

MONTE CARLO CALCULATION OF CHARACTERISTICS OF VISION SYSTEMS CONTAINING AN OVERCAST CLOUD LAYER

Maria A. Alekseenko, Irina Yu. Gendrina, Anna S. Kvach

National Research Tomsk State University, Lenin Avenue, 36, Tomsk, Russia

Abstract

Monte Carlo algorithms for determining of vision systems characteristics are used. The conditions with and without overcast cloud layer in the atmosphere are considered. The regression relations for simulation data are analyzed. The statistical certainty of received regressions is studied.

Key words: vision system, Monte Carlo method, the regression analysis

1. INTRODUCTION

The theory of image transfer in scattering media is based on two divisions of the modern science: linear system theory and radiative transfer theory. In particular, the linear system theory makes it possible to determine the transfer characteristics, required to describe the image transfer process. In this work, we present the calculations of the point spread function (PSF) for vision system, comprising the underlying surface, aerosol-molecular atmosphere containing overcast cloud layer, and ideal optical device. (Marchuk et al. 1976)

2. MAIN CONCEPTS OF THE LINEAR SYSTEM THEORY

Suppose that point-like mass $\delta(x - x_1, y - y_1)$, located at the point (x_1, y_1) , is an input signal of system. The resulting output signal will be the function of (x, y) and parameters $L[\delta(x - x_1, y - y_1)] = h(x, y; x_1, y_1)$. This function is called the point-impulse response or the point spread function. An arbitrary function $f(x, y)$ can be represented as a superposition (integral) of point masses

$$f(x, y) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x_1, y_1) \delta(x - x_1, y - y_1) dx_1 dy_1 \quad (1)$$

Then, the output signal (image) can be represented as:

$$g(x, y) = L[f(x, y)] = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x_1, y_1) h(x, y; x_1, y_1) dx_1 dy_1. \quad (2)$$

Obviously, regularities of the image distortion due to impact of any system can be studied by analyzing the effect of this system on the point spread function. Thus, the system is defined by two-parameter family of functions.

We will consider shift-invariant systems. A system is called shift-invariant system if a shift of the input signal leads to equal shift of the output signal, i.e., if $L[f(x, y)] = g(x, y)$, then $L[f(x - x_0, y - y_0)] = g(x - x_0, y - y_0)$. For shift-invariant systems, image of an arbitrary object is described by the formula [Papoulis]:

$$g(x, y) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x_1, y_1) h(x - x_1, y - y_1) dx_1 dy_1 = f(x, y) * h(x, y). \quad (3)$$

We will consider a system “underlying system – atmosphere – receiving device” which can be regarded as a linear system (Zuev et al. 1997). These systems are conventionally called the vision systems. Image distortion in the vision systems may be caused by the properties of scattering medium and underlying surface, and by characteristics of receiving optical device. The available images of any objects should be analyzed, and possible distortions of object images should be predicted, by studying the point spread function of this system. One of the methods for the PSF determination in this case is to calculate the angular distribution of brightness of surface-based point source, measured with receiving device at the top of the atmosphere (TOA). Change in the brightness of radiation of point source in the medium in stationary case is described by the following integro-differential transfer equation:

$$(\vec{\omega}, \text{grad } I(\vec{r}, \vec{\omega})) = -\sigma(\lambda, \vec{r})I(\vec{r}, \vec{\omega}) + \sigma_s(\lambda, \vec{r}) \int_{\Omega} I(\vec{r}, \vec{\omega}')g(\vec{r}, \vec{\omega}', \vec{\omega})d\vec{\omega}' + \Phi_0(\vec{r}, \vec{\omega}) \quad (4)$$

Here, $\vec{x} = (\vec{r}, \vec{\omega})$ is a point of phase space $X = R \times \Omega$ of coordinates $\vec{r} \in R$ and directions $\vec{\omega} \in \Omega$. $\Phi_0(\vec{r}, \vec{\omega})$ is the distribution density of sources. $I(\vec{r}, \vec{\omega})$ is the intensity (brightness) at point $\vec{x} = (\vec{r}, \vec{\omega})$.

3. PROBLEM FORMULATION AND CALCULATION SCHEME

Plain-parallel, stratified-homogeneous scattering medium is assumed in simulation. The point source of unit power is located at the bottom boundary of the medium (at the Earth's surface), and receiver is located at the top of the atmosphere at height of $h = 30 \text{ km}$ (Fig.1).

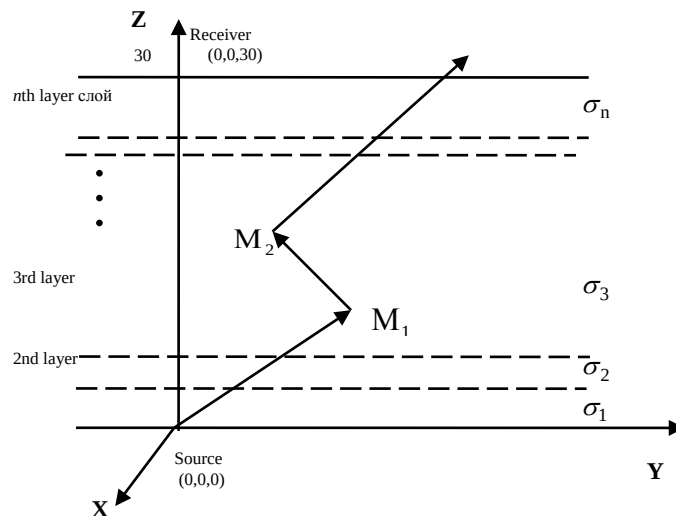


Fig.1. Schematic representation of the plane-parallel model of the atmosphere.

Two types of point source are used: isotropic and Lambertian, which differ by various distribution density.

The isotropic distribution density is $\Phi_0(\vec{\omega}) = \frac{1}{2\pi}$.

The Lambertian distribution density is $\Phi_0(\vec{\omega}) = \frac{\mu}{\pi}$. Here μ - the cosine of the angle between $\vec{\omega}$ and z -axis.

The optical model of the atmosphere implies specification of the following parameters. 1) The coefficients of aerosol scattering $\sigma_s(h, \lambda)$ and absorption $\sigma_a(h, \lambda)$. Extinction coefficient $\sigma = \sigma_s + \sigma_a$. Here, h is the height above the Earth's surface, and λ is the wavelength. The coefficients σ_s and σ_a are assumed to be piecewise constant, since the atmosphere is divided into homogeneous layers. 2) The scattering phase function $g(h, \mu, \lambda)$. Here, $\mu = (\vec{\omega}', \vec{\omega})$ is the cosine of the scattering angle. The scattering phase function is specified by dividing the atmosphere into layers, in each of which the scattering phase function is assumed to be constant with altitude h .

Two models of the atmosphere are considered: aerosol-molecular clear-sky and aerosol-molecular, containing overcast cloud layer. The first model is corresponding to the model of clear sky for midlatitude winter and summer (Krekov and Rakhimov, 1986). There are examples of these models in Table 1 presented.

Table 1. Coefficients of absorption $\sigma_a(h, \lambda)$, and extinction $\sigma(h, \lambda)$.

h , km	$\sigma(h, \lambda)$, $\lambda = 0.347$ μm	$\sigma_a(h, \lambda)$, $\lambda = 0.347$ μm	$\sigma(h, \lambda)$, $\lambda = 0.694$ μm	$\sigma_a(h, \lambda)$, $\lambda = 0.694$ μm
1	2	3	4	5
0	0.1673	0.0144	8.826E-02	5.188E-03
1	2.573E-02	2.467E-03	1.620E-02	9.005E-04
2	1.303E-02	1.48E-03	8.107E-03	5.854E-04
3	6.414E-03	7.366E-04	3.883E-03	3.224E-04
4	3.683E-03	3.941E-04	2.188E-03	1.738E-04
5	2.128E-03	2.144E-04	1.261E-03	9.464E-05
6	1.240E-03	1.193E-04	7.408E-04	5.366E-05
7	9.849E-04	7.934E-05	5.383E-04	3.548E-05
8	7.926E-04	5.463E-05	3.967E-04	2.427E-05
9	6.427E-04	3.874E-05	2.945E-04	1.698E-05
10	1.015E-03	5.258E-05	4.240E-04	2.258E-05
11	8.584E-04	5.542E-05	4.215E-04	4.473E-05
1	2	3	4	5
12	5.759E-04	2.987E-05	2.579E-04	1.291E-05
14	4.619E-04	2.265E-05	1.960E-04	9.745E-06
16	3.744E-04	1.803E-05	1.543E-04	7.698E-06
18	3.089E-04	1.556E-05	1.332E-04	6.754E-06
20	1.467E-04	6.839E-06	5.210E-05	2.905E-06
22	3.451E-05	1.702E-06	1.277E-05	7.450E-07
24	2.426E-05	1.165E-06	8.792E-06	5.143E-07
26	1.707E-05	7.967E-07	6.049E-06	3.503E-07
28	1.203E-05	5.432E-07	4.153E-06	2.360E-07
30	8.491E-06	3.706E-07	3.963E-06	1.98E-07

Another model contains the cloud layer with characteristics “Water Haze H” (Table 2) and “Cloud C1” (Table 3).

Table 2. Characteristics for Water Haze H

	$\lambda = 0,45 \mu m$		$\lambda = 0,70 \mu m$		$\lambda = 1,19 \mu m$	
h, km	σ	Single scattering albedo	σ	Single scattering albedo	σ	Single scattering albedo
0-2	0,02014	1,0000	0,009888	1,0000	0,002877	0,9999
2-12						
12-30						

Table 3. Characteristics for Cloud C1

	$\lambda = 0,45 \mu m$		$\lambda = 0,70 \mu m$		$\lambda = 1,19 \mu m$	
h, km	σ	Single scattering albedo	σ	Single scattering albedo	σ	Single scattering albedo
0-2	16,33	1,0000	16,73	1,0000	17,29	0,9994
2-12						
12-30						

One of the most universal methods for solving equation (4) is the method of imitation simulation, or the Monte Carlo method. This method is based on the integral transfer equation of the second kind with generalized kernel for the particle collision density:

$$f(\vec{x}) = \int_X k(\vec{x}', \vec{x}) f(\vec{x}') d\vec{x}' + \psi(\vec{x}).$$

Monte Carlo method is usually used to estimate linear functionals of the form (5):

$$I_\varphi = (f, \varphi) = \int_X f(\vec{x}) \varphi(\vec{x}) d\vec{x}. \quad (5)$$

If $\{\vec{x}_n\}$ is a “physical” chain of collisions, then $I_\varphi = M\xi$ где $\xi = \sum_{n=0}^N Q_n \cdot \varphi(x_n)$.

We single out two main algorithms of the Monte Carlo method.

1) The algorithm of direct simulation. This method is based on simulation of random trajectories of photon passage through the scattering medium. It is noteworthy that the characteristics of radiation process, necessary for analysis, are estimated in accordance with their physical meaning. A disadvantage of the direct simulation is that such characteristics as intensity, illumination, and others cannot be calculated with a sufficient accuracy. However, the direct simulation can be used to construct some other methods which make it possible to perform the required calculations.

One of these methods is the algorithm of local estimate.

2) Algorithm of local estimate.

The algorithm of local estimate consists of the calculation of the following functional:

$$J(\theta_i) = \int_{\theta_i} \Phi(\vec{r}^*, \vec{\omega}^*) d\vec{\omega}^* = \int_X l_i(\vec{x}', \vec{x}^*) f(\vec{x}') d\vec{x}' = M \sum_{n=0}^N Q_n \cdot l_i(\vec{x}_n, \vec{x}^*),$$

$$l_i(\vec{x}, \vec{x}^*) = \frac{\exp[-\tau(\vec{r}, \vec{r}^*)] \cdot g(\mu^*)}{2\pi |\vec{r} - \vec{r}^*|^2} \Delta_i(\vec{s}^*).$$

Here, $\vec{s}^* = \frac{\vec{r}^* - \vec{r}}{|\vec{r}^* - \vec{r}|}$, $\mu^* = (\vec{\omega}, \vec{s}^*)$. $\Delta_i(\vec{s})$ is the indicator of the region θ_i ,

$\Phi(\vec{r}^*, \vec{\omega}^*)$ is the particle flux at a preset point of the phase space $\vec{x}^* = (\vec{r}^*, \vec{\omega}^*)$.

Q_n is the particle “weight”. We do not simulate the absorption, but multiply the “weight” by the scattering probability and, namely, by the single scattering albedo. It is noteworthy that the variance decreases, and the average time of trajectory simulation on computer increases.

This algorithm is used to calculate the angular distribution of brightness, which represents the following quantity: $I(\Theta) = \frac{J(\Theta)}{\Theta}$, where Θ is the value of the corresponding to θ solid angle.

4. NUMERICAL SIMULATION RESULTS

The angular brightness distribution is obtained for various wavelengths from spectral windows. Some results for clear-sky are presented in our work (Gendrina and Kvach, 2013). The similar values for cloud containing atmosphere are offered in Table 4.

Table 4. The scattered radiation brightness for Haze H, $1/\text{m}^2 \cdot \text{steradian} \cdot \mu\text{m}$

The observation angle, grad	Wavelength, μm						
	$\lambda=0,374$	$\lambda=0,530$	$\lambda=0,694$	$\lambda=0,860$	$\lambda=1,060$	$\lambda=3,390$	$\lambda=10,60$
4,5	2,24E-05	1,67E-05	1,38E-05	1,13E-05	1,19E-05	5,55E-06	3,51E-06
13,5	1,09E-06	7,65E-07	6,60E-07	5,30E-07	4,56E-07	2,09E-07	1,43E-07
22,5	2,23E-07	1,83E-07	1,55E-07	1,39E-07	1,12E-07	4,84E-08	3,51E-08
31,5	8,44E-08	5,63E-08	5,54E-08	4,73E-08	3,85E-08	1,95E-08	1,32E-08
40,5	3,49E-08	2,73E-08	2,81E-08	6,65E-08	4,33E-08	8,70E-09	5,38E-09
49,5	1,86E-08	5,15E-08	1,54E-08	1,18E-08	9,30E-09	4,23E-09	4,59E-09
58,5	1,30E-08	1,10E-08	1,71E-08	7,75E-09	6,64E-09	3,58E-09	3,57E-09
67,5	1,94E-08	1,12E-08	7,95E-09	2,11E-08	1,73E-08	8,16E-08	6,37E-09
76,5	1,58E-07	2,13E-08	4,96E-09	3,68E-09	2,90E-09	1,99E-09	1,18E-09
85,5	1,20E-08	6,37E-09	1,23E-09	1,03E-09	1,00E-09	5,13E-11	1,16E-11

The functional dependence of brightness from atmospheric optical parameters the regression relations are obtained. The follow regression equation is considered: $y = \frac{b_1}{x} + b_0$, where y corresponds to the

brightness and λ - to the wavelength. For equation receiving is used the operation mode "Regression" from Microsoft Excel. The coefficients b_1 and b_0 for clear-sky are presented in Table 5, for cloud atmosphere – in Table 6.

Table 5. The regression coefficients for clear-sky

The observation angle, grad	b_0	b_1	Determination coefficient, R^2
4,5	1,19595E-05	3,25534E-05	0,993636438
13,5	2,31401E-07	5,05694E-07	0,976885608
22,5	6,98539E-08	1,19799E-07	0,927503534
31,5	3,92659E-08	4,04551E-08	0,784773208
40,5	2,4403E-08	1,51266E-08	0,570060008
49,5	1,39106E-08	6,51344E-09*	0,482543448
58,5	6,82884E-09	3,64745E-09	0,609744683
67,5	2,74359E-09	2,35355E-09	0,771155104
76,5	5,21933E-10	1,23544E-09	0,907220265
85,5	3,00774E-11	1,7624E-10	0,929769833

Table 6. The regression coefficients for Haze H

The observation angle, grad	b_0	b_1	Determination coefficient, R^2
1	2	3	4
4,5	3,52884E-06	7,12796E-06	0,98542826
13,5	1,08652E-07	3,63939E-07	0,997272
22,5	3,63765E-08	7,53979E-08	0,973075322
31,5	1,26022E-08	2,66418E-08	0,976384876
1	2	3	4
40,5	1,88417E-08*	9,68718E-09*	0,173678221*
49,5	3,07946E-09*	1,10407E-08*	0,367039*
58,5	3,68558E-09*	4,34001E-09	0,598507887
76,5	-3,34288E-08*	5,0401E-09	0,606097561
85,5	-2,37483E-09*	4,50822E-09	0,809969895

Comment: * implies insignificant coefficient.

The statistical evaluation of presented equations is analyzed using F-criterion and determination coefficients. It is arguable that the statistical certainty of the regression relations is no less than 90%. It may be noted that between the brightness and the wavelength exists the relation which can be described by means of hyperbolic evaluation. It is typically for almost all angles except for 40,5 and 49,5 grades. The obtained evaluations are convenient to use in algorithms for correction of satellite images.

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