INTERACTIVE SYSTEM FOR ASSESSING THE EFFECT OF THE ATMOSPHERE ON PROPAGATION OF OPTICAL RADIATION (ISAEAPOR)

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An interactive system for predicting and taking into account the effect of the totality of linear optical phenomena in the real atmosphere on the accuracy and energy characteristics of opto–electronic systems and devices is presented. The interactive system consists of two packages of programs for IBM PC/AT.

INTRODUCTION

For a wide range of problems in atmospheric optics – range finding, laser detection and ranging, and navigation – we need routine data on the effect of optical phenomena on the accuracy and energy characteristics of opto–electronic systems used in experiment.[1–3]

This paper presents the description of an interactive system capable to predict and to take into account the effect of the atmosphere in real time on the characteristics of optical radiation.

The ISAEAPOR is a set of application programs relying on the engineering techniques and summarising the results of fundamental scientific studies in atmospheric optics.

When calculating the parameters of propagation of the optical–radar signal through the atmosphere, the data are needed on zonal and seasonal variations in the altitude profiles of distribution of the parameters of absorbing gases, aerosols, clouds, meteorological parameters, and characteristics of the turbulent air fluxes. Since the reliability of predicting the optical radiation propagation at various altitudes is affected by the degree of statistical adequacy of the employed vertical profiles of the optical parameters of the atmosphere, at the Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences on the basis of a large body of experimental data we developed the integrated optical model of the atmosphere[4] which includes the vertical profiles of the atmospheric meteorological parameters and optical characteristics of the atmosphere and provides the basis for the development of the database for the ISAEAPOR.

PURPOSE AND POSSIBILITIES OF THE ISAEAPOR

The interactive system for assessing the effect of the atmosphere on propagation of optical radiation is intended for to predict and to take into account the totality of the linear optical phenomena in the real atmosphere on the accuracy and energy characteristics of really existing opto–electronic systems and devices or those under design.

The interactive system controls the following operations:

1) calculation of the correction for distance and refraction angle on slant and horizontal paths during propagation of laser and optical radiation in the visible and IR ranges through the atmosphere,

2) estimate of the energy losses due to absorption on the path,

3) determination of the pulse backscattering characteristic which enables one to calculate the intensity of the backscattered radiation at the aperture of a receiving system,

4) estimate of illumination in the receiving channel caused by radiation from natural noise sources, namely, daytime cloudless sky radiation and heat radiation of the underlying surface and atmosphere, and

5) calculation of the statistical characteristics of optical beams associated with the effect of the atmospheric turbulence.

It is well known that the refraction phenomenon in the Earth's atmosphere and the change of the signal velocity along the beam path during the operation of range–finding devices lead to errors in determining the true angle of elevation and distance from an observed object.[5–8] Therefore, calculation of the corrections for distance and a refraction angle is especially important in assessing the effect of the atmosphere on propagation of optical radiation. In practice, direct measurements of the corrections for refraction an arbitrary paths are unavailable and for this reason approximate methods[5,6] are used for their estimate. The essence of these methods is that depending on the desired accuracy and effectiveness of taking into account the refraction corrections, the approximate vertical profile of the refractive index or of the meteorological parameters determining it, i.e., density, pressure, temperature, and temperature lapse rate are specified.

The assignment of the vertical profiles of the meteorological characteristics for various wavelengths, seasons, time of a day, and Earth's climatic zones is provided for in the interactive system to obtain more exact values of corrections for the distance and refraction angle. The algorithms for determining the correction for distance and refraction angle are implemented in which an account of the lidar location and the observation angle are taken and which are capable to calculate simultaneously the errors in determining these values (standard deviations of the refraction angle and correction for the measured distance).[8] Let us describe, by way of example, an algorithm for determination of the refraction angle r'' (second of arc) and the correction ΔS (m) for an airborne lidar and observation of the objects located beyond the horizon (the nadir angle $\varphi < \pi/2$).

The refraction angle is calculated from the formula

$$r'' = r_f \tan\left\{\varphi + \frac{3\rho'(H - H_o)}{2R_0} \times \right.$$

$$\left. \times \tan\varphi \left[1 - \frac{1}{g + R_d\gamma}\left(\frac{2T_o - R_d}{H - H_o} - C_0\frac{P(g - R_d\gamma)}{Tr_f}\right)\right]\right\}, \quad (1)$$

where

$$H_o = \sqrt{S^2 + (R_0 + H)^2 - 2S(R_0 + H)\cos\varphi} - R_0 ,$$

$$r_f = C_0\left[\frac{R_d(P_o - P)}{g(H - H_o)} - \frac{P}{T}\right],\ \gamma = \frac{T_g - T}{H - H_g},$$

$$C_0 = \begin{cases} 16.072; \\ 16.000; \\ 15.992; \end{cases} \quad \lambda = \begin{cases} 1.06, \\ 3.8, \\ 10.6\ \mu\text{m}, \end{cases}$$

$$P = P_g\,[1 - \gamma\,(H - H_g)/T_g]^{g/R_d\gamma},\ \text{for } H < 16\ \text{km} .$$

The air temperature T_o and pressure P_o at the altitude of the object are

$$T_o = T_g - \gamma\,(H_o - H_g),\ P_o = P_g\,[1 - \gamma\,(H_o - H_g)/T_g]^{g/R_d\gamma} .$$

Here H is the altitude of the lidar, H_o is the altitude of the object, and H_g is the altitude of the sensors of temperature and pressure above the sea level, T and T_g are the air temperature near the lidar and at the ground, respectively, P and P_g are the air pressure near the lidar and at the ground, respectively, S is the distance from the object, λ is the radiation wavelength, ξ is the zenith angle of observation of the object, and γ is the mean temperature lapse rate. The constant values are the specific gas constant of dry air $R_d = 287.05\ \text{m}^2/(\text{sec}^2\ \text{K})$, $g = 9.81\ \text{m/sec}^2$, $\rho' = 3438$, and the Earth radius $R_0 = 6371000$ m.

The correction for distance is calculated from the formula

$$\Delta S = 10^3(n_0^g - 1)\left[\sqrt{(R_0 + H_g + H_e)^2 - (R_0 + H_g)^2\sin^2\xi} - (R_0 + H_g)\cos\xi\right] + \delta S, \qquad (2)$$

where the group refractive index is given by the formula $n_0^g = 1 + 10^{-6}\,N_0^g(\lambda)$, the coefficient $N_0^g(\lambda)$ under standard conditions is given by the following formula:

$$N_0^g(\lambda) = N_0(\lambda) + 0.28439\,\frac{P_o}{T_o}\left[\frac{48120.6\lambda^{-2}}{(130 - \lambda^{-2})^2} + \frac{319.94\lambda^{-2}}{(38.9 - \lambda^{-2})^2}\right],$$

$$N_0(\lambda) = 0.28439\,\frac{P_o}{T_o}\left[83.4213 + \frac{24060.3}{130 - \lambda^{-2}} + \frac{159.97}{38.9 - \lambda^{-2}}\right],$$

$$H_e = 10^{-3}\,\frac{R_d T_o}{g}\left(1 - \frac{P}{P_o}\right) .$$

For other lidar locations and path geometry the formulas for calculations of the refraction angle and correction for distance differ from the above and are also implemented in the form of algorithms and application programs which are part of the ISAEAPOR.

Estimate of the energy losses due to the absorption on the path means an account of the total molecular and aerosol attenuation of the optical radiation.

Estimates of the optical radiation attenuation due to the molecular absorption on the slant and horizontal paths call for knowledge of the meteorological parameter distribution. In the ISAEAPOR the calculation of the altitude profile of the coefficient of molecular attenuation and optical thickness is provided for as a function of the radiation wavelength, geographic zone, seasonal and diurnal variations in the meteorological parameters on the basis of the humidity and CO_2 concentration databases.[10]

Outside the bands of molecular absorption (in the transparency windows of the atmosphere) scattering and absorption by the atmospheric aerosol are the main factors determining the energy attenuation of the optical radiation.[9,11] The basic quantitative characteristic determining the aerosol attenuation is the coefficient of aerosol attenuation α_a, which depends on the wavelength λ. Near the Earth's surface the approximate value of α_a^r for the given wavelength is estimated, taking into account the real synoptic situation, from the single–parameter equation for the root–mean–square regression

$$\alpha_a^r(\lambda,\ 0) = K_1(\lambda)\ \alpha_a(0.55) + K_0(\lambda), \qquad (3)$$

where $\alpha_a(0.55) = 3.9/S_m\ \text{km}^{-1}$ is the coefficient of the aerosol attenuation in the visible range. The regression coefficients K_1 and K_0 are selected for the concrete types of optical weather from the tables borrowed from Ref. 12.

To calculate more exact values of the altitude profile of the aerosol attenuation coefficient $\alpha_a^r(\lambda,\ h)$, the correction $\alpha_a^c(\lambda,\ h) = \Delta e^{-[h/C]^2}$ is used, which enables one to approach the shape of the model profile of the aerosol attenuation coefficient $\alpha_a^m(\lambda,\ h)$ assymptotically to its real altitude distribution

$$\alpha_a^r(\lambda,\ h) = \alpha_a^m(\lambda,\ h) + \alpha_a^c(\lambda,\ h)\ , \qquad (4)$$

where $\Delta = \alpha_a^r(\lambda,\ 0) - \alpha_a^m(\lambda,\ 0)$, $\alpha_a^r(\lambda,\ 0)$ and $\alpha_a^m(\lambda,\ 0)$ are the real and model aerosol attenuation coefficients for the wavelength λ at the altitude $h = 0$. The scaling coefficient C depending on the visual range is given by the formula

$$C = \begin{cases} 0.3; & 0 < S_m < 2\ \text{km}\ , \\ -\,0.375 + 0.3375\,S_m; & 2 < S_m < 10\ \text{km}\ , \\ 3.0; & S_m > 10\ \text{km}\ . \end{cases}$$

In the ISAEAPOR the model profile of the aerosol attenuation for the given wavelength is calculated on the basis of the available databases of the aerosol absorption and scattering in the atmosphere.[3,4,12]

When determining the maximum ranges of vision, detection, and identification of objects it is necessary to estimate the illumination in the receiving channel from natural sources of background illumination and noise, because the background noise deteriorates the apparent brightness contrast of the object and reduces the dynamic range of the receiving channel.

The background radiation depends on the coordinates of the Sun, direction of observation, working wavelength range, optical–meteorological situation, season, time of a day, and geographic factors as well as on the parameters of measuring devices.[14] In connection with great variety of possible background situations and accompanying conditions of observations it is practically impossible to obtain not only the universal mean but also statistical characteristics for the estimates of the background noise. In the ISAEAPOR the calculation of spectral brightness of the cloudless sky, heat radiation of the underlying surface, and the power of illumination of the receiving system by backscattered radiation of the source is realized. Approximate methods are used for their calculation with an error of 15–20%.

To calculate impulse transfer function (ITF) $I(t)$ as a function of time of arrival of the backscattered optical radiation, the formula (at the scattering angle $\beta = \pi$)

$$I(t) = \frac{c}{2t^2}\beta_\pi(h)T_a$$

is used, where t is the time of arrival of the scattered radiation, c is the velocity of light, $\beta_\pi(h)$ is the volume backscattering coefficient at the altitude h, T_a is the factor of attenuation of radiation due to aerosol and molecular attenuations on the double path length.

To calculate the intensity of the backscattered radiation incident at the receiving aperture, it is necessary to multiply the ITF by the pulse energy.

The estimate of the spectral brightness of the daytime cloudless sky is determined by the scattered solar radiation and is calculated from the formulas applicable at the observation angles and solar zenith angles not less than 15° (Ref. 13)

$$b_{H\lambda} = \left\{\pi S_{0\lambda}\frac{0.06\tau_R(1+\cos^2\varphi) + \eta(e^{-3\varphi} - 0.009)}{\tau}\times\right.$$
$$\times\left(\frac{e^{-\tau_a \sec Z_0} - e^{-\tau_a \sec h}}{\sec\theta - \sec Z_0}\right)\sec\theta + \frac{C_a}{4}S_{0\lambda}e^{-\tau_a\sec Z_0}\times$$
$$\left.\times\,\tau_a\sec Z_0\left(\frac{1 - e^{-\tau_a \sec h}}{1 - e^{-\tau_a\sec Z_0}}\right)\right\}e^{-\tau_{oz}\sec Z_0},\ \theta \ne Z_0; \quad (5)$$

$$b_{H\lambda} = \left\{\pi S_{0\lambda}\frac{0.06\tau_R(1+\cos^2\varphi) + \eta(e^{-3\varphi} - 0.009)}{\tau}e^{-\tau_a\sec Z_0}\times\right.$$
$$\left.\times\,\tau_a\sec Z_0 + \frac{C_a}{4}S_{0\lambda}e^{-\tau_a\sec Z_0}\tau_a\sec Z_0\right\}e^{-\tau_{oz}\sec Z_0},\quad \theta = Z_0,\ (6)$$

where $\pi S_{0\lambda}$ is the spectral solar constant given by the formula

$$\pi S_{0\lambda} = \frac{0.78715259}{\lambda^5\left(e^{C_2/\lambda 5985} - 1\right)},$$

$C_a = 0.133 + 1.33q$, where q is the albedo of the examined region taken from the tables of Ref. 12, τ_a and τ_R are the aerosol and Rayleigh components of the optical thickness τ, τ_{oz} is the optical thickness of radiation absorption due to ozone, $\eta = 2.33(\tau_a + 0.062\tau_R)$, Z_0 is the solar zenith angle, θ is the zenith angle of the observation point of the sky, φ is the angular distance from the Sun, and $C_2 = 14386.5$ µm·K. When implementing the algorithm, the values of τ_R and τ_{oz} were taken to be equal to zero in view of their negligible contribution to scattering and absorption by the atmosphere in the IR range.

The spectral density of the Earth's heat radiation neglecting the energy attenuation in the atmosphere is determined by the Planck function

$$r(\lambda, T) = C_1\lambda^{-5}\left[\exp\left(\frac{C_2}{\lambda T} - 1\right)\right]^{-1},$$

where $C_1 = 37400$ W·µm^5/(cm^2·µm).

The background power P_{bg}(W·cm^{-2}·µm^{-1}) in the field of view of the source is calculated from the formula

$$P_{bg} = \pi R_r^2\,\Omega\left(b_{H\lambda} + \frac{r(\lambda, T)}{\pi}\right), \quad (7)$$

where R_{bg} is the radius of the lidar receiving aperture, Ω is the solid angle of the field of view of the lidar receiver.

The statistical characteristics of the optical beam on the slant paths are the standard deviations of the fluctuations in the direction of the optical beam propagation and of the position of the object image in the focal plane of the receiving optical system. In the system these values are calculated based on the algorithms presented in Ref. 15.

COMPOSITION AND SPECIFIC FEATURES OF IMPLEMENTATION OF THE PROGRAM PACKAGES

The ISAEAPOR is intended for operation on the IBM PC/AT compatible computers and comprises two subsystems:

1) subsystem for selection of the program and refinement of the input parameters and

2) subsystem for estimating the energy and accuracy characteristics of a concrete optical system.

The subsystem for selection of the program and refinement of the input parameters was developed on the basis of the CLARION system of the unified database which ensures the flexible system service making easier the work of a nonprogrammer user.

The subsystem for selection has a four–level menu. The upper level incorporates the general advertisement of the system application and the menu for selection of five programs:

1) input of the parameters used in calculation,
2) model calculation,
3) calculation,
4) browsing of results, and
5) logout.

The second level is the system menu which is responsible for input and updating the parameters. At this level the input parameters (parameters of the path, lidar, geoatmosphere, and model parameters) are entered the special–purpose fields. The model parameters are selected in a separate menu (at the third level), which has five parameters characterizing the state of the atmosphere on the path. They are the geographic zone (subzone), season, time of a day, optical weather, and type of the underlying surface. The listed parameters, in their turn, are determined by the concrete list of their acceptable values (at the fourth level).

The analysis of the input values and control of their correspondence to the preset ranges are provided for in the system as well as the warning messages in the case of unacceptable combinations of the input parameters.

The distinguishing feature of the given subsystem is the possibility of estimating the necessary characteristics in the regime "Model calculation" under conditions of uncertainty in the geoatmospheric parameters. In the regime "Calculation" all these parameters or part of them can be assigned. The uncertain parameters are formed according to the model state on the path and the available databases of this system. In the case of variation in the basic input values (the altitude of the lidar, distance, elevation angle, solar zenith angle, and solar azimuthal angle) the cyclic calculation for these parameters is provided for retrieving the data arrays in real time. The obtained results are represented either in the form of a unified table comprising all the basic calculated values, or in the form of complete tables for every variant of calculation.

Subsystem for estimating the energy and accuracy characteristics is the software package computed in FORTRAN–77 and implemented in a load module automatically switched on by the subsystem of the selection of the program when an user enters the regime "Calculation" or "Model calculation". Input data for this system are a file formed by the subsystem of the selection of the program. The subsystem of estimation has the modular structure and contains 20 subprograms with a total volume of 88 Kbytes. The result of its operation is the file transmitted to the subsystem of the selection of the program for the visualization in the form of the tables of the calculated values.

The ISAEAPOR has the overlay structure which enables one to save the main storage of a computer and together with the databases occupies 650 Kbytes of the disk memory.

The system is open, can be simply modified, and used for the solution of a wide range of problems in the atmospheric optics including range finding, study of the optical characteristics of ground–based and other objects under various atmospheric conditions, etc.

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