CALCULATION OF AMBIENT BACKGROUND ILLUMINATION IN OPTICAL SYSTEMS

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The mechanisms of ambient background illumination in different optical systems are elucidated. A numerical method for calculating this background illumination in the focal plane of an optical system is described. The results of calculations of the ambient background illumination as a function of the angle of incidence of illuminating radiation are given. Contributions from different mechanisms of radiation scattering to the ambient background illumination in the focal plane are analyzed.

1. The ambient background illumination is acknowledged to be one of the factors which reduce image contrast in the focal plane of an optical system. This results in deteriorating detectability of opto–electronic systems. The background illumination from intense background radiation sources in the focal plane can lead to illumination of an opto–electronic system. The main reasons for background illumination are[1]:

– radiation diffraction in an optical system;

– radiation scattering on its inner (optical and nonoptical) surfaces;

– radiation re-reflection by optical surfaces of refractive optical parts (reflections);

– self–(thermal) radiation of the optical parts of the system into the focal plane (for IR spectral range).

At present the methods for calculating the ambient background illumination due to reflections[2,3,4] and self–radiation[5] have been described at length. The problems of scattering of background radiation in an optical system, for which the estimates were obtained in Ref. 6, and cooperative effects of the above-enumerated factors are less well understood. The present paper is devoted to the method for calculating the ambient background illumination in the focal plane of an optical system, which allows one to consider the scattering in the optical system, diffraction effects, and reflections.

2. The ambient background illumination $E_{\rm bg}$ at an arbitrary point of the focal plane is equal to a sum of the following components:

$$E_{\rm bg} = E_{\rm bg1} + E_{\rm bg2} + E_{\rm bg3} + E_{\rm bg4} + E_{\rm bg5} + E_{\rm bg6} + E_{\rm bg7} , \quad (1)$$

where $E_{\rm bg1}$ is the component of background illumination due to scattering of incident radiation on optical surfaces, $E_{\rm bg2}$ is the component caused by multiple scattering of radiation on inner optical and nonoptical surfaces, $E_{\rm bg3}$ is the component produced by diffraction of incident radiation by the input aperture of the system, $E_{\rm bg4}$ is the component resulted from primary diffraction of radiation by the edge of a blind and secondary diffraction by the input aperture of the optical system, $E_{\rm bg5}$ is the component blind and subsequent scattering of radiation in the optical system, produced by primary diffraction of radiation by the edge of the $E_{\rm bg6}$ is the component caused by diffraction of radiation scattered on optical surfaces into the focal plane, and $E_{\rm bg7}$ is the component resulted from re-reflection of radiation by refractive optical parts.

Using the relations obtained in Refs. 6 and 7, the expression

$$E_{\rm bg1} = E_{\rm in}\, \tau \cos(\varepsilon)\, \frac{\pi D_{\rm in}^2}{4 f'^2} \sum_{k=1}^{N_{\rm s}} S_k(\varepsilon)\, r_k , \quad (2)$$

can be derived for the background illumination produced by diffuse scattering of radiation on the optical surfaces. Here $E_{\rm in}$ is the illuminance at the input aperture of the optical system, τ is the transmittance of the optical system, ε is the angle of incidence of radiation, $D_{\rm in}$ is the diameter of the input aperture, f' is the focal length of the optical system, $S_k(\varepsilon)$ is the coefficient of illumination of the kth surface produced by the incident radiation, r_k is the brightness coefficient of the kth surface, and N_s is the number of optical surfaces.

The illumination $E_{\rm bg2}$ allows for multiple scattering of radiation on surfaces of blinds, mounts, diaphragms, and frame walls as well as on the optical surfaces. On account of the results obtained in Refs. 6 and 8, the formula for $E_{\rm bg2}$ takes the form

$$E_{\rm bg2} = E_{\rm in}\, \tau \cos(\varepsilon)\, \frac{\pi D_{\rm in}^2}{4 f'^2} \sum_{k=1}^{N_{\rm s}} (1 - S_k(\varepsilon))\, r_k\, \rho_{\rm w}^b , \quad (3)$$

where $\rho_{\rm w}$ is the reflection coefficient of nonoptical surfaces and b is the number of reflections of radiation before scattering on an optical surface.

In the focal plane the distribution of illuminance caused by radiation diffraction by an input aperture of the optical system to within a constant factor represents the square modulus of the Fourier transform of a complex field amplitude at an exit pupil of the optical system.[9] In paraxial approximation for an optical system with screening of its central part we may write

$$E_{\rm bg3} = E_{\rm in}\, \tau \cos(\varepsilon)\, \frac{D_{\rm in}\, f'\, (1 - K_{\rm bl})\, \lambda}{4\, \pi^2\, y^3\, (1 - K_{\rm sc})\, (1 - K_{\rm sc}^2)} , \quad (4)$$

where λ is the wavelength, $K_{\rm bl}$ is the coefficient of screening of the input aperture by a blind, $K_{\rm sc}$ is the coefficient of screening of the central part of the optical system, and y is the coordinate in the focal plane counted off from the center of a diffraction pattern.

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To calculate the ambient background illumination due to cooperative effects of diffraction and scattering of radiation in the optical system, the formulas derived in Refs. 10 and 11 were used. When the radiation is incident on the blind, a definite fraction of radiation diffracts into primary optical system. Then the secondary diffraction of this radiation by optical parts occurs. The background illumination caused by double diffraction is found from the formula

$$E_{\mathrm{bg4}} = E_{\mathrm{in}} \frac{\lambda\, D_{\mathrm{bl}}\, (1 + \cos(\varepsilon))^2}{16\, \pi^2\, L^2 \sin^3(\varepsilon)} \frac{\tau\, \lambda \cos(\xi_d)}{D_{\mathrm{m}}\, \pi^3 \sin^3(\xi_d)}, \tag{5}$$

where D_{bl} is the diameter of the blind edge, L is the blind length, and D_{m} is the diameter of mount of the primary optical system, ξ_d is the angle of radiation diffraction into the primary optical system.

The fraction of radiation diffracted by the blind edge undergoes multiple scattering in the optical system. In this case the background illumination is determined from the expression

$$E_{\mathrm{bg5}} = E_{\mathrm{in}} \frac{\lambda\, D_{\mathrm{bl}}\, (1 + \cos(\varepsilon))^2}{4\pi^2\, (D_{\mathrm{bl}}^2 + L^2) \sin^3(\varepsilon)}\, \tau \cos(\xi_d) \frac{\pi D_{\mathrm{in}}^2}{4 f^2} \sum_{k=1}^{N_{\mathrm{s}}} S_k(\xi_d)\, r_k. \tag{6}$$

A component of the background illumination produced by radiation diffracted by the mounts of the optical parts into the focal plane of the optical system has the form

$$E_{\mathrm{bg6}} = E_{\mathrm{in}}\, \tau \cos(\varepsilon) \frac{\pi D_{\mathrm{in}}^2}{4 f^2} \sum_{k=1}^{N_{\mathrm{s}}} (1 - S_k(\xi_k))\, r_k\, \rho_{\mathrm{w}}^b \frac{\lambda f^3}{\pi^3 D_k\, y_{\mathrm{k}}^3}, \tag{7}$$

where D_k is the light diameter of the kth surface, ξ_k is the angle of radiation scattering on the kth surface, and y_k is the coordinate in the focal plane counted off from the center of a diffraction image of the kth optical part.

A component of the background illumination E_{bg7} due to radiation reflections in the optical system is determined from the ratio of transmittances and output angular apertures of reflecting and reference optical systems[4]:

$$E_{\mathrm{bg7}} = \sum_{i=1}^{N_{\mathrm{r.s.}}} S_{\mathrm{r.s}i} \frac{\tau_{\mathrm{t}.i}\, u_{\mathrm{o}.i}'^2}{\tau_{\mathrm{t}}\, u_{\mathrm{o}}'^2}, \tag{8}$$

where $N_{\mathrm{r.s.}}$ is the number of pairs of reflecting surfaces in the optical system, $S_{\mathrm{r.s}.i}$ is the coefficient of background illumination of the ith reflecting surface by direct and scattered radiation, $\tau_{\mathrm{t}.i}$ is the transmittance of the ith reflecting system, τ_{t} is the transmittance of the reference system, $u'_{\mathrm{o}.i}$ is the output angular aperture of the ith reflecting system, and u'_{o} is the output angular aperture of the reference system.

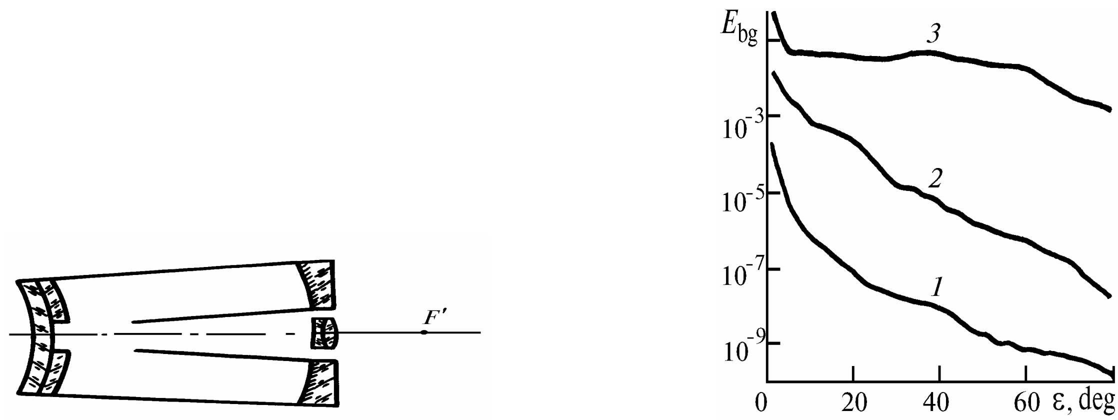
Thus relations (2)–(8) can be used to calculate the value of the ambient background illumination E_{bg} by formula (1).

3. By way of example we give the results of calculation of the ambient background illumination for two optical systems: an MTO–1000 A mirror–lens objective and a Schmidt mirror–lens objective. The brightness coefficients of optical surfaces were determined by the formula

$$r(\alpha, \beta) = \frac{A}{|\alpha - \beta|^B}, \tag{9}$$

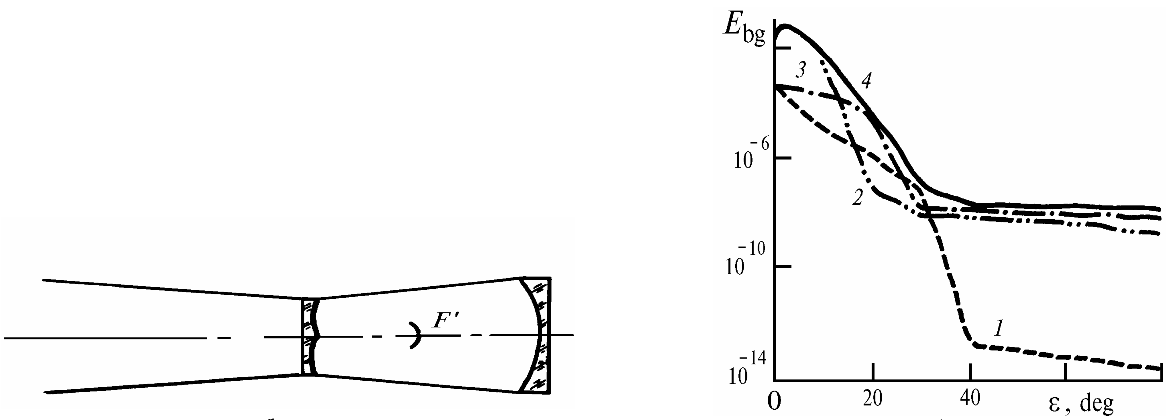
where α is the radiation scattering angle with respect to the normal to the surface (in degrees), β is the angle of radiation incidence (in degrees), and A and B are the coefficients depending on the radiation wavelength λ and the characteristics of the surface.[12] The brightness coefficients of the frame and blind surfaces were taken from Ref. 8. The optical scheme of the MTO–1000 A objective is depicted in Fig. 1 *a*. Figure 1 *b* shows the ambient background illumination E_{bg} as a function of the angle of incidence of input radiation ε. The calculations were made for the illuminance at the input aperture $E_{\mathrm{in}} = 1$. Contributions of diffraction, scattering, and re-reflection of radiation to the ambient background illumination are shown by curves *1*, *2*, and *3*, respectively. A comparison of these components shows a predominant contribution of re-reflection which is accounted for by the large number of refracting optical surfaces. The plot of ambient background illumination due to reflections vs the angle of incidence of input radiation is flatter than others since the first optical element is constantly illuminated by incident radiation. The total value of E_{bg} almost coincides with the value of the background illumination caused by reflections. For this reason it is not shown on the plot.

An optical scheme of the Schmidt mirror–lens objective is shown in Fig. 2 *a*. The ambient background illuminations E_{bg} vs the angle of incidence ε, calculated for this optical system, are depicted in Fig. 2 *b*. It is seen from their comparison that at the angles smaller than $\varepsilon = 30°$ the predominant contribution to the total background illumination comes from radiation scattering in the optical system, and at the angles larger than this angle the main contribution comes from radiation re-reflection by a correcting plate. This can be accounted for by the smaller number of optical surfaces by which radiation is re-reflected. At the incidence angles larger than 30° the decisive role in reduction of the ambient background illumination is played by a sun-screening blind since only the radiation scattered on the blind enters the input aperture of the optical system.



a b

FIG. 1. The mirror–lens MTO–1000 A objective. a) optical scheme of the objective and b)ambient background illumination in the focal plane of the optical system vs the angle of incidence of input radiation. Contributions from diffraction (1), scattering (2), and re-reflection (3) of radiation in the optical system to the ambient background illumination.



a b

FIG. 2. The Schmidt mirror–lens objective and a) optical scheme of the objective; b) ambient background illumination in the focal plane of the optical system vs the angle of incidence of input radiation. Contributions of diffraction (1), scattering (2), and re-reflection of radiation (3) in the optical system to the ambient background illumination and the total ambient background illumination vs the angle of incidence of input radiation (4).

A comparison of the ambient background illumination of the two optical systems at small angles of incidence of input radiation allows us to conclude that the Schmidt mirror–lens objective produces lower background illumination in the focal plane, all other factors being equal, due to the smaller number of optical surfaces.

Thus the technique has been developed which can be used to calculate the ambient background illumination in the focal plane of optical systems as a function of radiation parameters, angles of radiation incidence, and constructional features of these systems. From the analysis of results of calculation of the ambient background illumination for two optical systems the following conclusions can be drawn:

– the ambient background illumination depends on the number of surfaces in an optical system and their optical properties,

– the relative contributions from diffraction, scattering, and re-reflection of radiation to the total ambient background illumination is determined by the scheme and construction of the optical system.

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