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Compensation method for atmospheric attenuation of laser radiation in active electro-optical systems with dynamic spectral processing of optical signals

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Abstract. This paper describes the compensation method for atmospheric attenuation of laser radiation, which can be implemented in active electro-optical systems with pre-detector dynamic spectral processing of optical signals. In these electro-optical systems, the spectral flux of sensing radiation is formed using multispectral laser signals based on *a priori* information about the spectral reflectance of the target and background. The sensing signal formed in this way ensures maximum suppression of the background signal at the output of system with minimal attenuation of the target signal. The influence of atmospheric radiation attenuation on operation of an active electro-optical system with dynamic spectral processing has been analyzed. It has been shown that the laser radiation attenuation in the atmosphere significantly affects the efficiency of dynamic spectral processing of optical signals (leads to a decrease in the target image contrast). The developed compensation method for atmospheric attenuation of radiation in active electro-optical systems with dynamic spectral processing is based on the fact that the spectral intensity of the sensing radiation is formed not only on the basis of *a priori* data on spectral characteristics of the target and background, but also takes into account the spectral transmittance of the optical radiation propagation medium.

Keywords: active electro-optical system, dynamic spectral processing, atmospheric attenuation of radiation, laser radiation.

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1. Introduction

Up to date, active electro-optical systems are intensively developed, which is caused, first of all, by the improvement of technologies for creating laser sources that provide formation of radiation with the required characteristics [1]. One of directions for developing the active electro-optical systems (AEOS), being of considerable interest, is to design spectral imaging systems with active illumination. These systems provide measuring spectral features of the targets [2–11].

According to the principles of signal processing, the active spectral imaging systems are separated into the systems with post-detector and pre-detector processing. In the systems with post-detector processing [3–9], the received radiation is first converted by a radiation detector into an electrical signal, digitized, and then digitally processed in accord with the selected algorithm. In AEOS with pre-detector processing of optical radiation, optical fields are processed, and then the processing results are recorded by a radiation detector [10, 11].

There are two ways to build active spectral imaging systems with post-detector processing. The first method involves the use of a broadband laser as a radiation source [3–6]. In this case, the reflected optical signal is decomposed into spectral components using a dispersing element, and then the radiation is recorded in the spectral channels and further processed. The second method of constructing active spectral imaging systems involves the use of a combination of a tunable laser in a certain spectral wavelength range and a panchromatic radiation detector [7–9]. In this case, spectral images are recorded sequentially in time and undergo further processing.

The source of radiation in active electro-optical systems with pre-detector processing is a set of laser emitters with different operating wavelengths [10, 11]. In this case, spectral processing is carried out by irradiating the target and the surrounding background with laser radiation, the spectral intensity of which is formed in such a way as to maximally suppress the background signal at the AEOS output with minimal attenuation of the signal reflected from the target. When forming the spectral composition of laser radiation, *a priori* information about the spectral characteristics of target and background signals is used.

It is known [12] that when operating in atmospheric conditions, both radiation attenuated due to the influence of the medium (multiplicative interference) and radiation scattered by the medium (additive interference) come to the input of the radiation receiver of the electro-optical system. In this case, the spectral flux of the input radiation is distorted, which significantly affects the efficiency of the electro-optical system (for example, the contrast and the signal-to-noise ratio at its output decrease).

The analysis of publications [2–11] devoted to active spectral imaging systems has shown that the issues of compensating the atmospheric interference were not considered in these works. Currently, only the range gating method [13] has been developed, which provides compensation for the additive atmospheric interference caused by radiation scattering. The method is widely used in panchromatic active electro-optical systems (2D/3D ladar) and assumes a pulsed mode of operation of the radiation source, as well as gating the receiving time of reflected radiation.

The range gating method can also be used in AEOS with pre-detector spectral processing of radiation to compensate the additive atmospheric interferences caused by radiation scattering. This is caused by the fact that in these systems it is possible to use the pulsed mode of operation of a multispectral radiation source. At the same time, the problem associated with compensating the effect on operation of AEOS with pre-detector spectral processing of multiplicative atmospheric interferences caused by attenuation of laser radiation is actual and needs to be studied.

The purpose of this paper is to develop a method that provides compensation of atmospheric attenuation of laser radiation in active electro-optical systems with dynamic spectral processing of optical signals.

2. Fundamentals of dynamic spectral processing of optical radiation

The theoretical foundations of dynamic spectral processing of optical radiation in active electro-optical systems are presented in [10]. It is shown that, for implementation of dynamic spectral processing of optical radiation in AEOS, it is necessary for the object space of its receiving part to be illuminated by a radiation source, which spectral radiance $L_{\Sigma e}(\lambda)$ is the weighted sum of the spectral radiances $L_{ek}(\lambda)$ of m monochromatic emitters:

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

where A_k is the weighting coefficient of the spectral radiance of the k-th radiation source; $\varphi_{ek}(\lambda)$ is the spectral radiance of the k-th source at $A_k=1$.

Then the radiation flux Φ_e, arriving at the radiation receiver of this active electro-optical system is defined by the scalar product of the vector of its instrumental function $\vec{F}=\left[f_1,\ldots,f_k,\ldots,f_m\right]^{\mathrm{T}}$ by the vector of the input optical signal $\vec{X}=\left[\mathrm{x}_1,\ldots,x_k,\ldots,x_m\right]^{\mathrm{T}}$ that corresponds to the spectral properties of the reflecting surface

$$\Phi_e=Q\sum_{k=1}^{m}f_kx_k=Q\cdot\vec{F}^T\vec{X}, \qquad (2)$$

where $Q=\dfrac{\pi D_1^2S_2}{16z^2}\cdot\left(\dfrac{D_2}{f'}\right)^2$ is a parameter that depends on the distance z to the sensed surface and design parameters of AEOS (D_1 is the diameter of the exit pupil of the optical system of the radiation source; D_2, f' are the diameter of the entrance pupil and the focal length of the optical system of the receiving channel of AEOS; S_2 is the area of radiation receiver in AEOS) [14, 15].

The coordinates of the vector of AEOS instrumental function $\vec{F}$ are the weighted values of the spectral radiances of the monochromatic components of the AOES radiation source: $f_k=A_k$. The coordinates of the vector $\vec{X}$ correspond to the radiation fluxes entering the input of the AEOS receiver for each monochromatic component of the radiation source:

$$x_k=\int_{\lambda_{\min}}^{\lambda_{\max}}\varphi_{ek}(\lambda)\tau_{o1}(\lambda)\tau_a^2(\lambda)\rho(\lambda)\tau_{o2}(\lambda)d\lambda, \qquad (3)$$

where $\tau_{o1}(\lambda)$, $\tau_{o2}(\lambda)$ are the spectral transmittances of optical system in the transmitting and receiving channels in AEOS; $\tau_a(\lambda)$ is spectral transmittance of the atmosphere; $\rho(\lambda)$ is the spectral reflectance of the sensing surface (with diffuse reflection) [14]; $\lambda_{\min}\ldots\lambda_{\max}$ is the operation range of wavelengths in AEOS.

The spectral intensities of laser sources are described by Gaussian functions, and the width of their spectral lines amount from fractions to a few nanometers. This allows in expression (3) to move from the integral of spectral functions multiplication to the corresponding effective (averaged) values multiplication [14]:

$$x_k=\tau_{a\,k}^2\rho_k\tau_{o1k}\tau_{o2k}\Psi_k, \qquad (4)$$

where $\Psi_k=\int_{\lambda_{\min}}^{\lambda_{\max}}\varphi_{ek}(\lambda)d\lambda$ is the effective radiance of the k-th radiation source; $\tau_{a\,k}^2$ is the atmosphere transmittance averaged over λ; ρ_k is the reflectance averaged over λ; τ_{o1k}, τ_{o2k} are λ-averaged transmittances of the optical systems of the transmitting and receiving channels of AEOS. It should be noted that

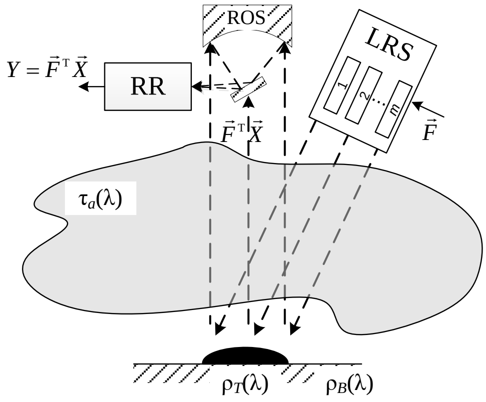

Fig. 1. Active electro-optical system with dynamic spectral processing of optical radiation.

the values $\tau_{a\,k}^2$, ρ_k , τ_{o1k} , τ_{o2k} are calculated by averaging the corresponding spectral functions within the emission band of the *k*-th radiation source.

To implement dynamic spectral processing of optical radiation, AEOS includes a laser radiation source (LRS), an optical receiving subsystem (ROS), and a radiation receiver (RR) (Fig. 1). The laser radiation source consists of a set of *m* monochromatic lasers operating at different wavelengths. This provides the ability to control the radiation intensity of each laser from a given set.

At the output of the radiation receiver of the active electro-optical system, a signal *Y* is proportional to (and in the ideal case equal to) the scalar product of the vector of its instrumental function $\vec{F}$ by the vector of the input optical signal $\vec{X}$, containing information on the spectral properties of the reflecting surface, and it will be recorded.

Further, using the vector representation of signals (2), we define the AEOS instrumental function, which simultaneously provides at its output both the maximum target signal and the minimum background signal (maximum contrast of the target image). Let's assume that when a target is irradiated, an optical signal received by the AEOS radiation detector is described by the vector $\vec{T} = [t_1,\ldots,t_k,\ldots,t_m]^{\mathrm{T}}$, and when the background is irradiated, it is described by the vector $\vec{B} = [b_1,\ldots,b_k,\ldots,b_m]^{\mathrm{T}}$. The coordinates of target and background vectors are defined by the following expressions (see Eq. (4)):

$$t_k = \tau_{a\,k}^2\, \rho_{T\,k} \tau_{o1k} \tau_{o2\,k} \Psi_k\,,$$

$$b_k = \tau_{a\,k}^2\, \rho_{B\,k} \tau_{o1k} \tau_{o2\,k} \Psi_k\,.$$

The contrast of target image at the output of AEOS with dynamic spectral processing of optical radiation is defined as the ratio of the difference between the output signals of target and background to their sum

$$C = \vec{F}^{\mathrm{T}}\left(\vec{T} - \vec{B}\right) \Big/ \vec{F}^{\mathrm{T}}\left(\vec{T} + \vec{B}\right).$$

To ensure maximum contrast *C* at the output of AEOS, the vector of its instrumental function $\vec{F}$ should be orthogonal to the background vector $\vec{B}$ and lie on the plane passing through the vectors $\vec{T}$ and $\vec{B}$ [11]:

$$\vec{F} = r\left(\vec{T} - N \cdot \vec{B}\right), \tag{5}$$

where $N = \vec{T}^{\mathrm{T}}\vec{B} \big/ \vec{B}^{\mathrm{T}}\vec{B}$ is the projection of the target vector $\vec{T}$ to the base vector $\vec{B}^o = \vec{B} \big/ \sqrt{\vec{B}^{\mathrm{T}}\vec{B}}$ of the background vector $\vec{B}$, normalized to its length $\left\|\vec{B}\right\| = \sqrt{\vec{B}^{\mathrm{T}}\vec{B}}$; *r* is a normalizing factor that maximizes the optical signal recorded by the AOES radiation receiver:

$$r = 1 \Big/ \max_k \left(t_k - N \cdot b_k\right).$$

Thus, dynamic spectral processing of optical radiation is a matched optical processing, which is based on calculating the dot product of a vector by a vector. One of the factors of this product characterizes the input optical signal, and the second one characterizes the instrumental function of the active electro-optical system. The maximum contrast of the target at the output of the active electro-optical system is gained when the vector of the instrumental function is perpendicular to the background vector and lies in the plane passing through the target and background vectors. When calculating the vector of the instrumental function, *a priori* information about the background and target optical signals is used.

3. Analysis of the atmospheric interference influence on operation of active electro-optical systems with dynamic spectral processing

Attenuation and distortion of optical signals in the atmosphere happens due to two main processes [14, 15]:

– absorption of radiation by gas components, as a result of which, transformation of radiation energy into its other types takes place;

– molecular and aerosol attenuation (scattering), which consists in changing the direction of radiation propagation.

The absorption of radiation is caused by the presence of various gases (water vapor, carbon dioxide, ozone, *etc.* in the atmosphere) and has a pronounced selective character. It manifests itself in the form of absorption bands separated by transmission windows, where absorption is absent at all or is very small.

The scattering of radiation energy by the particles that make up the medium is manifested in the deviation of the radiation flow from the initial direction, and here the absorption of energy by the matter of these particles is also possible. The presence of a large number of suspended particles in the atmosphere (aerosol, mineral and organic dust, smoke particles, *etc.*) leads to intense light scattering and appearance of some kind of a light veil. Diffuse light creates an atmospheric haze that reduces the target image contrast and also decreases probability of detection.

Let us study how the atmospheric attenuation of laser radiation affects the operation of an active electro-optical system with dynamic spectral processing of optical signals. In general, the process of attenuation of optical radiation in the atmosphere can be described with the following optical characteristics of the medium:

– spectral extinction coefficient of the atmosphere – $\varepsilon(\lambda)$,

– spectral transmittance of the atmosphere – $\tau_a(\lambda)$.

Under the condition of single scattering of radiation in an optically homogeneous atmosphere, its spectral transmittance is defined by the following expression [15]:

$$\tau_a(\lambda) = I(\lambda)/I_0(\lambda) = \exp[-\varepsilon(\lambda)\cdot l], \tag{6}$$

where $I(\lambda)$ is the spectral intensity of radiation that has passed the path l; $I_0(\lambda)$ is the spectral intensity at the beginning of the path. This expression is known in the literature as the Beer–Lambert–Bouguer law.

To determine the extinction coefficient of the medium, we use the Koschmieder expression [15], which establishes the relationship between the extinction coefficient of the atmosphere at the wavelength 0.55 µm and the meteorological optical range (meteorological range) R_{vis}. The meteorological optical range (MOD) is the distance at which the contrast between a certain type of source (test object) and the surrounding background $C_0 = 1$ is reduced to the threshold of contrast sensitivity of the eye $C_T = 0.05$ (in accordance with the requirements of the International Commission on Illumination [13]):

$$R_{vis} = \frac{1}{\varepsilon_{0.55}}\ln\left(\frac{C_0}{C_T}\right) = \frac{3}{\varepsilon_{0.55}}.$$

Calculation of the spectral extinction coefficient in the wavelength range of 0.4...3 µm (in the "transparency windows") is carried out according to the following formula [15]:

$$\varepsilon(\lambda) = \frac{3}{R_{vis}}\left(\frac{0.55}{\lambda}\right)^{0.585R_{vis}^{1/3}}, \tag{7}$$

where the meteorological optical range R_{vis} is expressed in kilometers and the wavelength λ is expressed in micrometers.

A feature of active electro-optical systems is that the influence of the atmosphere introduces attenuation in two sections of laser radiation propagation: in the path from the radiation source to the sensed surface, and then from the surface to the receiving device of AEOS. Therefore, the spectral transmittance of the medium, which is included in Exp. (3), will be defined as follows:

$$\tau_a^2(\lambda, z) = \exp[-2\cdot\varepsilon(\lambda)\cdot z], \tag{8}$$

where $z = l/2$ is the range to the surface that is irradiated by AEOS.

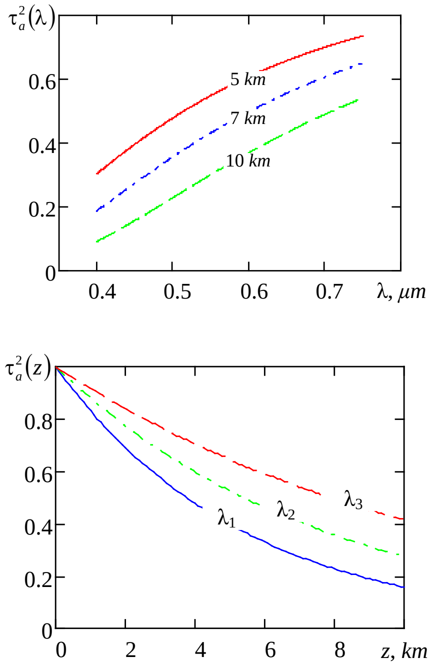

Fig. 2. Dependences of the squared spectral transmittance of the atmosphere on the wavelength and distance for the meteorological optical range R_{vis} = 50 km.

Using Exps. (7) and (8), dependences of the spectral transmittance squared of the atmosphere on the wavelength λ and distance z at MOD R_{vis} = 50 km (corresponds to "good visibility" according to the International Visibility Code) were constructed. The plots in Fig. 2a illustrate the dependence of squared atmospheric transmittance $\tau_a^2(\lambda)$ on the wavelength of optical radiation in the visible range at three values of the distance z to the sensed surface: 5 km (solid line), 7 km (dashed-dotted line) and 10 km (dashed line). Fig. 2b shows the dependences of atmospheric transmittance squared $\tau_a^2(z)$ as a function of the distance to the sensed surface for three wavelengths: λ_1 = 0.45 µm (solid line); λ_2 = 0.532 µm (dash-dotted line); λ_3 = 0.635 µm (dashed line).

An analysis of the dependences presented in Fig. 2a showed that the value of the atmospheric transmittance decreases with decreasing the wavelength of optical radiation. In this case, the difference in the values of transmittances for different wavelengths increases with increasing distance to the sensed surface (see Fig. 2b). Calculations have shown that even with "good visibility" (R_{vis} = 50 km), atmospheric attenuation of optical signals is significant at large distances and must be taken into account in spectral processing.

As shown above, dynamic spectral processing in order to enhance the contrast of target image is a matched processing of optical signals, in which the vector of AEOS instrumental function is determined as based on *a priori* knowledge of the target and background signals.

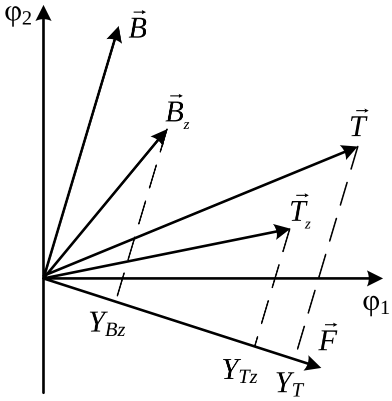

Fig. 3. Influence of atmospheric attenuation on dynamic spectral processing of optical radiation in the active electro-optical system.

Therefore, if the input optical signals of the target and background differ from those known *a priori* due to atmospheric attenuation, then the target contrast at the output of AEOS will decrease.

Using the example of AEOS, let us show how atmospheric attenuation of radiation leads to a decrease in the efficiency of dynamic spectral processing, which provides an increase in the target image contrast. One should assume that the vector of the AEOS instrumental function $\vec{F}$ was calculated on the basis of the target $\vec{T}$ and background $\vec{B}$ vectors obtained under the condition: $\forall k \to \tau_{a\,k}^2 = 1$. These vectors are shown as an example in the two-dimensional Euclidean spectral space of laser radiation bands $\{\varphi_1, \varphi_2\}$ (Fig. 3). If the input of AEOS receives signals that coincide with the vectors $\vec{T}$ and $\vec{B}$, then only the target signal $Y_T = \vec{F}^{\mathrm{T}}\vec{T}$ will be recorded at its output, *i.e.*, target image contrast will be equal to $C = 1$.

Now suppose that the target is at a distance z from AEOS. As a result, the input of the electro-optical system will receive target and background signals, which correspond to the vectors $\vec{T}_z$ and $\vec{B}_z$ ($\forall k \to \tau_{a\,k}^2 \neq 1$). These vectors differ from the vectors $\vec{T}$ and $\vec{B}$, on the basis of which the vector $\vec{F}$ is calculated both in its length and location in the spectral space. Accordingly, both the target signal $Y_{Tz} = \vec{F}^{\mathrm{T}}\vec{T}_z$ ($Y_{Tz} < Y_T$) and the background signal $Y_{Bz} = \vec{F}^{\mathrm{T}}\vec{B}_z$ will be recorded at the output. In this case, the target image contrast at the output of AOES will be less than unity $C < 1$.

Thus, atmospheric attenuation of radiation significantly affects the efficiency of dynamic spectral processing of optical signals in active electro-optical systems (leads to a decrease in the target image contrast at the AOES output). Therefore, it is necessary to develop a method that should provide compensation of the atmospheric attenuation for laser radiation, which can be applied in AEOS with pre-detector dynamic spectral processing.

4. Compensation method for atmospheric attenuation of radiation in active electro-optical systems with dynamic spectral processing

The developed method is aimed at minimizing the effect of multiplicative atmospheric interferences on operation of an active electro-optical system with dynamic spectral processing of optical radiation. When developing the method, we took into account the feature of pre-detector spectral processing in AEOS that involves the possibility of implementing only operations of multiplying and adding optical signals.

To develop the method, we first transform Eq. (2) for the radiation flux at the input of the AEOS radiation receiver by substituting Exp. (4) into it:

$$\Phi_e = Q\sum_{k=1}^{m} f_k \tau_{a\,k}^2 \rho_k \tau_{o1k} \tau_{o2k} \Psi_k \,. \tag{9}$$

Analysis of the obtained Eq. (9) shows that if each component of the sum is divided by the value of the atmospheric transmittance squared $\tau_{a\,k}^2$, then the influence of the propagation medium on the value of the radiation flux Φ_e at the input of the AEOS receiver will be compensated:

$$\Phi_e =$$

$$= Q\sum_{k=1}^{m} f_k \tau_{a\,k}^{-2} \tau_{a\,k}^2 \rho_k \tau_{o1k} \tau_{o2k} \Psi_k = Q\sum_{k=1}^{m} f_k \rho_k \tau_{o1k} \tau_{o2k} \Psi_k \,.$$

Let us introduce the concept of the correction vector $\vec{F}_{corr} = \left[f_{1corr}, \ldots, f_{k\,corr}, \ldots, f_{m\,corr}\right]^{\mathrm{T}}$, which coordinates are defined as the ratio

$$f_{k\,corr} = f_k \big/ \tau_{a\,k}^2 \,. \tag{10}$$

The correction vector $\vec{F}_{corr}$ determines the instrumental function of AEOS, which provides dynamic spectral processing of optical radiation with atmospheric attenuation correction. Since the coordinates $f_{k\,corr}$ of this vector are weight coefficients, their values must satisfy the condition: $\left|f_{k\,corr}\right| \le 1$.

Let us normalize the coordinates $f_{k\,corr}$, as a result we obtain a normalized correction vector $\vec{F}_{corr\,n} = \left[f_{1corr\,n}, \ldots, f_{k\,corr\,n}, \ldots, f_{m\,corr\,n}\right]^{\mathrm{T}}$. The coordinates of this vector are defined as:

$$f_{k\,corr\,n} = K_n f_{k\,\mathrm{corr}} = \frac{f_k \tau_{a\,\max}^2}{\tau_{a\,k}^2 f_{\max}} \,, \tag{11}$$

where $K_n = \max\limits_k \left(\tau_{a\,k}^2 \big/ f_{k\,corr}\right) = \tau_{a\,\max}^2 \big/ f_{\max}$ is the normalizing factor; $\tau_{a\,\max}^2$ and $f_{\max}$ are the square of the atmospheric transmittance and the coordinate of the correction vector, the ratio of which is maximum.

The normalized correction vector $\vec{F}_{corr\,n} = \left[f_{1\,corr\,n}, \ldots, f_{k\,corr\,n}, \ldots, f_{m\,corr\,n}\right]^{\mathrm{T}}$ determines the spectral radiance of the sensing radiation of an active electro-optical system with dynamic spectral processing. The radiation flux $\Phi_{e\,corr}$ at the input of the radiation receiver in AEOS for this case, up to a normalizing factor K_n, will correspond to the radiation flux Φ_e under ideal conditions (there is no attenuation of signals by the atmosphere):

$$\Phi_{e\,corr} = Q \cdot \vec{F}^{\mathrm{T}}_{corr\,n} \vec{X} = \frac{\tau^2_{a\,\max}}{f_{\max}} \Phi_e . \qquad (12)$$

Thus, the method that provides compensation for the atmospheric attenuation of laser radiation in active electro-optical systems with dynamic spectral processing is as follows:

- the vector of the AEOS instrumental function $\vec{F}$ is calculated, which provides an increase in contrast (5) or signal-to-noise ratio for ideal conditions ($\tau^2_a(\lambda) = 1$, it means no attenuation of signals by the atmosphere);
- the correction vector $\vec{F}_{corr}$ is determined, which provides compensation for the influence of atmospheric attenuation for certain operation conditions of the active electro-optical system (Eq. (10));
- the normalized correction vector $\vec{F}_{corr\,n}$ is calculated (Eq. (11));
- dynamic spectral processing of optical radiation is carried out by calculating the scalar product (12) of the input signal vector $\vec{X}$ with the normalized correction vector $\vec{F}_{corr\,n}$.

It is known [10] that the goal of dynamic spectral processing of optical radiation in AEOS is either to increase the target image contrast at its output (semi-automatic detection) or to increase the signal-to-noise ratio (automatic detection). Therefore, we will evaluate the influence of the developed method on these detection indicators. To do this, using Exp. (12), as well as the ratios for the contrast C and signal-to-noise ratio q^2, which are given in [10, 15], we can write

$$C = \frac{\vec{F}^{\mathrm{T}}_{corr\,n}\left(\vec{T}_z - \vec{B}_z\right)}{\vec{F}^{\mathrm{T}}_{corr\,n}\left(\vec{T}_z + \vec{B}_z\right)} = \frac{\vec{F}^{\mathrm{T}}\left(\vec{T} - \vec{B}\right)}{\vec{F}^{\mathrm{T}}\left(\vec{T} + \vec{B}\right)}, \qquad (13)$$

$$q^2 = \frac{\left(E\left\langle \vec{F}^{\mathrm{T}}_{corr\,n}\left(\vec{X}_z - \vec{B}_z\right)\right\rangle\right)^2}{E\left\langle \vec{F}^{\mathrm{T}}_{corr\,n}\left(\vec{X}_z - \vec{B}_z\right)\left(\vec{X}_z - \vec{B}_z\right)^{\mathrm{T}} \vec{F}_{corr\,n}\right\rangle} = \frac{\left(E\left\langle \vec{F}^{\mathrm{T}}\left(\vec{X} - \vec{B}\right)\right\rangle\right)^2}{E\left\langle \vec{F}^{\mathrm{T}}\left(\vec{X} - \vec{B}\right)\left(\vec{X} - \vec{B}\right)^{\mathrm{T}} \vec{F}\right\rangle}. \qquad (14)$$

where $E\langle\bullet\rangle$ is the expected value of random variable, $\vec{T}_z$ and $\vec{B}_z$ are the target and background vectors that characterize the optical signals of the target and background distorted by the atmosphere, which are located at a distance z from AEOS; $\vec{X}_z$ is the input vector that characterizes the optical signal distorted by the atmosphere of an arbitrary element of the observed scene, which is located at a distance z from AEOS; $\vec{T}$, $\vec{B}$, $\vec{X}$ are the corresponding vectors obtained under ideal conditions (there is no atmospheric attenuation); $\vec{F}$ is the AEOS instrumental function calculated for ideal conditions (*i.e.*, no atmospheric attenuation).

An analysis of the obtained Exps. (13) and (14) shows that the developed method enables to compensate the effect of atmospheric interference on operation of AEOS with dynamic spectral processing and to obtain the same values for the target image contrast and the signal-to-noise ratio at its output under conditions of no atmospheric attenuation.

Thus, the developed method enables to compensate atmospheric attenuation in AEOS with dynamic spectral processing, which is based on the fact that the spectral intensity of the sensing radiation is formed not only on the basis of *a priori* data on the spectral characteristics of the reflecting surfaces of the target and background, but also takes into account the spectral transmittance of the propagation medium optical signal.

5. Conclusions

In active electro-optical detection systems with dynamic pre-detector spectral processing of an optical signal, the spectral composition of sensing radiation is formed by using multispectral laser signals based on *a priori* data about the spectral characteristics of the target and background. The sensing signal formed in this way enables to ensure maximum suppression of the background signal at the output of active electro-optical system, with minimal attenuation of the signal intensity to the object.

However, when propagating, the sensing signal is exposed to atmospheric interference, which leads to a change in its spectral density and a decrease in the efficiency of pre-detector processing in AEOS. Developed in this paper has been the method enabling the possibility to compensate atmospheric attenuation of laser radiation by implementing dynamic spectral processing in active electro-optical systems. The method is based on the fact that the spectral intensity of the sensing radiation is formed not only on the basis of *a priori* data on the spectral reflectances of the target and background, but also takes into consideration the *a priori* known spectral transmittance of the optical radiation propagating in medium.

References

1. McManamon P.F. Review of ladar: a historic, yet emerging, sensor technology with rich phenomenology. *Opt. Eng.* 2012. **51**, No 6. P. 060901-1–13. https://doi.org/10.1117/1.OE.51.6.060901.
2. 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.
3. Johnson B., Joseph R., Nischan M. *et al.* A compact, active hyperspectral imaging system for the detection of concealed targets. SPIE Conf. on Detection and Remediation Technologies for Mines and Mine-like Targets IV, April 1999. *Proc. SPIE.* **3710**. P. 144–153. https://doi.org/10.1117/12.357002.
4. Manninen A., Kääriäinen T., Parviainen T. *et al.* Long distance active hyperspectral sensing using high-power near-infrared supercontinuum light source. *Opt. Exp*. 2014. **22**, Issue 6. P. 7172–7177. https://doi.org/10.1364/OE.22.007172.
5. Liu Y., Tao Z., Zhang J. *et al.* Deep-learning-based active hyperspectral imaging classification method illuminated by the supercontinuum laser. *Appl. Sci.* 2020. **10**, Issue 9. P. 3088(1–17). https://doi.org/10.3390/app10093088.
6. Guo Z., Liu Y., Zheng X., Yin K. Active hyperspectral imaging with a supercontinuum laser source in the dark. *Chinese Phys. B.* 2019. **28**, No 3. P. 034206. https://doi.org/10.1088/1674-1056/28/3/034206.
7. Hempler N., Nicholls J., Malcolm G. Active hyperspectral sensing and imaging for remote spectroscopy applications. *Laser Focus World*. 2013. **49**, No 11. http://www.laserfocusworld.com/articles/print/volume-49/issue-11/features/spectral-imaging-active-hyperspectral-sensing-and-imaging-for-remote-spectroscopy-applications.html.
8. El Fakir C., Poffo L., Billiot B. *et al.* Active hyperspectral mid-infrared imaging based on widely tunable QCL laser. In: *2019 21st Int. Conf. on Transparent Optical Networks (ICTON)*, 2019 Jule 9. IEEE. P. 1–4. https://doi.org/10.1109/ICTON.2019.8840448.
9. El Fakir C., Hjeij M., Le Page R. *et al.* Active hyperspectral mid-infrared imaging based on a widely tunable quantum cascade laser for early detection of plant water stress. *Opt. Eng. SPIE*. 2021. **60**, Issue 2. P. 023106-1–023106-15. https://doi.org/10.1117/1.OE.60.2.023106.
10. Kupchenko L.F., Karlov V.D., Rybiak A.S. *et al.* Active electro-optical system of targets detection with dynamic spectral processing of optical radiation. *SPQEO*. 2021. **24**, No 2. P. 218–226. https://doi.org/10.15407/spqeo24.01.218.
11. Kupchenko L.F., Goorin O.A., Karlov V.D. *et al.* Active electro-optical system with dynamic spectral processing of optical radiation. In: *2019 IEEE 8th Int. Conf. on Advanced Optoelectronics and Lasers (CAOL).* Proc. Sozopol, Bulgaria, 6–8 September 2019. IEEE. P. 489–492. https://doi.org/10.1109/CAOL46282.2019.9019458.
12. Griffin M.K., Burke H.K. Compensation of hyperspectral data for atmospheric effects. *Lincoln Laboratory Journal*. 2003. **14**, No 1. P. 29–54.
13. Christnacher F., Schertzer S., Metzger N. *et al.* Influence of gating and of the gate shape on the penetration capacity of range-gated active imaging in scattering environments. *Opt. Exp*. 2015. **23**, Issue 26. P. 32897–32908. https://doi.org/10.1364/OE.23.032897.
14. Schott J.R. *Remote Sensing the Image Chain Approach*, 2nd ed. Oxford University Press, 2007.
15. Holst G.C. *Electro-Optical Imaging System Performance*, 6th ed. SPIE Press Book, 2017.

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Метод компенсації атмосферного ослаблення лазерного випромінювання в активних оптико-електронних системах з динамічною спектральною обробкою оптичних сигналів

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Анотація. Викладено метод компенсації атмосферного ослаблення лазерного випромінювання, який може бути реалізованим в активних оптико-електронних системах з переддетекторною динамічною спектральною обробкою оптичних сигналів. У таких оптико-електронних системах спектральна густина потоку зондуючого випромінювання формується з використанням багатоспектральних лазерних сигналів на основі апріорних відомостей про спектральні коефіцієнти відбиття об'єкта спостереження та фону. Сформований таким чином зондуючий сигнал забезпечує максимальне заглушення на виході системи сигналу фону з мінімальним ослабленням сигналу, який належить об'єкту. Проведено аналіз впливу атмосферного ослаблення випромінювання на роботу активної оптико-електронної системи з динамічною спектральною обробкою. Показано, що ослаблення лазерного випромінювання в атмосфері суттєво впливає на ефективність динамічної спектральної обробки оптичних сигналів (призводить до зниження контрасту зображення об'єкта). Розроблено метод компенсації атмосферного ослаблення лазерного випромінювання в активних оптико-електронних системах з динамічною спектральною обробкою, який полягає в тому, що спектральна густина інтенсивності зондуючого випромінювання формується не тільки на основі апріорних даних про спектральні характеристики відбивних поверхонь об'єкта та фону, але і з урахуванням спектрального коефіцієнта пропускання середовища поширення оптичного сигналу.

Ключові слова: активна оптико-електронна система, динамічна спектральна обробка, атмосферне ослаблення випромінювання, лазери.