STATISTICAL MODELING OF SPREAD OF OPTICAL FIELDS IN FIRES

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Abstract: Application of Monte-Carlo method for determination of optical radiation flow density of forest fires in a cloudless atmosphere with dependence on optic-geometrical parameters of surface's relief for the case of multi and single scattering is offered in this work. The use of initial directions of photon trajectory, free path length of the photon, coordinates of interact points between the photon and environment, also probabilities of photon's getting to a receiver into the statistical modeling of direction of distribution of optical radiation of fires is proposed.

Keywords: Monte-Carlo method, photon trajectory, radiation transfer.

ACM Classification Keywords: I.6 Simulation and Modeling. I.6.8 Types of Simulation - Monte Carlo.

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Introduction

The checking of anthropogenic and natural objects and phenomenon which because chemical (the aerosols, gases) and heat (thermal) soiling are source of potential or direct risk for biological systems and habitat, plays important role in applied ecology. To such objects first of all follows to attribute the fires and smokes, which origin can be due various reasons [Потапов, 2002]. Emphasizing unconditional importance of this problem, necessary also to take into attention the direct influence of optical radiation (its heat component first of all) on atmosphere and underlying surface. This influence has more energy power and duration during big fires that permits to include its in special aspect of applied ecology - heat soiling the ambience [Доррер, 1979]. Given problem is actual because directed checking optical (heat) of radiation overland objects and atmospheric phenomenon within the framework of separate regions, continents, water areas and planets as a whole have not sufficient volume. Measuring of the flow of heat radiation on fires is very complicated task that is why calculations parameters and possibility of their modeling are playing great practical importance.

The numerical method of calculating the characteristics of the light field

At present most acceptable for a calculation of optical fields is the Monte-Carlo method [Соболь, 1968] sense of which in modeling of paths of the photons and events, which with them can occur.

The strategy of calculation of density of flow of scattered radiation from point source with single power [Марчук, 1967] bases on using of three arrays of input data.

The parameters which characterize external habitat compose first array: meteorological visibility, S_M, km, aerosol indicatrix of scattering χ_a, molecular indicatrix of scattering χ_M, optical thickness of atmosphere τ_0, terrestrial surface albedo A, height of slopes of relief h, lay l, orientation of slopes β.

The second array of input data includes the spectral features of source - lengths of waves of radiation λ, μm.

The third array includes parameters which define geometry of source and receiver: height of a radiation source H_u, km, distance between the receiver and epicenter of the source R, km, height of receiver above the surface

H_n, km, visual angle of optical device 2ξ, grad, visual angles of device of observe ($2\xi_в$ – vertical, $2\xi_г$ – horizontal angular field of view) grad, orientation of the receiver to the source of radiation (θ,φ).

The parameters of first group S_M, τ_0, χ_a and χ_M are interdependent therefore at decision of problem they are represented like functions one variable – meteorological range of visibility S_M.

For calculating the parameters of the third group (H_u, R, H_n, ξ, θ,φ) proposes to use the method of dependent tests, according to which in the calculation of optical flow in several receivers can use the same path of photons. At fixed location of the receiver of radiation a calculation is conducted with changing arguments S_M, A, h, β.

The process of radiation transfer is composed from independent "paths" of photons. This possible consider as homogeneous Markov chain states of which are a positions of particles in space of coordinates and directions [Ермаков, 1975]. Casual transition of the photon from one state to other is considered as row of casual events: reflection, scattering or absorption. End result of calculating of free path length of the photon after a new collision is mean value of desired functional [Чандрасекар, 1993]. In this task such functional can be the stream of photons at the point of the receiver. The method of local estimation of the flow of photons is proposed [Зигель, 1975] to calculate such functional. Estimation of complete flow of photons in the receiver carry out by average of statistical weight of the photon – probabilities that the photon hit in receiver – on all collisions.

$$\Phi = \frac{e^{-L(r)}\chi_{(\mu)}T_{(r)}\cos\theta_1}{2\pi r^2}, \tag{1}$$

where r – the distance between the receiver and the point of the photon interaction with environment;

$L(r)$ – optical distance passable the photon along the path r, $L(r)=\int_0^r \sigma(r)dr$;

$\sigma(r)$ – scattering index of environment;

$\chi_{(\mu)}$ – indicatrix of scattering, defined by expressions (3.6-3.7);

$T(r)$ – function of radiation transmission by atmospheric gases along the path r;

θ_1 – angle between the normal to the plane of the receiver and the direction of motion of the photon from the point of collision to the receiver.

Since the calculation is conducted under restrictions imposed by the receiver parameters (2ξ), the receiver having a round hole, the condition of getting the photon in the receiver will be determined by the type of inequality

$$\cos\theta_1 \ge \cos\xi, \tag{2}$$

for receiver with square-wave input hole - system of inequalities

$$\begin{cases} \dfrac{z_1 - z_n}{\sqrt{(x_1-x_n)^2+(y_1-y_n)^2+(z_1-z_n)^2}} \le \sin\xi_в \\ \dfrac{n_x(x_1-x_n)+n_y(y_1-y_n)}{\sqrt{(x_1-x_n)^2+(y_1-y_n)^2}} \ge cos\xi_г \end{cases}, \tag{3}$$

where, x_1, y_1, z_1 – coordinates of the photon interaction with environment;

x_n, y_n, z_n – coordinates of receiver П.

If values of F had found by expression (1), the expression for calculating the flow of radiation from source with single unit capacity of power at the point of the receiver has the following form:

$$\Phi^{*} = \frac{\sum\limits^{\{R_r\}} \Phi}{N}, \tag{4}$$

where, $\{R_r\}$ – set of points of interaction within the solid angle Ω which depends on angle of view of optical device;

N – number of modeled paths of photons.

The finding of the photon in the solid angle carries out by system of inequalities

$$\begin{aligned} &-200\text{ km} \le x \le 200\text{ km},\\ &-200\text{ km} \le y \le 200\text{ km},\\ &0\text{ km} \le z \le 80\text{ km} \end{aligned} \tag{5}$$

The task of radiation transfer in the above formulation is solved by modeling the trajectories of particles (photons). Input data for modeling are parameters describing the environment (the first group of parameters), the spectral characteristics of the source (the second group of parameters), the geometry of the source and the receiver (the third group of parameters).

Values of scattered radiation of the first and second group of parameters, as well as the height of the source H_u and the receiver H_n are defined as constants. The distance from the fire epicenter R, angle of view of the receiver 2ξ and orientation of the receiver to the source (θ, φ), as well as the height h and orientation β of slope terrain appears to be an array of variable information.

Photons enumerator provides to go to the next photon, and to control the number of calculated cycles for a given number of photons. End result is formed when all photons are checked.

The first calculated cycle begins with the choice of initial trajectories for the photon and then calculated the length of free path of photons in a given direction. In a heterogeneous environment (clear atmosphere) the length of free path of photons is determined according

$$-\ln j_4 = \frac{a}{\alpha_0 m}\left[1 + \left\{\frac{\lambda_0}{\lambda}\right\}^4\right](1 - e^{-\alpha_0 m l_{np}})e^{-\alpha_0 h_\Phi} + \frac{\text{в}\lambda_0}{\beta_0 m\lambda}(1 - e^{-\beta_0 m l_{np}})e^{-\beta_0 h_\Phi}, \tag{6}$$

where $m = cos\zeta$ – cosine of the angle ζ between the initial direction of motion of the photon and the normal to the surface of the Earth;

h_Φ – the height of the point of the photon scattering on the ground surface.

After that coordinates of the point of the photon interaction with the environment be calculated. But inside area of calculation the photon can interact with environment, for example, absorbed of atmospheric gases and the Earth, scattered on aerosol particles and the molecular environment, reflected from the Earth.

The probability that a photon is not absorbed by atmospheric gases (mainly water vapor), is characterized by function

$$T(r) = \frac{1}{1 + K_\lambda G(r, \mu_1)}, \tag{7}$$

where K_λ – spectral absorption coefficient of water vapor in the visible light spectrum $K_\lambda \approx 0$, infrared K_λ = 0,076 cm^2 / g;

$G(r,\mu_1)$ – volume of «besieged» water along the path defined by the distance *r*, and $\mu_1 = \cos(90^0 - \theta_n)$, where θ_n – polar angle of vector between the interaction point and the receiver

$$G(r,\mu_1) = G_0 \int_0^r e^{-\sigma_0 z(r,\mu_1)} dr\,, \tag{8}$$

where G_0 – concentration ratio of water vapor in the surface layer, the value of which vary widely depending on weather conditions and geographical areas. The average value of this ratio for the summer is 10 g/m^3, for the winter – 2 g/m^3, σ_0 – approximation ratio equal to 0.6 km^{-1}.

Calculation of the integral of (8) along free path of photons gives us

$$G(l_{np},m) = \frac{G_0}{\sigma_0 m} e^{-\sigma_0 Hu} (1 - e^{-\sigma_0 m l_{np}})\,, \tag{9}$$

where $m = cos\zeta$.

Volume of «besieged» water along the path from the interaction point till the receiver

$$G(r,\mu_1) = \frac{G_0}{\sigma_0 \mu_1} e^{-\sigma_0 Hn} (1 - e^{-\sigma_0 r \mu_1})\,, \tag{10}$$

Thus, by defining of function $G(r,\mu_1)$ it is possible to decrease statistical weight of the photon *Ф* by multiplying its on probability of “hit” *T*(*r*) during every part of interaction between the photon and environment.

Type of photon interaction with the environment is determined according to the condition

$$L(l_{np}) > -\ln j_\sigma\,, \tag{11}$$

where $L(l_{np})$ – optical distance passable along the length of the photon free path. If condition is not right, "albedo situation" exist. In other words, the photon can be absorbed with probability 1-*A* or be reflected with probability *A* which equivalent of terrestrial surface albedo.

In moment then the photon is absorbed *y* Earth, new photon are defined and modeled its trajectory.

After establishing the fact of crossing the path of the photon, the coordinates of the point of intersection are finding.

If a regular model of the terrain are using, coordinates (*x*, *y*, *z*) of the intersection point are searching from a set of three equations, two of which describe the motion of the photon after the last interaction point (x_0, y_0, z_0) (departure from the source) and third equation is represented by piecewise-linear approximation.

After this reflection of the photon with attention to orientation of terrain slope can be modeled: directional cosines normal $\overrightarrow{n_0}$ to the elementary surface area slope $n_{0x}, n_{0y}.n_{0z}$ are calculating, the angle between the direction of the photon moving and the normal $\overrightarrow{n_0}$ determined, indicatrix of reflection is determined.

If the photon is in the direct line of sight from the point of reflection to the receiver, functional *Ф(R)* that determine the contribution of the act of reflection in the total flow of radiation *Ф* coming into the receiver are calculated according to the formula

$$\hat{O}(R) = \frac{\chi_{\hat{\imath}\grave{o}\eth}\ (\theta_1)\grave{A}}{2\pi r^2} \exp(-L(\vec{r}))\Delta(\overrightarrow{x},\overrightarrow{x_n})\,, \tag{12}$$

where $\chi_{omp}(\theta_1)$ – indicatrix of reflection from the surface with condition of normalization $\int\limits_0^{\pi} \chi_{omp}(\theta_1)\sin\theta_1 d\theta_1 = 1$;

A – albedo into intersection point;

$\vec{r}$ – distance between intersection point and the receiver;

$\Delta(\vec{x},\vec{x_n})$ – pointer of condition of “hit” of the point into view area of the receiver. This pointer can be equal 1 if the condition is right, and 0 – in contrary.

$(\vec{x},\vec{x_n})$ – coordinates in phase space $R \times \Omega$ of points of intersections between trajectory of the photon and underlying surface or between trajectory of the photon and the receiver accordingly.

If the photon does not come into receiver after reflection, new direction of moving of the photon are determined. And new value of angle of scattering γ is selected and whole procedure of calculations of distances, orientations and angle fields are repeated.

Thus, result of one modeling cycle is the probability of getting a given number of photons $N = K$ in the receiver for the given matrixes of distances $\{R\}$, orientations $\{\theta,\varphi\}$, visual angles of the receiver $\{2\xi\}$ or $\{2\xi_{в} \times 2\xi_{г}\}$ is completed for condition $N \geq K$.

Qualitative estimation of the reliability of the developed method

Qualitative estimation of the reliability of the developed method was carried out by the way comparing received results to results by calculations based on the Monte Carlo method and based on finite-difference method of solving the transport equation.

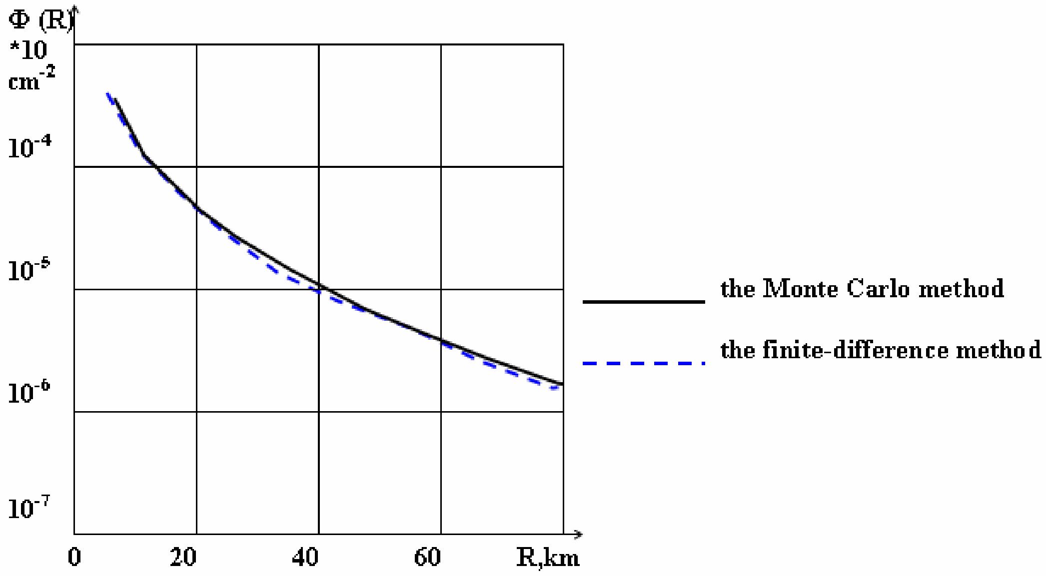

Fig. 1 Comparing received results to results by calculations based on the Monte Carlo method and based on finite-difference method.

Initial data for these calculations are: height of a radiation source H=1km, the Earth's albedo A = 0, lengths of wave of radiation λ = 0,45 μm, measuring range of distances – from 5 to 100 km, the radiation is taken from the whole upper hemisphere.

Due to fig.1 it is seen that the results in reference points at $h \to 0$ have satisfactory agreement with literature data. At the molecular atmosphere, the maximum divergence between the results is 15% for single scattering (include the two curves shown in fig. 1). Given that divergence between curves in fig. 1 obtained by different methods are varied in the same range, reference options can be considered like coordinated and responsive to the real picture of radiation transfer.

Conclusion

Proposed numerical method of calculating the characteristics of the light field, which is based on the Monte Carlo method, are well in line with probability sense of the problem. Equation of radiative transfer which solved by the Monte Carlo method, takes into account the many scattered and reflected components of radiation, allows the use of a stratified model of the atmosphere and any method of mathematical modeling of the underlying surface. Using the proposed technology for calculating the density of optical radiation as a component of geoinformation system allows simulating the spread of optical radiation fire that will enhance the effectiveness of measures to eliminate it.

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