SOME PROBLEMS IN CREATING THE ATMOSPHERIC ADAPTIVE OPTO–ELECTRONIC VISION SYSTEMS

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Some problems in creating the atmospheric adaptive opto–electronic vision systems for acquisition of current information about the atmosphere and forecasting its parameters, among them the modulation transfer function and the spectral transmission function are considered.

Creation of adaptive analogs of the opto–electronic vision systems (OEVS's) for the Earth's surface observation (ESO), capable of varying their parameters and structure in the course of acquisition of information about change of parameters of the atmospheric–optical channel (AOC) of the surface being sensed and of a platform in order to achieve the optimum in the preset characteristics,[1–3] is a fundamental perspective of the future development of the OEVS's.

The necessity of operative and accurate measurements of the optical transfer function (OTF) and spectral transmission function (STF) of the atmosphere along vertical and slant paths[1–6] leads to problems of an adaptive control by a stochastic process of the Earth's surface observation through the atmosphere.

Spatio–temporal distributions of such AOC parameters as the size of scattering particles $a_s(x, y, z, t)$, the structural constant of the refractive index $C_n^2(x, y, z, t, \lambda)$, the air temperature $T(x, y, z, t)$, water vapor column density $w(x, y, z, t)$, the air density $\rho(x, y, z, t)$, and the atmospheric pressure $p(x, y, z, t)$, which change in space and time randomly, essentially affect these characteristics.

The necessity of using the OTF of the turbulent and turbid atmosphere which are integral–averaged over the ranges of changes of the AOC parameters and over the range of working spectrum of the OEVS's becomes obvious in order to make possible elaboration of algorithms for functioning of an adaptive OEVS with the reference and forecasting models. Because the vision systems are noncoherent OEVS's below we shall deal with modules of polychromatic functions of the modulation transfer in the turbulent and turbid atmosphere.

In general the averaged modulation transfer function (MTF) of the atmospheric–optical channel can be represented in the form

$$T(\nu)=\left(\Delta\lambda\prod_{i=1}^{n}\Delta p_i\right)^{-1}\int\limits_{p_{11}}^{p_{12}}\dots\int\limits_{p_{n1}}^{p_{n2}}T(\nu,\lambda,p_1,\dots,p_n)\mathrm{d}\lambda\mathrm{d}p_1\dots\mathrm{d}p_n\,, \qquad (1)$$

where $\Delta\lambda = \lambda_2 - \lambda_1$, λ_1 and λ_2 are the spectrum boundaries of the OEVS, $p_{11} \dots p_{12}, \dots, p_{n1}, \dots p_{n2}$ are the boundaries of variations of the parameters $p_1, \dots, p_n$.

In this paper the analytical relations for the statistically averaged over the atmospheric parameters MTF of the turbulent and turbid atmosphere are obtained based on the results of Refs. 2 and 3. Averaged over $C_n^2(\lambda)$ values the polychromatic MTF of the turbulent atmosphere under conditions of weak spectral dependence of this function in the working spectral range of the OEVS has, after integration, the form

$$m\{T_{\mathrm{t\,a}}(\nu,\Delta\lambda,\Delta C_n^2)\}=(\Delta C_n^2)^{-1}\times$$

$$\times\int\limits_{C_{n1}^2}^{C_{n2}^2}\left[1+\frac{3a}{2\Delta\lambda}(\lambda_2^{2/3}-\lambda_1^{2/3})+\frac{3\,a^2}{2\Delta\lambda}(\lambda_2^{1/3}-\lambda_1^{1/3})\right]\mathrm{d}(C_n^2)\,,$$

$$m\{T_{\mathrm{t\,a}}(\nu,\Delta\lambda,\Delta C_n^2)\}=1-a_1(C_{n1}^2+C_{n2}^2)+a_2\frac{C_{n2}^6-C_{n1}^6}{\Delta C_{n2}^2}\,, \qquad (2)$$

where

$a_1 = 8.58(H\sec\beta)\,\nu^{5/3}(\lambda_2^{2/3}-\lambda_1^{2/3})$,

$a_2 = 32.72(H\sec\beta)^2\times\lambda^{10/3}(\lambda_2^{1/3}-\lambda_1^{1/3})$,

H is the height of observations, β is the angle of observations counted from the vertical direction, ν is the unified spatial frequency, and m is the symbol of mathematical expectation.

The turbulent layer of the AOC can be represented by successively linked linear systems with the MTF $\overline{T}_i(\nu)$ which differ by the values of the parameters H and C_n^2. The general MTF of such a vertical turbulent path of the atmosphere is equal to

$$\overline{T}_i(\nu)=\exp\left(-k(\nu)\,C_{ni}^2\,\Delta H_i\right),$$

$$\overline{T}_i(\nu)=\exp\left(-k(\nu)\,C_{n1}^2\,\Delta H_1\right)\exp\left(-k(\nu)\,C_{n2}^2\,\Delta H_2\right)\dots\times$$

$$\times\exp\left(-k(\nu)\,C_{nm}^2\,\Delta H_m\right)=\exp\left(-k(\nu)\sum_{i=1}^{m}C_{ni}^2\,\Delta H_i\right),$$

where $k(\nu)$ is a certain function of spatial frequency, C_{ni}^2 is the structural function of the refractive index of the ith layer, and ΔH_i is the thickness of the ith layer.

The MTF of the turbid atmosphere depends on the scattering parameter[10] $\rho_s = 2\pi a_s\lambda^{-1}$, where a_s is the size of a scattering particle. Thus the initial monochromatic MTF for the turbid atmosphere[9] should be successively averaged over λ and a_s. Averaging over λ gives the relation

$$m\{T_{\mathrm{tb\,a}}(\nu,\Delta\lambda)\}=(\Delta\lambda)^{-1}\int\limits_{\lambda_1}^{\lambda_2}\left[1+\left(\frac{f'\nu}{2\pi}\right)^2\frac{\lambda^2}{a_s^2}\right]^{-1}\mathrm{d}\lambda\,,$$

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$$m\{T_{\text{tb a}}(\nu,\ \Delta\lambda)\} =$$

$$= (\Delta\lambda)^{-1}\left\{\left[\left(\frac{2\pi a_s}{f'\nu}\right)^2 + \lambda_2^2\right]^{0.5} - \left[\left(\frac{2\pi a_s}{f'\nu}\right)^2 + \lambda_1^2\right]^{0.5}\right\}, \quad (3)$$

where f' is the focal length of the receiving objective of an OEVS.

As a result of averaging Eq. (3) over a_s, we obtain

$$m\{T_{\text{tb a}}(\nu,\ \Delta\lambda,\ \Delta a_s)\} = (\Delta\lambda\Delta a_s)^{-1} \times$$

$$\times\left\{\int\limits_{a_{s1}}^{a_{s2}}\left[\left(\frac{2\pi a_s}{f'\nu}\right)^2 + \lambda_2^2\right]\mathrm{d}a_s - \int\limits_{a_{s1}}^{a_{s2}}\left[\left(\frac{2\pi a_s}{f'\nu}\right)^2 + \lambda_1^2\right]\mathrm{d}a_s\right\},$$

$$m\{T_{\text{tb a}}(\nu,\ \Delta\lambda,\ \Delta a_s)\} = (\Delta\lambda\Delta a_s)^{-1}\left\{\frac{1}{2}\left[a_s\left[a_s^2 + \left(\frac{\lambda_2 f'}{2\pi}\right)^2\nu^2\right]^{0.5} + \right.\right.$$

$$\left.\left. + \left(\frac{\lambda_2 f'}{2\pi}\right)^2\nu^2 \ln\left|a_s^2 + \left[a_s^2 + \left(\frac{\lambda_2 f'}{2\pi}\right)^2\nu^2\right]^{0.5}\right|\right]\right|_{a_{s1}}^{a_{s2}} -$$

$$-\frac{1}{2}\left[a_s\left[a_s^2 + \left(\frac{\lambda_1 f'}{2\pi}\right)^2\nu^2\right]^{0.5} + \left(\frac{\lambda_1 f'}{2\pi}\right)^2\nu^2 \times\right.$$

$$\left.\left.\times\ \ln\left|a_s^2 + \left[a_s^2 + \left(\frac{\lambda_1 f'}{2\pi}\right)^2\nu^2\right]^{0.5}\right|\right]\right|_{a_{s1}}^{a_{s2}}\right\}. \quad (4)$$

A turbulent boundary layer, which distorts spatial spectrum of the imaged surface, can appear during the motion of the OEVS platform. The monochromatic MTF of the turbulence caused by the appearance of a boundary layer is described by the relation[11]

$$T_{\text{b l}}(\nu,\ \mu) = \exp\left[-\frac{4\pi^2\Delta^2\nu^2}{(\nu_0^2 + \nu^2)\,\lambda^2}\right], \quad (5)$$

where $\nu_0 = \delta(10\lambda f')^{-1}$, δ is the depth of the boundary layer, Δ is the average standard deviation of the wave front, m, and for $M < 2$ the approximate formula[11]

$$\Delta = 3{\cdot}10^{-6}\delta\rho M^2\,(1 + 0.1\,M^2)^{-1}$$

is valid, where ρ is the relative air density and M is the Mach number.

We reduce formula (5) to a more convenient form

$$T_{\text{b l}}(\nu,\ \mu) = \exp\,(-\,a_b\lambda_t^2)\,, \quad (6)$$

where $a_b = 4\pi^2\Delta^2\nu^2(\nu + \nu^2)^{-1}$ and $\lambda_t = \lambda^{-1}$, and find the relation for the MTF

$$\overline{T}_{\text{b l}}(\nu) = \frac{1}{\Delta\lambda}\int\limits_{\lambda_1}^{\lambda_2}\exp\,(-\,a_b\lambda_t^2)\ \mathrm{d}\lambda\,.$$

Let us express $\mathrm{d}\lambda$ through λ_t

$$\mathrm{d}\lambda = -\,\lambda_t^{-2}\ \mathrm{d}\lambda_t\,.$$

Then we reduce Eq. (6) to the relation

$$\overline{T}_{\text{b l}}(\nu) = \frac{1}{\Delta\lambda}\int\limits_{\lambda_1}^{\lambda_2}\frac{\exp\,(-\,a_b\lambda_t^2)}{\lambda_t^2}\ \mathrm{d}\lambda_t\,. \quad (7)$$

Let us make use of the tabular integral of the form[12]

$$\int\frac{\exp\,(-ax^2)}{x^p}\mathrm{d}x = -\frac{\exp\,(-ax)^2}{(p-1)\,x^{p-1}} - \frac{2a}{p-1}\int\frac{\exp\,(-ax^2)}{x^{p-2}}\mathrm{d}x. \quad (8)$$

After integration we obtain

$$\overline{T}_{\text{b l}}(\nu) =$$

$$= -\frac{1}{\Delta\lambda}\left[-\frac{\exp\,(-\,a_b\lambda_t^2)}{(2-1)\lambda_t^{(2-1)}}\right|_{\lambda_1}^{\lambda_2} - \left.\frac{2a_b}{2-1}\int\limits_{\lambda_1}^{\lambda_2}\frac{\exp\,(-\,a_p\lambda_t^2)}{\lambda_t^{(2-2)}}\,\mathrm{d}\lambda_t\right] =$$

$$= \frac{1}{\Delta\lambda}\left[\frac{\exp\,(-\,a_b\lambda_t^2)}{\lambda_t}\right|_{\lambda_1}^{\lambda_2} + \left.2a_b\int\limits_{\lambda_1}^{\lambda_2}\exp\,(-\,a_b\lambda_t^2)\ \mathrm{d}\lambda_t\right]. \quad (9)$$

To calculate the integral entering into Eq. (9) let us make use of the tabular integral[12]

$$\int\limits_0^x \exp\,(-\,a_1^2\,x^2)\ \mathrm{d}\,x = \frac{\pi^{0.5}}{2a_1}\ \mathrm{erf}(a_1\,x)\,. \quad (10)$$

We find the sought integral as the difference of integrals of the form (10)

$$\int\limits_{\lambda_1}^{\lambda_2} = \int\limits_0^{\lambda_2} - \int\limits_0^{\lambda_1},\ \text{i.e.,}$$

$$\int\limits_{\lambda_1}^{\lambda_2}\exp\,(-\,a_1^2\lambda_t^2)\ \mathrm{d}\lambda_t = \int\limits_0^{\lambda_2}\exp\,(-\,a_1^2\lambda_t^2)\ \mathrm{d}\lambda_t - \int\limits_0^{\lambda_1}\exp\,(-\,a_1^2\lambda_t^2)\ \mathrm{d}\lambda_t =$$

$$= \frac{\pi^{0.5}}{2a_1}\mathrm{erf}(a_1\lambda_2) - \frac{\pi^{0.5}}{2a_1}\mathrm{erf}(a_1\lambda_1) = \frac{\pi^{0.5}}{2a_1}\,[\mathrm{erf}(a_b^{0.5}\lambda_2) - \mathrm{erf}(a_b^{0.5}\lambda_1)]. \quad (11)$$

In relations (10) and (11) $a_1 = a_b^{0.5}$, $\mathrm{erf}(a_b^{0.5}\lambda_2)$, and $\mathrm{erf}(a_b^{0.5}\lambda_1)$ are the probability integrals over corresponding arguments.

After substitution of Eq. (11) into Eq. (9) we obtain the relation for the polychromatic MTF of the turbulent boundary layer

$$\overline{T}_{\text{b l}}(\nu) = \frac{1}{\Delta\lambda}\left\{\ \lambda\exp\,(-\,a_b\lambda^{-2})\Big|_{\lambda_1}^{\lambda_2} + \right.$$

$$\left. + \,a_b\,\frac{\pi^{0.5}}{a_b^{0.5}}\,[\mathrm{erf}(a_p^{0.5}\lambda_2) - \mathrm{erf}(a_b^{0.5}\lambda_1)]\right\}, \quad (12)$$

where $a_b = a_b(\nu)$.

One should substitute the average value of the parameter ν_0 into Eq. (12) (see Eq. (5)). As a result of overaging over λ we obtain

$$\bar{\nu}_0 = \frac{1}{\Delta\lambda}\int\limits_{\lambda_1}^{\lambda_2} \nu_0(\lambda)\, d\lambda = \frac{1}{\Delta\lambda}\int\limits_{\lambda_1}^{\lambda_2} \frac{\delta}{10 f'}\frac{d\lambda}{\lambda} ,$$

$$\bar{\nu}_0 = \frac{\delta}{10 f'\Delta\lambda}(\ln\lambda_2 - \ln\lambda_1) .$$

With the onboard detectors one should predict a dependence of the size of the scattering particles and the structural function of the refractive index at the height in the visible region and substitute their mathematical expectations for C_n^2 and a_s in formulas (2) and (4). The calculational results on the average polychromatic MTF for different values C_n^2 and a_s and for different angles of observation of the OEVS are shown in Figs. 1 and 2.

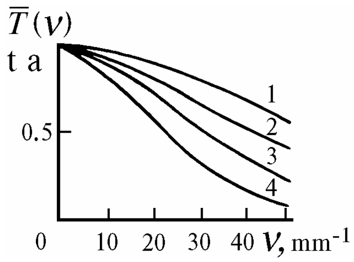

FIG. 1. Averaged polychromatic MTF of the turbulent atmosphere obtained for $H = 500$ m and $\bar{\lambda} = 4$ μm: 1) $C_n^2 = 10^{-15}$ $m^{-2/3}$ and $\beta = 0$, 2) $C_n^2 = 10^{-9}$ $m^{-2/3}$ and $\beta = 0$, 3) $C_n^2 = 10^{-9}$ $m^{-2/3}$ and $\beta = 30^\circ$, and 4) $C_n^2 = 10^{-9}$ $m^{-2/3}$ and $\beta = 60^\circ$.

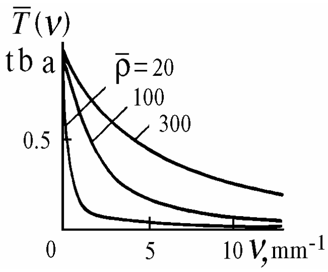

FIG. 2. Averaged polychromatic MTF of a turbid atmosphere ($\bar{\rho} = 2\pi a_s \bar{\lambda}^{-1}$).

When radiation passes through the atmospheric layer, the energy extinction caused by the molecular absorption and aerosol scattering takes place, therefore the STF can be given in the form

$$\tau_A(\lambda) = \tau_{A1}(\lambda)\, \tau_{A2}(\lambda)\, \tau_{A3}(\lambda) ,$$

where $\tau_{A1}(\lambda)$, $\tau_{A2}(\lambda)$, $\tau_{A3}(\lambda)$ are the components of the STF due to the molecular scattering, absorption, and the aerosol scattering, respectively. Because $\tau_{A1}(\lambda) \approx 1$ in the IR spectral region,[13] we shall estimate components $\tau_{A2}(\lambda)$ and $\tau_{A3}(\lambda)$.

The component $\tau_{A2}(\lambda)$ of the STF takes into acount the absorption of radiation by the atmospheric gases and depends on their concentration and on the length of a sounding path. The water vapor, carbon dioxide, and ozone are the main absorbing gases

$$\tau_{A2}(\lambda) = \tau_{A2}^{(H_2O)}(\lambda)\, \tau_{A2}^{(CO_2)}(\lambda)\, \tau_{A2}^{(O_3)}(\lambda) .$$

The effect of the water vapor is predicted by creating a model of a vertical slant path based on the principle of division of the atmospheric column of the height Z into N layers with the equally small heights. Then, one can state that the main atmospheric parameters within the layer are stable along the z axis.[14] The value $\tau_{A2}^{(H_2O)}(\lambda)$ is estimated using the Passmann–Larmor tables.[15] For this it is necessary to determine the water vapor column density $w(x, y, z, t)$ which is a function of the atmospheric parameters

$$w(x, y, z, t) = F(Z, f, p, T) = \sum_{j=1}^{N} w_j(Z, f, p, T) ,$$

$$w_j(Z, f, p, T) = 289.4(273 + T_j)^{-1} q_j P_j (622 + 0.378\, q_j)^{-1} f\Delta Z,$$

where $q_i = q_0\exp(-0.5\Delta Z_j)$ is the specific humidity of air in the jth layer, $\Delta Z = Z/N$ is the thickness of the layer, $q_0 = 622e(P_0 - 0.378\, e)^{-1}$ is the specific humidity at the height $Z = 0$, $P_j = \exp\{\ln P_0 - g_0[(T - T_0)N^{-1}R]^{-1}\ln(T_j T_0^{-1})\}$ is the atmospheric pressure in the jth layer, $e = \exp\{\ln 4.58 + [7.5\,(\tau/237.3 + \tau)]\ln 10\}$ is the water vapor pressure of saturation, p_0 and T_0 are the pressure and temperature of air on the Earth's surface, j is the number of a layer, g_0 is the acceleration of gravity; T is the temperature at the height Z; R is the universal gas constant for air; $T_j = T_0 + [(T - T_0)/N]$ is the air temperature in the jth layer; f is the relative air humidity on the Earth's surface, and τ is the dew point.

The transmission coefficient due to absorption of radiation by carborn dioxide $\tau_{A2}^{(CO_2)}(\lambda)$ is determined from the tables,[15] where the input parameter is the equivalent path length

$$Z_{eq} = \sum_{j=1}^{N} \Delta Z_j \left(\frac{P_{zj}}{P_{z(j-1)}}\right)^{1.5} .$$

The mean statistical data from Ref. 10 have been used to estimate $\tau_{A3}^{(O_3)}(\lambda)$.

The atmospheric transmission coefficient due to aerosol scattering $\tau_{A3}(\lambda)$ depends essentially on the size and number density of particles. The value $\tau_{A3}(\lambda)$ was estimated by the method proposed in Ref. 10

$$k(\lambda, Z_1, Z_2, \beta) = \sec\beta\cdot 3.912 S_m^{-1}\omega(\lambda) b^{-1}[\exp(-bZ_1) - \exp(-bZ_2)],$$

where $b = 2.78 - 0.46\log S_m(0)$, $k(\lambda, Z_1, Z_2, \beta)$ is the aerosol scattering factor, β is the angle of the path slope, S_m is the meteorological visibility range, Z_1 and Z_2 are the heights of the low and upper boundaries of the atmospheric column, $w(\lambda) = \alpha(\lambda)\,\alpha(0.5)^{-1}$, and $\alpha(\lambda)$ and $\alpha(0.5)$ are the extinction coefficients at the wavelengths λ and 0.5 μm, respectively.

Under the atmospheric conditions aerosol particles have, as a rule, a water shell. Therefore, the refractive index of the particle with the water shell becomes a complex value what complicates the calculations of $\tau_{A3}(\lambda)$.

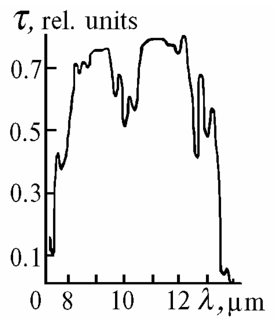

FIG. 3. The dependence of the spectral transmission function of the atmosphere on the wavelength under certain conditions of observations. P_0 = 730 mm *Hg,* τ_0 = 293 K, H = 1000 m, f = 70 %, *and* $S_m(0)$ = 1 km.

Numerical modelling allowed us to obtain the dependence of the STF on the wavelength in the range 7–14 μm (see Fig. 3), which well agrees with the results from Refs. 9, 10, and 13, however, the precision of its prediction essentially depends on the precision of the onboard detectors, measuring the atmospheric parameters. To a great extent the STF depends on the precision of the measurement of air temperature, thus a change of this value by 1 K leads to the change of $\tau_A(\lambda)$ by 1.3% that is in a good agreement with the results from Ref. 13. The change of other atmospheric parameters affects the propagation of radiation essentially weaker.

Thus, the main problems in creating of the atmospheric–adaptive OEVS's and their algorithmic support include the measurement and prediction of a vertical profile of temperature, pressure, relative humidity, structural function of the refractive index, as well as of the aerosol types in the near–ground layer of the atmosphere and vertical profiles of aerosol size and concentration with a preset accuracy.

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