STABILIZATION OF IMAGE QUALITY IN ATMOSPHERIC ADAPTIVE OPTO–ELECTRONIC OBSERVATIONAL SYSTEMS

S.A. Pokotilo

Academy of the Armed Forces of Ukraine, Kiev
Received February 7, 1994

The distorting effect of atmospheric optical channel (AOC) on the quality of image formed with an opto–electronic observational system (OEOS) as well as some controllable engineering parameters are considered in the paper. The data on AOC and corresponding adjustable OEOS parameters as well as patterns of optical radiation interaction with atmospheric aerosol are generalized and systematized. Adaptive OEOS and iconic process are defined. Expediency is shown of joint adaptive control over power (spectral) and spatial–frequency characteristics of OEOS. A method of changing the spectral range of OEOS operation with the help of an interference wedge–shaped filter and an algorithm for identification adaptation of OEOS adjusted to standard surface fields are proposed.

A major problem in developing adaptive opto–electronic observational systems (OEOS's) is stabilization of image quality in the presence of distorting effect of the turbulence and turbidity of atmospheric optical channel (AOC) located between a sounded surface (SS) and an observational system.[1]

Let us consider the effect of distorting factors characterizing AOC on the basic parameters of OEOS using an infrared system (IRS) as an example. The energy equation for the IRS has the form[2]

$$\gamma_x \gamma_y \Delta T_{\rm thr} = \frac{k_1}{T^3} \frac{1}{D^*(\lambda)\,\tau_0} \frac{\pi (V_n h^{-1})^{0.5}}{D_0\, \ddot{O}\, (\Delta \ln\lambda)_{\rm eff}} M^{0.5} , \qquad (1)$$

where γ_x and γ_y are the values of instantaneous field–of–view angles in the directions of scanning (X) and instrumentation vehicle flight (Y), $\Delta T_{\rm thr}$ is the noise–equivalent temperature difference[3] (NETD), T is the SS thermodynamic temperature, D_0 and $\ddot{O}$ are the diameters of the input aperture of the objective and its relative aperture, $D^*(\lambda)$ is the specific detecting power of the optical radiation receiver (ORR), τ_0 is the transmittance of the objective, $(\Delta\ln\lambda)_{\rm eff}$ is natural logarithm of the effective bandwidth of the system,[2] V_n and h are the absolute speed and the absolute flight altitude of the vehicle, M is the number of the ORR sensitive elements, and k_1 = const.

The minimum resolvable temperature difference[3] (MRTD) in a one–dimensional form is

$$\Delta T_{\rm res}(\nu) = \frac{k_2 \Delta T_{\rm thr} S_{\rm s}(\nu)}{\prod\limits_{i=1}^{n} |T_{{\rm ext}_i}(j\nu)|^2 \prod\limits_{j=1}^{m} |T_{{\rm s}_j}(j\nu)|^2 S_{\rm n}(\nu)} , \qquad (2)$$

where k_2 = const, $S_{\rm s}(\nu)$ and $S_{\rm n}(\nu)$ are the spectral power densities of signal and noise, $T_{{\rm ext}i}(j\nu)$ is the optical transfer function (OTF) of the ith section characterizing the external factors of observation, $T_{{\rm s}j}(j\nu)$ is the OTF of the jth section of IRS, and ν is the spatial frequency in the direction of scanning.

In the left–hand side of Eq. (1) there are the parameters that determine the angular resolution and temperature sensitivity of the system, and in the right–hand side of it there are the atmospheric parameters, e.g., spectral transmittance $\tau_{\rm a}(\lambda)$:

$$(\Delta\ln\lambda)_{\rm eff} = f(M_{\rm e}(\lambda), \tau_{\rm a}(\lambda)) , \qquad (3)$$

$$\tau_{\rm a}(\lambda) = f(T(h), w, p(h)) , \qquad (4)$$

where $M_e(\lambda)$ is the spectral power density of the SS emissivity, $T(h)$ and $p(h)$ are the vertical profiles of air temperature and pressure, and w is the amount of precipitated water.

In formula (2) the randomly variable parameters of the environment (AOC) are concentrated in

$$T_{\rm ext}(j\nu) = \prod_{i=1}^{n} T_{{\rm ext}i}(j\nu) = T_{\rm tt,a}(j\nu)\, T_{\rm td,a}(j\nu) \prod_{i=3}^{n-2} T_{{\rm ext}i}(j\nu) , \qquad (5)$$

where $T_{\rm tt,a}(j\nu)$ and $T_{\rm td,a}(j\nu)$ are the OTF's of the turbulent and turbid atmosphere. They are functions of the following parameters:

$$T_{\rm tt,a}(j\nu) = f(C_n^2(h), \Delta\lambda, h, \beta) , \qquad (6)$$

$$T_{\rm td,a}(j\nu) = f(a_{\rm s}(h), \Delta\lambda, h, f') , \qquad (7)$$

where $C_n^2(h)$ and $a_{\rm s}(h)$ are the vertical profiles of the structure constant of the refractive index and size of scattering particles, $\Delta\lambda$ is the wavelength range of IRS operation, β is the viewing angle, and f' is the focal length of the OEOS objective.

In Eqs. (1) and (2) there are also the parameters and characteristics that can be used for compensating for the effect of the AOC parameters on the quality of formed image: in Eq. (1) these are $D^*(\lambda)$, D_0, $\tau_0(\lambda)$, $\ddot{O}$, and M, while in Eq. (2) these are $\prod\limits_{j=1}^{m} T_{{\rm s}j}(j\nu)$ and $\Delta T_{\rm thr}$ as well as the flight altitude h and the noise bandwidth $\Delta f_{\rm n}$ entering into the expression for $\Delta T_{\rm thr}$. Here $\Delta T_{\rm thr} = f((\Delta f_{\rm n})^{0.5})$ (see Ref. 3).

Expressions (1)–(7) can be used to evaluate substantial effect of the AOC parameters on the OEOS basic parameters and to illustrate the need for adaptive control over the parameters and characteristics of OEOS to construct an image of required quality. The data on variations of the AOC parameters as well as the characteristics and the corresponding adjustable parameters of OEOS are summarized in Table I (see Refs. 1 and 4–10).

In what follows an iconic process (an image formation process) is understood as a controllable random process characterized by a set of pairs of functions of spatio–spectro–temporal (SST) coordinates representing its input and output and describing abstract SST processes. In general, the iconic process (IP) incorporates a sounded surface, AOC, and movement parameters of the vehicle and OEOS. An adaptive OEOS is a controllable iconic system that forms an SS image and yields the current information about the IP state, i.e., identifies it, compares the current performance of OEOS with the required (or optimum) one, and based on this information, arrives at a decision to adapt OEOS so that its performance approaches the required one. This system realizes the needed change in its parameters and structure, i.e., self–modification.

Table II systematizes patterns of optical radiation interaction with an atmospheric aerosol. A real scattering atmosphere is inhomogeneous and uneven medium.

It is possible to identify the following most typical patterns of photon interaction with aerosol particles (see Table II): 1) polychromatic radiation interacts with quasimonodisperse medium (item 2.1), 2) polychromatic radiation interacts with polydisperse medium (item 3.1), and 3) monochromatic radiation interacts with polydisperse medium consisting of aerosols of size $a_s \geq \lambda$ and $a_s \leq \lambda$ (item 3.2).

TABLE I.

Parameter characterizing the variable conditions of observation	Adjustable parameter of OEOS (method of compensation for the effect)	Aim of adaptation
Spectral transmittance of the atmosphere	a) spectral range of operation; b) automated choice of optimum spectral regions; c) transition to the other spectral range	Maximization of input signal
Turbulence of the atmosphere Turbidity of the atmosphere	a) Identification of the parameters and structure of IP and optimal control over them; b) filtration of video–signal in real time	Constancy of resolution and signal–to–noise ratio

TABLE II.

Parameter 1 Type of atmospheric aerosol		Parameter 2 Type of optical radiation		
Characteristics of a medium	Serial number of case	Polychromatic	Monochromatic	
		1	2	3
Monodisperse	1	1.1	1.2	1.3
Quasimonodisperse	2	2.1	2.2	2.3
Polydisperse	3	3.1	3.2	3.3

In the first case the radiation is scattered in a given wavelength range $\Delta\lambda_{sc} = \lambda_{2sc} - \lambda_{1sc}$ from the entire range of radiation $\Delta\lambda = \lambda_2 - \lambda_1$ ($\Delta\lambda_{sc} < \Delta\lambda$) incident on a boundary of a scattering medium. In the second case the radiation is scattered in the entire wavelength range. If in this case the values of concentration of particles of different size are equal, the radiation will be obviously attenuated neutrally. If the values of concentration of aerosols are different, the radiation will be scattered selectively, and the action of AOC will be similar to that of a selective optical filter. This is the most complicated pattern of interaction of optical radiation with atmospheric aerosol from the viewpoint of adaptation for aerosol (AA) of OEOS since continuous adaptive selection of optimum spectral ranges for system operation must be realized. To this end, one must identify spectral maxima of radiation scattering and corresponding inoperative wavelength ranges. In the last case it is necessary to choose a spectral range of AA of OEOS operation in the ranges beyond $\lambda < a_s$ and $\lambda > a_s$, respectively.

The foregoing calls for a joint adaptive control over energy and spatio–frequency characteristics (SFC's) of OEOS.

An efficient method of control over energy sensitivity of OEOS is the use of wedge–shaped interference filters (WSIF's). The narrow sections in the optical radiation spectrum are selected by way of linear movement of these filters in the direction parallel to the focal plane of an objective depending on spectral transmittance of AOC and related input signal power. This method of transition from one spectral range to the other $[(\Delta\lambda)_i \Leftrightarrow (\Delta\lambda)_j]$ is promising for creating "polychromatic" arrays of ORR, each element of which is sensitive to a narrow spectral section of received radiation. Spectral selection of the received polychromatic radiation with the help of WSIF allows one not only to choose the required spectral range, but also to "color a video signal" based on its amplitude, spatio–frequency, and spectral characteristics. This makes interpretation of obtained images easier.[11] A theoretical prerequisite for developing WSIF is the dependence of the wavelength of radiation incident on a filter on a refraction angle[12]

$$\lambda = \frac{4\pi l\ (n^2 - \sin^2\sigma_n)^{0.5}}{2\varphi - \varphi_0}, \tag{8}$$

where l and n are the thickness and the refractive index of a substrate, 2φ is the phase difference between successively interfering beams, and φ_0 is the phase shift caused by reflection from a semitransparent layer.

It follows from a plot of $\lambda(\sigma_n)$ shown in Fig. 1 that the maximum derivative of this function corresponding to the straight segment *AB* of the curve is $d\lambda/d\sigma_n = 0.08$ μm·deg^{-1}.

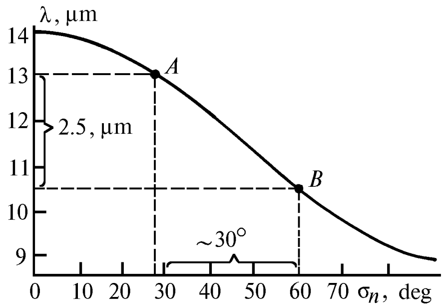

FIG. 1. Radiation wavelength at the exit from a wedge–shaped interference filter as a function of the refraction angle σ_n (n = 3, l = 1 mm).

Thus at $\sigma_n = 10°$ it is possible to obtain the bandwidth $\Delta\lambda = 0.08$ μm.

The spatio–frequency characteristics of iconic process consist of modulation transmission functions (MTF's) of turbid $T_{\rm td}$ and turbulent $T_{\rm tt}$ atmosphere and OEOS $T_{\rm s}$:

$$T^{\rm sc}_{\rm i.p}(\nu) = T_{\rm td,a}(\nu)\, T_{\rm tt,a}(\nu)\, T_{\rm s}(\nu) \ . \qquad (9)$$

Since MTF of turbid atmosphere $T_{\rm td}(\nu, a_{\rm s}, \lambda)$ is a function of scattering particle size and radiation wavelength, it also can be corrected through a controllable transition $(\Delta\lambda)_i \overset{U}{\Leftrightarrow} (\Delta\lambda)_j$ based on the results of determining the current values of the aerosol scattering coefficient.[13] From this it follows that a joint adaptive control over "energetics" and SFC of OEOS can be fulfilled with the help of adjustable optical filters.

Compensation for the effect of turbulent atmosphere MTF $T_{\rm tt,a}(\nu, \lambda, C_n^2)$ on SFC of OEOS assumes measurement of the turbulence parameter C_n^2 as well as the use (for coherent OEOS) of phase conjugation principle that, in the first approximation, is independent of the received radiation wavelength. This makes it possible to compensate for perturbations from nonmonochromatic sources[14] or to apply the principle of aperture sounding.[15]

The joint adaptive control of the total OTF of iconic process (9) attendant to changes in the AOC characteristics can be efficiently realized based on identification of OTF given by Eq. (9) during observation of standard surface fields in the region of observation. The problem of identification of iconic process consists in determining its optical transfer function from an analysis of standard input signal described by the random function $I(x, y, \Delta\lambda, t)$, where x and y are the spatial coordinates of a sounded surface, $\Delta\lambda$ is the wavelength range of operation, and t is time.

When sounding a reference section of the surface with known spectral power density $S_{\rm ref}(\nu, \mu(\Delta\lambda)^{-1}, t^{-1})$, whose digital model obtained under ideal conditions

$$T_{\rm td,a}(\nu)\, T_{\rm tt,a}(\nu) = 1 \ , \qquad (10)$$

is in the computer memory, its current value is

$$S_{\rm c}(\nu,\mu,(\Delta\lambda)^{-1},t^{-1}) = |T^{\rm sc}_{\rm i.p}(\nu,\mu,(\Delta\lambda)^{-1},t^{-1})|^2\, S_{\rm ref}(\nu,\mu,(\Delta\lambda)^{-1}. \qquad (11)$$

Then

$$T^{\rm sc}_{\rm i.p}(\nu, \mu, (\Delta\lambda)^{-1}, t^{-1}) = \left|\frac{S_{\rm c}(\nu, \mu, (\Delta\lambda)^{-1}, t^{-1})}{S_{\rm ref}(\nu, \mu, (\Delta\lambda)^{-1}, t^{-1})}\right|^{0.5} . \qquad (12)$$

Formula (12) describes a real model of iconic process, and its reference model $T^{\rm ref}_{\rm i.p}$ can be expressed via OTF of OEOS (see condition (10)). Then comparing Eqs. (9) and (12) we obtain a generalized OTF of an atmospheric optical channel

$$T_{\rm ao.c}(\nu, \mu, (\Delta\lambda)^{-1}, t^{-1}) = \frac{T^{\rm sc}_{\rm i.p}(\nu, \mu, (\Delta\lambda)^{-1}, t^{-1})}{T^{\rm ref}_{\rm i.p}(\nu, \mu, (\Delta\lambda)^{-1}, t^{-1})} , \qquad (13)$$

where

$$T^{\rm ref}_{\rm i.p}(\nu, \mu, (\Delta\lambda)^{-1}, t^{-1}) = T_{\rm s}(\nu, \mu, (\Delta\lambda)^{-1}, t^{-1}) \ .$$

A mathematical model of an adaptive OEOS (Fig. 2) implies an adaptive unit which forms a control signal $u = f(a_1, \ldots, a_n)$, where $a_1, \ldots, a_n$ are the parameters of iconic process and criterion of its efficiency, based on an analysis of the result

$$u' = \left[S_{\rm c}\,(S'_{\rm ref})^{-1}\right]^{0.5} , \qquad (14)$$

where $S'_{\rm ref} = S_{\rm ref}$ when $T_{\rm s}(\nu) = 1$.

The opto–electronic observational systems are linear in radiation intensity (amplitude squared).[2,3] Therefore, their OTF's are real functions of iconic process parameters.

This is a decisive premise for physical implementation of algorithm (11)–(14). For a structure of adaptive OEOS depicted in Fig. 2 this algorithm is written in the form

$$S'_{\rm ref}(\nu) = T^2_{\rm s}(\nu)\, S_{\rm ref}(\nu) \ , \qquad (15)$$

$$S_{\rm c}(\nu) = S'_{\rm ref}(\nu) = T^2_{\rm ao.c}(\nu)\, T^2_{\rm s}(\nu)\, S_{\rm ref}(\nu) \ , \qquad (16)$$

$$u' = T^2_{\rm ao.c}(\nu)\, T^2_{\rm s}(\nu)\, S_{\rm ref}(\nu)\, [T^2_{\rm s}(\nu)\, S_{\rm ref}(\nu)]^{-1}; \ \ u' = T^2_{\rm ao.c} \ . \qquad (17)$$

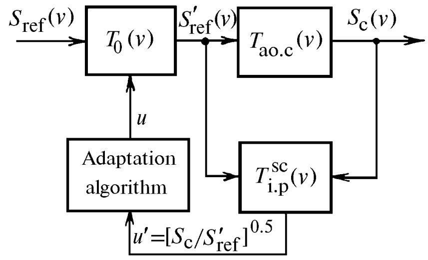

FIG. 2. Block diagram of adaptive OEOS with identification of OTF of AOC by reference surface fields.

It follows from Refs. 1 and 16 that

$$T_{\rm ao.c} = T_{\rm td,a}\, T_{\rm tt,a} = f(\Delta\lambda, f', h, \beta) \ , \qquad (18)$$

where f' is the focal length of the OEOS objective, and h and β are the altitude above the sounding surface and the viewing angle of OEOS.

The parameters f', h, and β govern the image scale $m = h \sec\beta\, (f')^{-1}$. It follows from Eq. (18) that control signal is a function of iconic process parameters

$$u = f(m, \Delta\lambda) \ , \qquad (19)$$

and by changing these parameters the OEOS can be adapted so that the required value P_r of the efficiency criterion $P \geq P_r$ can be attained. The aim of adaptation in this case has the form

$$\lim_{\substack{m \to m_r \\ \Delta\lambda \to \Delta\lambda_r}} \left[P_r(m_r, \Delta\lambda_r) - P(m, \Delta\lambda) \right] = 0, \quad (20)$$

where m_r and $\Delta\lambda_r$ are the required values of m and $\Delta\lambda$.

Probability of correct recognition of the obtained images is often used as the efficiency criterion P in the problems of remote sounding.[3]

Thus to stabilize the image quality in atmospheric adaptive OEOS's, it is necessary, based on measurement results of AOC characteristics, to control the following engineering parameters of OEOS: working wavelength range, relative aperture of the objective, and scale of the imaging. The control over OEOS temperature sensitivity enables one to stabilize a level of video signal at low spatial frequencies. In connection with the foregoing, the search for methods and means of adjustment of the aforementioned engineering parameters of OEOS in real time is an urgent problem.

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