values, it becomes apparent that the vector $\vec{F}$ can have at least one negative coordinate at the dynamic spectral processing. It means that the radiation intensity must accept a negative value within a certain spectral interval. In this case, to realize the radiation processing, it is necessary to use the operation of subtraction of the signals obtained by means of the two weight vectors $\vec{F}^+$ and $\vec{F}^-$.

The values of these vectors are formed when decomposing the vector $\vec{F}$ into two vectors with positive coordinates. While forming the vector $\vec{F}^+$, we assume that all the negative values of the coordinates reflecting the negative value of spectral components are equal to zero. When forming the vector $\vec{F}^-$, we assume all the coordinates having positive values as equal to zero, and those having negative values – with the ‘plus’ sign. For example, if the vector $\vec{F}$ has the representation $\vec{F} = [f_1, -f_2, -f_3]^{\mathrm{T}}$, then it would be necessary to represent the vectors $\vec{F}^+$ and $\vec{F}^-$ in the following way: $\vec{F}^+ = [f_1, 0, 0]^{\mathrm{T}}$, $\vec{F}^- = [0, f_2, f_3]^{\mathrm{T}}$.

3. Functional and block diagrams of the electro-optical systems with dynamic spectral processing of optical signals

The above-mentioned basics of dynamic spectral processing the optical radiation within AEOS allow developing the functional and block diagrams of this system. When developing the functional diagram of AEOS, we perform its comparison with the similar diagram of the passive system.

Let us consider the simplified functional diagrams of the passive and active electro-optical systems with dynamic spectral processing of signals, which enables to substantiate their common features and differences. Fig. 2a represents the functional layout illustrating the principles of forming the optical signals within the passive electro-optical system with the dynamic spectral filtration. The abbreviations shown in this figure are as follows: DSF – dynamic spectral filter, RR – radiation receiver.

It is shown (see Fig. 2a) that two multipliers participate in performance of mathematical operation of “multiplication” within the passive electro-optical systems – the first multiplier is represented by the vector $\vec{F}$ (the instrumental function) that characterizes the spectral transmittance of the selective device; the second multiplier is represented by the vector $\vec{X}$ that characterizes the properties of the light flux reflected from the sensed surface.

Within the passive systems with the dynamic spectral filtration, the operation of multiplication is realized as the result of diffraction of the received optical radiation on the multi-frequency and controlled by its amplitude ultrasonic wave. Here, the light diffraction on the acoustic waves is the physical mechanism that provides the transfer of electrical signals to the light carrier.

Fig. 2b shows the functional diagram of forming the optical signals within AEOS with dynamic spectral processing. The designations shown in Fig. 2b are as follows: LRS – laser radiation source (laser unit), RR – radiation receiver.

AEOSs with dynamic spectral processing of optical radiation are the result of further development: firstly, the passive systems of spectral filtration; secondly, the laser vision systems that use laser illumination under the conditions of insufficient natural illumination. The difference from the passive electro-optical systems is as follows: instead of the selective device (acousto-optical filter), which provides the dynamic spectral filtration within the passive system, applied in the active system is the laser emitters unit with the multi-spectral sensing signal. The power spectral density of the multi-spectral signal is determined using *a priori* information about the characteristics of the target and background, so that to decrease the value of spectral components of the signal reflected from the surface of background.

In AEOS (see Fig. 2b), the signal at its output is also the result of the mathematical operation of dot product, in which two multipliers take part. The first multiplier $\vec{X}$ corresponds to the reflecting properties of the sensed surface. The second multiplier $\vec{F}$ characterizes the spectral density of multi-spectral light flux. Intensities of the spectral components of this multiplier are calculated on the basis of *a priori* information about spectral characteristics of the reflecting surface.

The developed functional layout of AEOS with dynamic spectral processing of optical radiation allows drawing its block diagram. Fig. 3 shows the block diagram of the active electro-optical system with dynamic spectral processing of signals that consists of the transmitting and receiving parts. The transmitting part of this system includes the library of spectral characteristics (*1*), instrumental function former (*2*), laser unit (*3*), and device for forming the multi-spectral laser beam (*4*). The receiving part of the system comprises the lens (*5*), radiation receiver (*6*) and electronic processing unit (*7*).

The instrumental function former is designed to create on the basis of *a priori* spectral characteristics of the target and background the controlling signal that provides the multi-spectral radiation with the required spectral density at the output of laser unit. The laser unit comprises a set of lasers generating the monochrome

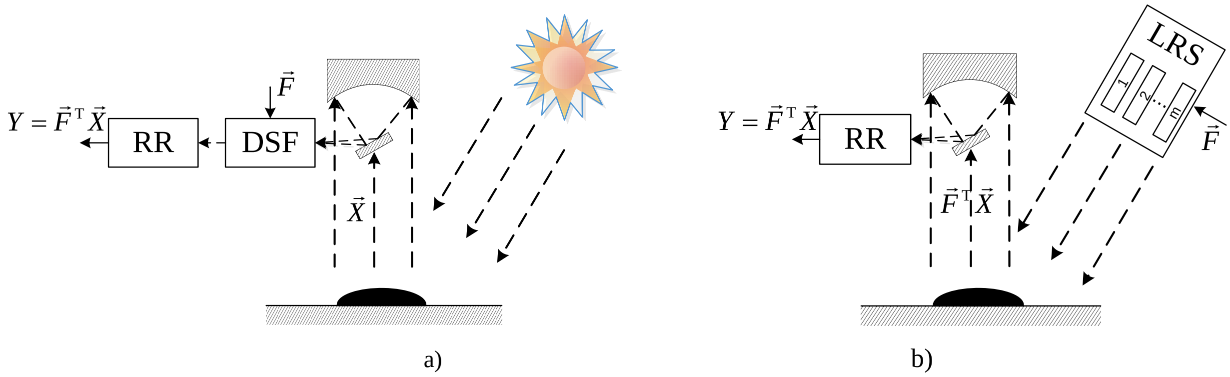

Fig. 2. Functional diagrams of forming the optical signals within the passive (a) and active (b) electro-optical systems with dynamic spectral processing. DSF – dynamic spectral filter, RR – radiation receiver, LRS – laser radiation source (laser unit).

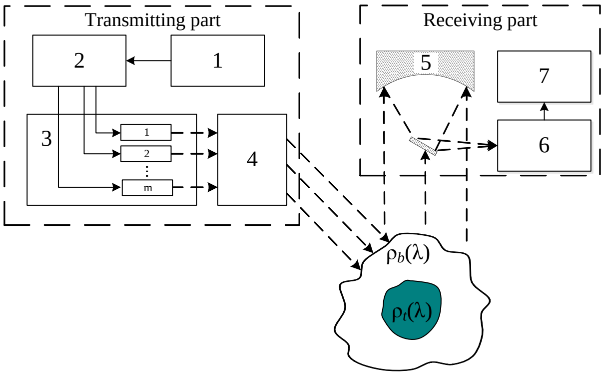

Fig. 3. Block diagram of active electro-optical system with dynamic spectral processing of radiation. *1* – library of spectral characteristics, *2* – instrumental function former, *3* – laser unit, *4* – device for forming the multi-spectral laser beam, *5* – lens, *6* – radiation receiver, *7* – electronic processing unit.

radiation. The device used for forming the multi-spectral laser radiation composes a set of monochrome laser signals into the light beam and provides control of its angular divergence. At the receiving end of the electro-optical system, the reflected polychrome optical radiation is transformed by the radiation receiver into the electrical signals and recorded in the electronic processing unit.

4. Algorithm for optimal detection of optical signals using an active electro-optical system with dynamic spectral processing

The paper [9] deals with developing the principles of designing an optimal detection device for optical signals on the basis of passive electro-optical systems with the dynamic spectral filtration. This paper shows that the dynamic spectral processing of optical radiation, which is implemented in both passive and active electro-optical systems, is described by the same mathematical model that includes performing the dot product of the instrumental function vector and the vector of input optical signal. Due to the differences in physical and engineering implementation of the processing, it turned out to be reasonable to consider particularities of designing an optimal detection device for optical signals on the basis of active electro-optical system with the dynamic spectral processing of optical radiation.

When illuminating the inhomogeneous surface with the laser emission, a random signal will be measured at the receiving part of AEOS. Therefore, the problem under consideration is a particular case of the general problem of statistical verification of two hypotheses – H_0 (the background signal is present) and H_1 (the target signal is present). Suppose that for H_0 the conditional probability density is normal and has the following representation: $p(\vec{X}/H_0) \sim N(\vec{\mu}_b, \Gamma_b)$, and for the hypothesis H_1 it is $p(\vec{X}/H_1) \sim N(\vec{\mu}_t, \Gamma_t)$. Here, $\vec{\mu}_b$ and $\vec{\mu}_t$, as well as Γ_b and Γ_t are the mathematical expectations and correlation matrices of realizations of the background and target signals, correspondingly.

Subsequently, we shall consider solely the equality of the correlation matrices $\Gamma_b = \Gamma_t = \Gamma$. Then the considered problem is reduced to solving the problem of the deterministic signal detection against the background of additive noise. The sample received by AEOS with dynamic spectral processing acquires the following representation:

$$\vec{Z} = \alpha\vec{\xi} + \vec{n}\,, \tag{5}$$

where $\vec{Z} = \vec{X} - \vec{\mu}_b$ is the reduced sample at the input of optical processing circuit; $\vec{\xi} = \vec{\mu}_t - \vec{\mu}_b$ – deterministic desired signal representing the difference between the mathematical expectations of the signals of target and background; α – random parameter accepting the values of either 1 or 0; $\vec{n}$ – random column vector of sampling values, which characterizes an additive noise with the following normal distribution: $N(0, \Gamma)$.

We select the Neyman–Pearson criterion as the optimality criterion when solving the problem of optical signal detection, because the *a priori* probabilities $P(H_1)$ and $P(H_0)$ are unknown. Usually, in order to make an optimal decision after receiving a multi-dimensional sample (5), it is calculated the logarithm for the probability ratio $\ell(\vec{Z}) = p_{sn}(\vec{Z})/p_n(\vec{Z})$, *i.e.*, the logarithm for probability densities ratio of one and the same sample of the received signal under two conditions: availability of both the signal and noise $p_{sn}(\vec{Z})$, and availability of the noise only $p_n(\vec{Z})$. Subsequently, the obtained value of the logarithm is compared with the threshold value.

The logarithm from the probability ratio for the problem under consideration will have the following representation:

$$\ln \ell(\vec{Z}) = Y^r - q^2/2\,, \tag{6}$$

where $Y^r = \vec{\xi}^{\mathrm{T}}\Gamma^{-1}\vec{Z} = \vec{F}^{\mathrm{T}}\vec{Z}$ is the reduced signal at the output of radiation receiver of AEOS with dynamic spectral processing; $q^2 = \vec{\xi}^T\Gamma^{-1}\vec{\xi}$ – signal-to-noise ratio in dependence on the power; $\vec{F} = \Gamma^{-1}\vec{\xi}$ – instrumental function (weight vector) of the AEOS transmitting part (Fig. 4).

As an example, Fig. 4 shows within the two-dimensional space the normal distributions of samples of the background and the target signals, as well as the vector corresponding to the instrumental function of the AEOS transmitting part, providing for optimal dynamic spectral processing.

Analysis of the expression (6) shows that optimal detection of the target signal can be performed by comparing the value of reduced signal at the output of radiation receiver of AEOS with dynamic spectral processing with the threshold value. However, the obtained algorithm is hard to be realized, because forming $\vec{Z} = \vec{X} - \vec{\mu}_b$ is possible only by the means of subtraction performed for the optical signals. To exclude

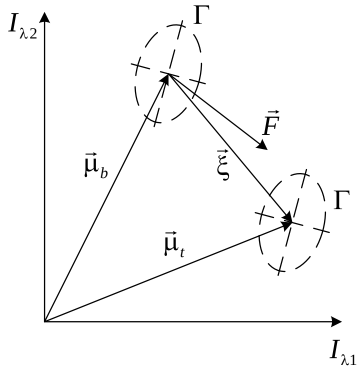

Fig. 4. Optimal dynamic spectral processing of optical radiation of an inhomogeneous target against the inhomogeneous background.

this operation, it is reasonable to transform the expression for the reduced signal at the output of radiation receiver of AEOS in the following manner:

$$Y^r = \vec{\xi}^{\mathrm{T}} \Gamma^{-1} \vec{Z} = \vec{F}^{\mathrm{T}} \vec{X} - \vec{F}^{\mathrm{T}} \vec{\mu}_b . \qquad (7)$$

Then, to compare with the threshold value, we shall use the signal at the output of radiation receiver of AEOS with dynamic spectral processing $Y = \vec{F}^{\mathrm{T}} \vec{X}$ instead of Y^r. Whereas, it will be compared with the threshold value, to which the value of the background signal at the output of AEOS is added: $m_b = \vec{F}^{\mathrm{T}} \vec{\mu}_b$.

When performing practical implementation of the dynamic spectral processing of optical radiation, it is necessary to maximize the optical signal arriving at the radiation receiver for each of the spectral components. Therefore, it is suggested to normalize the instrumental function of the transmitting part of AEOS as follows:

$$\vec{F}_n = r \Gamma^{-1} \vec{\xi} , \qquad (8)$$

where $r = 1 \Big/ \left| \vec{s}_{\max} \vec{\xi} \right|$ is the normalizing multiplier that maximizes the intensity of radiation of one of the monochrome emitters; $\vec{s}_{\max}$ – row vector of the inverse correlation matrix, for which the absolute value of the dot product is maximal $\left| \vec{s} \vec{\xi} \right| \Rightarrow \max$.

Therefore, to perform comparison with the threshold value, we shall use the normalized value of the signal Y_n at the output of radiation receiver of the active electro-optical system with dynamic spectral processing:

$$Y_n \underset{H_0}{\overset{H_1}{\gtrless}} h_n , \qquad (9)$$

where $Y_n = \vec{F}_n^{\mathrm{T}} \vec{X}$ is the normalized signal at the output of AEOS; $h_n = Y_0 + \vec{F}_n^{\mathrm{T}} \vec{\mu}_b$ – normalized threshold.

The obtained algorithm (9) allows developing the block diagram (Fig. 5) of an optimal detection device, in which the dynamic spectral processing of optical radiation is used. In this figure, the scalar values are shown with single arrows and the vector values – with the vector arrows. The threshold device (ThD) forms the signal $\hat{\alpha} = 0$ (H_0 is true) or $\hat{\alpha} = 1$ (H_1 is true) depending on the level of the output signal Y_n and the calculated threshold value $Y_0 + \vec{F}_n^{\mathrm{T}} \vec{\mu}_b$.

According to the Neyman–Pearson criterion, the value of the threshold is selected as being based on the given false alarm probability P_{FA} by using the following expression:

$$h_n = qr\Phi^{-1}(1 - P_{FA}) + \vec{F}_n^{\mathrm{T}} \vec{\mu}_b , \qquad (10)$$

where $\Phi^{-1}(\bullet)$ is the quantile function inverse to the probability integral.

Whereas the conditional probability of correct detection of P_{CD} will be equal to:

$$P_{CD} = \int_{h_n}^{\infty} p_{sn}(Y_n) dY_n = 1 - \Phi\left(\Phi^{-1}(1 - P_{FA}) - q \right). \qquad (11)$$

Using the obtained expressions (10) and (11), the dependences of conditional probabilities of correct detection on the signal-to-noise ratio q were plotted (Fig. 6). The curves of conditional probabilities of correct detection were plotted under various levels of the conditional false alarm probability.

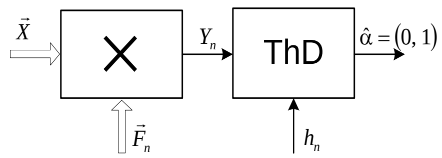

Fig. 5. Block diagram of an optimal detection device for the inhomogeneous target against the inhomogeneous background. ThD – threshold device, × – multiplier.

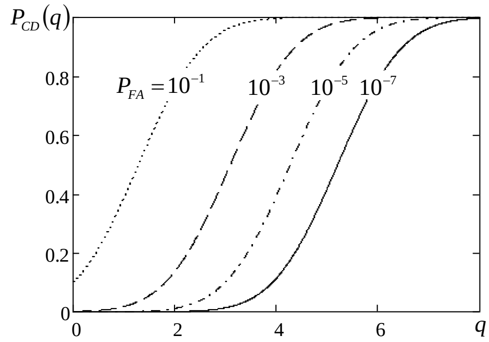

Fig. 6. Dependences of conditional probabilities of correct detection upon the signal-to-noise ratio at different values of the false alarm probability.

Therefore, the algorithm for optimal detection of optical signals is developed using basics of the dynamic spectral processing of optical radiation in AEOS. Qualitative characteristics for the developed detection device are determined on the basis of AEOS with dynamic spectral processing, which allow, at the given level of the false alarm, determining the conditional probability of correct detection of the target under observation depending on the value of the signal-to-noise ratio.

5. Mathematical modeling of optimal detection of the target signal

This section of the paper represents the results of mathematical modeling of the process of optimal detection of the target signal by using AEOS with dynamic spectral processing of optical radiation.

The following provisions are applied to develop the mathematical model of the optimal processing of optical signals within the active electro-optical system:

- the RGB-model of color digital images [14] that assumes representation of the color of any point in the image as a vector within the Euclidian space of three main colors;
- independence of the radiation processing arriving from the spatial resolution elements of the electro-optical system [15];
- representation of optical radiation processing of the image elements in the form of a dot product of the input signal and the instrumental function of the electro-optical system with matched processing of optical signals.

In accordance with the applied RGB-model, each element of the initial color image with the coordinates (i, j) is represented as the vector $\vec{X}(i,j)=\left[x_R(i,j), x_G(i,j), x_B(i,j)\right]^{\mathrm{T}}$ within the three-dimensional Euclidian space, where x_R, x_G, x_B are the radiance values measured in the red (R – red), green (G – green) and blue (B – blue) spectral channels.

Mathematical modeling has been performed using the Mathcad computer software package for engineering calculations and consisted of two stages. At the first stage, we focused on forming basic data required to perform modeling. Performed at the second stage was immediate mathematical modeling of the dynamic spectral processing of optical radiation within the active electro-optical system for the purpose to detect the searched target.

The first stage of the mathematical modeling consisted of forming an initial image with the required spectral and statistical characteristics. We formed the initial image so that the background and target signals in three spectral channels (RGB) were the realizations of the following independent normalized random values:

$$\begin{aligned} &x_{bR}(i,j) \sim N(100,100); && x_{tR}(i,j) \sim N(160,100);\\ &x_{bG}(i,j) \sim N(170,225); && x_{tG}(i,j) \sim N(105,225); \quad (12)\\ &x_{bB}(i,j) \sim N(123,625); && x_{tB}(i,j) \sim N(100,625). \end{aligned}$$

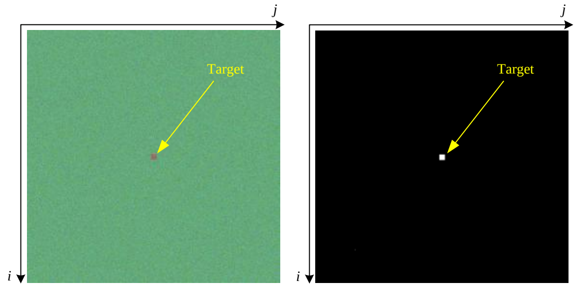

Fig. 7. Initial (a) and output (b) images formed in the process of mathematical modeling.

The initial image had the dimensions of 300×300 elements. The rectangular target to be detected was positioned in the center of the image. The target dimensions were equal to 11×11 pixels. The initial image is shown in Fig. 7a.

The following sequence of operations was performed at the second stage.

1. Calculation of the normalized weight vector $\vec{\mathbf{F}}_n$ and the normalized value of the threshold h_n by using the previously obtained expressions. Calculation of the weight vector $\vec{\mathbf{F}}_n$ was performed using the equation (8) with account of *a priori* information about the spectral and statistical characteristics of the background and target signals:

$$\vec{\mu}_b = \begin{bmatrix} 100 \\ 170 \\ 123 \end{bmatrix}; \; \vec{\mu}_t = \begin{bmatrix} 160 \\ 105 \\ 100 \end{bmatrix}; \; \Gamma = \begin{bmatrix} 100 & 0 & 0 \\ 0 & 225 & 0 \\ 0 & 0 & 625 \end{bmatrix}.$$

The threshold h_n was calculated using the formula (10) for the following value of the false alarm probability: $P_{FA} = 10^{-5}$.

2. Modeling of the process of dynamic spectral processing of optical radiation was performed by means of calculating the dot product of weight vector and the input vector for each point of the initial image:

$$Y_n(i,j) = \vec{F}_n^{\mathrm{T}} \vec{X}(i,j).$$

3. Threshold processing of the signals. The mathematical equation (9) was used for modeling at this stage. In this case, the point (i, j) of the output image was assigned to the value of unity, if the value of dot product exceeded the threshold, and the value of zero – in the opposite case.

The binary image obtained as the result of optimal processing is shown in Fig. 7b.

Analysis of the image obtained in the course of the mathematical modeling shows that we have managed to separate the desired signal at the output by suppressing the optical signal of the inhomogeneous background as the result of optimal dynamic spectral processing of optical radiation in AEOS.

6. Conclusions

Active electro-optical systems with dynamic processing of signals represent further development of passive spectral filtration systems as well as the laser vision systems using laser illumination under the conditions of insufficient natural illumination.

The difference from the passive electro-optical systems is that instead of the selective device (acousto-optical filter), which provides the dynamic spectral filtration within the passive system, applied in the active system is a laser emitter unit with the multi-spectral sensing signal. The power spectral density of the multi-spectral signal is determined using *a priori* information about the characteristics of the target and background, so that to decrease the value of spectral components of the signal reflected from the surface of the background.

The algorithm for optimal detection of optical signals has been developed using basics of the signal detection theory, as well as of the developed principles for dynamic spectral processing of optical radiation in AEOS. There have been defined the quantitative characteristics of the developed detector device, which enables, at the set level of false alarm, to determine the conditional probability of correct detection of the target, depending on the value of signal-to-noise ratio.

Mathematical modeling of the process of target detection against an inhomogeneous background has been performed, and it has been shown that optimal dynamic spectral processing of optical radiation in AEOS allows selecting the desired signal by full suppressing the optical signal of the inhomogeneous background.

References

1. McManamon P.F. Review of ladar: a historic, yet emerging, sensor technology with rich phenomenology. *Opt. Eng*. 2012. **51**, No 6. P. 060901. https://doi.org/10.1117/1.OE.51.6.060901.
2. Steinvall O., Renhorn I., Ahlberg J. *et al.* ACTIM: an EDA initiated study on spectral active imaging. *Proc. SPIE*. 2010. **7835**. P. 78350C. https://doi.org/10.1117/12.865041.
3. Steinvall O. Active spectral imaging and mapping. *Adv. Opt. Techn*. 2014. **3**, No 2. P. 161–178. https://doi.org/10.1515/aot-2013-0064.
4. Johnson B., Joseph R., Nischan M. *et al.* A compact, active hyperspectral imaging system for the detection of concealed targets. *Proc. SPIE*. 1999. **3710**. https://doi.org/10.1117/12.357002.
5. Skvortsov L.A. Active spectral imaging for standoff detection of explosives. *Quantum Electron*. 2011. **41**, No 12. P. 1051–1060. https://doi.org/10.1070/QE2011v041n1.
6. Tan S., Narayanan R.M. Design and performance of a multiwavelength airborne polarimetric lidar for vegetation remote sensing. *Appl. Opt*. 2004. **43**, No 11. P. 2360–2368. https://doi.org/10.1364/AO.43.002360.
7. Nischan M.L., Joseph R.M., Libby C.J., Kerekes J.P. Active spectral imaging. *Lincoln Lab. J.* 2003. **14**, No 1. P. 131–144.
8. Liu Yu, Tao Z., Zhang J. *et al.* Deep-learning-based active hyperspectral imaging classification method illuminated by the supercontinuum laser. *Appl. Sci.* 2020. **10**, No 9. P. 3088. https://doi.org/10.3390/app10093088.
9. Kupchenko L.F., Rybiak A.S., Goorin O.A. Dynamic spectral filtering of signals in optoelectronic systems of target detection. *Telecomm. Radio Eng*. 2018. **77**, No 4. P. 689–704. https://doi.org/10.1615/TelecomRadEng.v77.i8.30.
10. Kupchenko L.F., Goorin O.A., Rybiak A.S. Experimental research of dynamic spectral filtration using laser radiation interaction with multifrequency acoustic wave. *2016 IEEE 7th Intern. Conference on Advanced Optoelectronics and Lasers (CAOL)*, Odesa, Ukraine, 12–15 September 2016. https://doi.org/10.1109/CAOL.2016.7851411.
11. Kupchenko L.F., Goorin O.A., Karlov V.D. *et al.* Active electro-optical system with dynamic spectral processing of optical radiation. *2019 IEEE 8th Intern. Conference on Advanced Optoelectronics and Lasers (CAOL)*, Sozopol, Bulgaria, 6–8 September 2019. https://doi.org/10.1109/CAOL46282.2019.9019458.
12. *Handbook of Optics: Vol. I – Geometrical and Physical Optics, Polarized Light, Components and Instruments*. M. Bass, Editor in Chief. McGraw-Hill Companies, Inc., 2010.
13. Yakushenkov Yu.G. *Electro-optical Devices: Theory and Design*. 4th ed. Moscow, Logos, 1999 (in Russian).
14. Gonzalez R.C., Woods R.E. *Digital Image Processing*, 3rd ed. Prentice Hall, New Jersey, 2008.
15. Schott J.R. *Remote Sensing The Image Chain Approach*, 2rd ed. Oxford University Press, 2007.

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Активна оптико-електронна система виявлення об’єктів з використанням динамічної спектральної обробки оптичного випромінювання

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Анотація. У статті розглянуто дослідження в області спектральної обробки зображень та лазерного бачення. За характером формування інформаційних полів (полів випромінювання) оптико-електронні системи можна поділити на пасивні та активні. Пасивні оптико-електронні системи використовують інформаційні поля, які формуються природними джерелами випромінювання, а активні передбачають використання штучних джерел. Проведено порівняльний аналіз математичних та фізичних аспектів побудови оптико-електронних систем з динамічною спектральною обробкою оптичного випромінювання пасивного та активного типів. Показано, що керована динамічна спектральна обробка оптичного випромінювання реалізується у пасивних та активних оптико-електронних системах за одним і тим же алгоритмом, який представляє собою роботу оптичного процесора, що виконує математичну операцію скалярного множення вектора на вектор. Розроблено структуру схеми активної оптико-електронної системи з динамічною спектральною обробкою. Із використанням основних положень теорії детектування сигналів розроблено алгоритм оптимального виявлення оптичних сигналів. Проведено математичне моделювання процесу виявлення об’єкта на неоднорідному фоні. Показано, що в результаті оптимальної динамічної спектральної обробки оптичного випромінювання в активній оптико-електронній системі вдалось виокремити корисний оптичний сигнал, повністю заглушивши при цьому сигнал фону.

Ключові слова: активна оптико-електронна система, динамічна спектральна фільтрація, оптимальне виявлення, лазерне бачення.