Vector spherical radiative transfer model MCC++: linearization with respect to BRDF surface properties

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ABSTRACT

The radiative transfer model MCC++ employs Monte Carlo algorithms for the multiple scattering simulation and takes into account radiance polarization and the sphericity of the atmosphere. A new version of the model may simulate the arbitrary isotropic bidirectional reflectance distribution function, including cases of the polarizing reflection. This version becomes capable to calculate the derivatives (the weighting functions) with respect to the albedo and to parameters describing the polarized BRDF. Such weighting functions are used in remote sensing of atmosphere and surface properties. This paper describes shortly principles of the simulation of the reflection of underlying surface by the model MCC++ and shows examples of radiance calculation significantly influenced by the surface reflection.

1 INTRODUCTION

A few operational and planned for lunch satellite instruments measure the sunlight scattered in the atmosphere and reflected by the ground to derive Earth's atmosphere and surface properties. These include spectrometers viewing each underlying ground point from one direction per orbit (SCIAMACHY, MODIS, OMI, GOME2), as well as radiometers viewing surface from several directions (MISR, POLDER, EOSP). The single-viewing-angle instrument usually can give information on the aerosol optical thickness. To derive this quantity, measurements are analyzed using a radiative transfer model adequately simulating surface reflectance. Multi-viewing-angle measurements, especially a combination of measurements of the intensity and the polarization, allow imposing more constraints on properties of surface and aerosol ([1], [2]). The determination of surface properties requires that a radiative transfer model calculates the derivatives (the weighting functions [3]) of radiance with respect to the surface reflectance.

The radiative transfer model MCC++ [4] was developed for application in remote sensing of the atmosphere, and simulates propagation of the sunlight in a spherical atmosphere taking into account the polarization. It treats the aerosol and molecular scattering, the gas and aerosol absorption. The model employs Monte Carlo algorithms for multiple scattering simulation. A new version of the model may simulate the arbitrary isotropic bidirectional reflectance distribution function (BRDF), including cases of the polarizing reflection typical, for example, for ocean [5]. This version becomes capable to calculate derivative with respect to albedo or to parameters describing the polarized BRDF.

This paper describes shortly principles of the simulation of the reflection of underlying surface by the model MCC++ and shows examples of radiance calculation significantly influenced by the surface reflection.

2 BIDIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION

2.1 Reflectance nomenclature

The bidirectional reflectance distribution function is introduced to characterize the angular dependence in the surface reflection for the monochromatic light. The BRDF for the incident direction Θ_i (centered on the zenith angle θ_i and the azimuth angle φ) and the reflection direction Θ_r

$$\rho(\Theta_i, \Theta_r) = \frac{dI_r / d\Theta_r}{I_i \cos\theta_i} \tag{1}$$

is defined as the ratio of the reflected radiance $\frac{dI_r}{d\Theta_r}$, $d\Theta_r = \sin\theta_r d\theta_r d\varphi$, to the irradiance I_i in the incident direction Θ_i. When radiance is treated like the Stocks vectors then the polarized BRDF is represented by the Mueller matrix $\mathbf{R}(\Theta_i, \Theta_r)$

$$d\mathbf{I}_r / d\Theta_r = \cos\theta_i \mathbf{R}(\Theta_i, \Theta_r)\mathbf{I}_i \,. \tag{2}$$

For the isotropic surface, the BRDF depends only on the relative azimuth angle between the incident and reflected directions. The integration of the BRDF over all incident and reflection angles gets the surface albedo (or the reflectance from the hemisphere to the hemisphere):

$$a = \frac{1}{\pi}\int \rho(\Theta_i, \Theta_r)\cos\theta_r \cos\theta_i d\Theta_r d\Theta_i \,. \tag{3}$$

If surface appears equally bright throughout the outgoing hemisphere and the reflected light is completely depolarized it is Lambertian reflector. The BRDF of the Lambertian surface is independent on the directions of incident and reflected light beams and is proportional to the surface albedo:

$$\rho(\Theta_i, \Theta_r) = \frac{a}{\pi}, \text{ or } \mathbf{R}_{11}(\Theta_i, \Theta_r) = \frac{a}{\pi} \text{ and } \mathbf{R}_{ij}(\Theta_i, \Theta_r) = 0 \text{ if } i \neq 1 \text{ or } j \neq 1 \tag{4}$$

in the vector radiative transport theory.

2.2 Monte Carlo simulation of surface reflection

The Monte Carlo method to problems of radiative transfer regards light propagation as a Markov chain of photon collisions with particles in an atmosphere. Any energy characteristic of the radiance field can be represented as a linear functional of the collision density with an appropriate response function [6], [4]. The BRDF of the surface defines the probability density of different directions of the photon reflection.

For the Lambertian surface, the reflected direction is sampled uniformly in the azimuth and by the formula

$$\cos\theta_r = \sqrt{\xi} \tag{5}$$

for the reflection angle θ_r [6]. Here ξ is the uniformly distributed in [0,1] random number. To take into account surface albedo l, the contribution of photon must be multiplied by l after each reflection event.

For an arbitrary BRDF $\rho(\theta_i, \theta_r, \varphi)$, it is possible to use the same Markov chain, but to change the contribution of each sampled photon to the estimation by the multiplicative weight

$$w = \pi\rho(\theta_i, \theta_r, \varphi)/l \,. \tag{6}$$

This weight [6] is equal to ratio of the target reflection probability density to the sampled one. The model MCC++ uses this algorithm as well as the algorithm of the direct sampling of the BRDF angular dependence.

3 DERIVATIVES WITH RESPECT TO SURFACE PROPERTIES

3.1 Derivative with respect to albedo

Representing the BRDF by multiplication of the albedo a and the BRDF normalized to the unit albedo $\tilde{\rho}(\theta_i,\theta_r,\varphi)$: $\rho(\theta_i,\theta_r,\varphi)=a\tilde{\rho}(\theta_i,\theta_r,\varphi)$, one may concludes from Eq.(6) that the contribution of photon is multiplied by a for each reflection event. Hence, any radiance characteristic I may be represented as a sum

$$I = I_0 + \sum_{j=1}^{\infty} a^j I_j \tag{7}$$

where I_j is the same characteristic, but for photons experienced j reflections by the surface only. Therefore, to estimate the derivative of the characteristic I with respect to the albedo, one need to calculate each I_j separately and use equivalence

$$\frac{\partial I}{\partial a} = \sum_{j=1}^{\infty} j a^{j-1} I_j\ , \tag{8}$$

which follows from differentiation of Eq. (7)

3.2 Derivatives with respect to surface parameter

Let consider a BRDF $\rho(\theta_i,\theta_r,\varphi,b)$ depending non-linearly on a parameter b, and the same as above Markov chain sampled for the Lambertian surface (5). The contribution of a photon is corrected totally by the weight

$$w = \prod_{j=1}^{n} \rho\left(\theta_i^j,\theta_r^j,\varphi^j,b\right), \tag{9}$$

where n is the number of reflection from the surface. Small change db of the parameter b gives change of the weight

$$dw = k\ db\text{, where } k = \sum_{l=1}^{n}\left\{\frac{\partial\rho\left(\theta_i^l,\theta_r^l,\varphi^l,b\right)}{\partial b}\prod_{j=1,\,j\neq l}^{n}\rho\left(\theta_i^j,\theta_r^j,\varphi^j,b\right)\right\}. \tag{10}$$

Other parts of the estimation of the radiance characteristic under investigation don't depend on the parameter b. Therefore, an estimation of the derivative with respect to the parameter b may be obtained on the basis of the same Markov chain if the weights k (10) are applied to the estimation.

4 EXAMPLES OF BRDF SIMULATION

Rahman et al. [7] developed a semi-empirical model of the surface reflectance:

$$\rho(\theta_i,\theta_r,\varphi) = \gamma_0 P(\theta_i,\theta_r,\varphi)\left(1+R(\theta_i,\theta_r,\varphi)\right)\left(\frac{\cos\theta_i\cos\theta_r}{\cos\theta_i+\cos\theta_r}\right)^{\gamma_2-1}.$$

It couples a Heyey-Greenstein phase function $P(\theta_i,\theta_r,\varphi)=\frac{1-\gamma_1^2}{\left(1+\gamma_1^2+2\gamma_1\xi\right)^{1.5}}$ with asymmetry parameter γ_1 with hot-spot function: $R(\theta_i,\theta_r,\varphi)=\frac{1-\gamma_0}{1+\Delta(\theta_i,\theta_r,\varphi)}$, where $\Delta(\theta_i,\theta_r,\varphi)=\frac{1}{\pi}\left(\tan\theta_i+\tan\theta_r+\sqrt{\tan^2\theta_i+\tan^2\theta_r-2\tan\theta_i\tan\theta_r\cos\varphi}\right)$ and $\xi=\cos\theta_i\cos\theta_r+\sin\theta_i\sin\theta_r\cos\varphi$. The parameter γ_2 determines the angular spread. Fig. 1 and Fig. 2 show the Rahman BRDF and its integral reflectance.

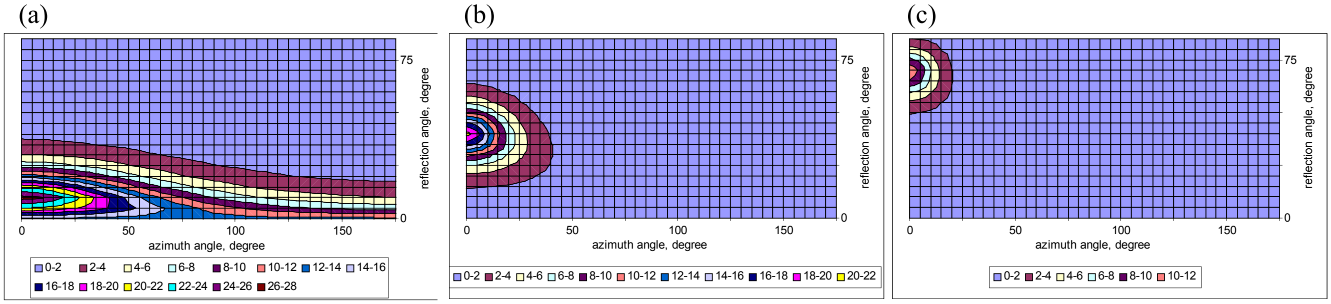
(a) (b) (c)

Fig. 1. The Rahman BRD function with parameters $\gamma_0=0.1, \gamma_1=0.8, \gamma_2=1.5$ and normalized to the unit albedo for the incident angles 10^{O} (a), 40^{O} (b), 70^{O} (c).

Fig. 3 and Fig. 4 show the modeled radiance observed from 300-km orbit above surfaces with the albedo equal to 0.2 but with the different (Lambertian and Rahman) BRDFs (Fig. 5 and Fig. 6 for albedo=0.5). The background MODTRAN aerosol model is used. The observed radiation is a mixture of light scattered in the atmosphere and light reflected from the surface. The former depends on the atmosphere scattering optical depth, the latter depends on the surface albedo. Therefore, the pattern of the BRDF is more evident at the visual wavelength and the small view nadir angle. The Earth's horizon is observer for the nadir viewing angle 73^{O} for used geometry. Apparently, for the view nadir angle equal to 70^{O} the optical depth becomes so large that it completely defines the observed radiance and the difference between the Lambertian and Rahman cases becomes invisible.

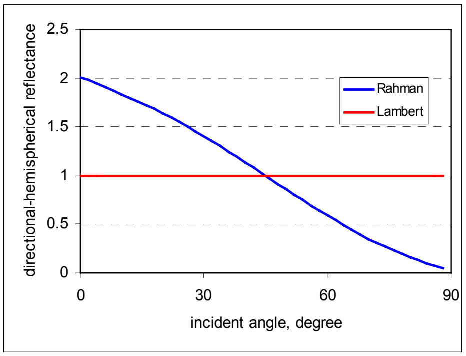

Fig. 2. The directional-hemispherical reflectance of the Rahman BRD function with parameters $\gamma_0=0.1$, $\gamma_1=0.8, \gamma_2=1.5$ and normalized to the unit albedo.

5 CONCLUSION

In this paper we shortly presented how the model MCC++ treats properties of the Earth's surface when it simulates radiative transfer in the atmosphere. The principals of Monte Carlo algorithms used in the model for the simulation of arbitrary isotropic BRDF reflection were provided, and these is illustrated with examples. Approaches to calculation of derivatives of radiance with respect to linear (albedo) and non-linear parameters simultaneously with radiance were given. The advantages of the efficiently fast calculation derivatives are manifested in remote sensing of the atmosphere and surface properties. The current version of the model becomes capable to calculate derivative with respect to parameters describing the polarized BRDF.

ACKNOWLEDGEMENTS

The work was partially supported by the Russian Foundation of Basic Researches by grant 05-05-65139.

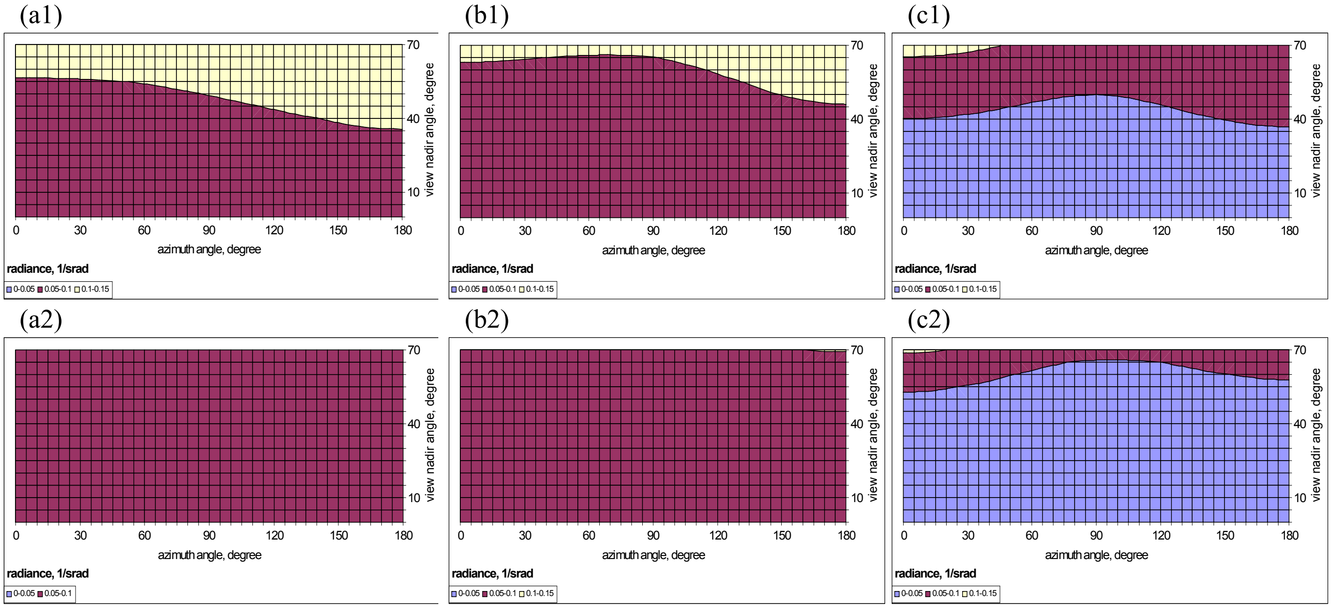

Fig. 3. The radiance reflected from the atmosphere-Earth system with the Lambertian surface for albedo=0.2 for the unit solar irradiance. Calculations for wavelengths 350 nm (row 1) and 440 nm (row 2), and the solar zenith angles 10^{O} (column a), 40^{O} (b), 70^{O} (c) are shown.

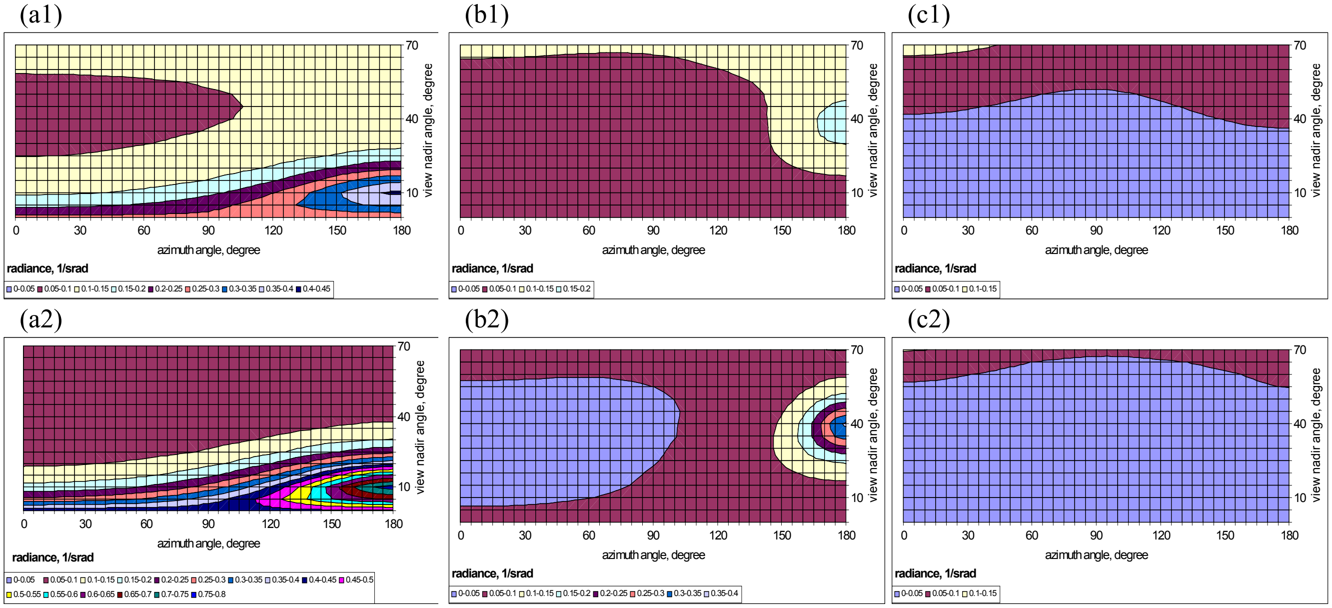

Fig. 4. The same as Fig. 3, but for the Rahman surface with parameters shown in Fig. 1 caption and albedo=0.2.

REFERENCES

[1] Chowdhary, J., B. Cairns, M. Mishchenko, L. Travis, Retrieval of aerosol properties over the ocean using multispectral and multiangle photopolarimetric measurements from the Research Scanning Polarimeter, *Geophys.Res.Lett*. 28, 243, 2001.

[2] Leroy, M., J.L. Deuze, F.M. Breon, O. Hautecoeur, M. Herman, J.C. Buriez, D. Tanre, S. Bouffies, P. Chazette, J.L. Roujean, Retrieval of atmospheric properties and surface bidirectional reflectances over land from POLDER/ADEOS, *J.Geophys. Res*. 102 17023-17037, 1997.

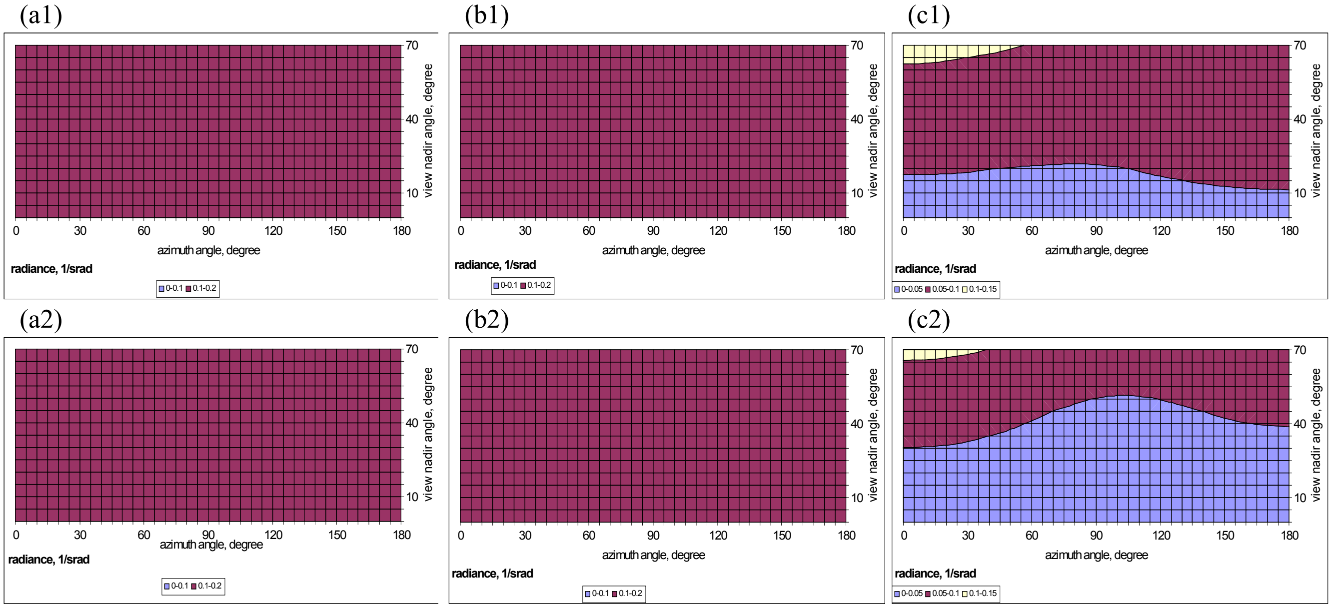

Fig. 5. The same as Fig. 3, but for albedo=0.5.

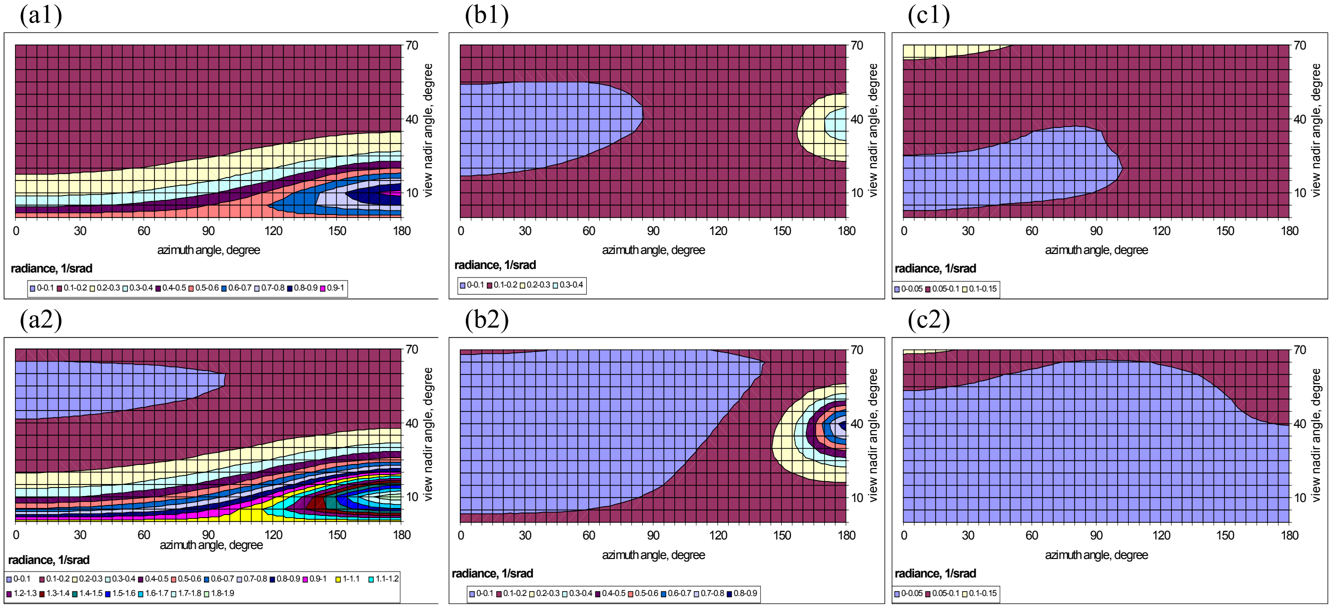

Fig. 6. The same as Fig. 4, but for albedo=0.5.

[3] Rodgers, C.D. Inverse methods for atmospheric sounding. Theory and practice. World Scientific: Singapore, 2000.

[4] Postylyakov, O.V. Linearized vector radiative transfer model MCC++ for a spherical atmosphere. *J. Quant. Spectrosc. Radiat. Transfer*, doi:10.1016/j.jqsrt.2004.01.009, 88(1-3), 297-317, 2004.

[5] Mishchenko, M. I., L. D. Travis, Satellite retrieval of aerosol properties over the ocean using polarization as well as intensity of reflected sunlight, *J.Geophys. Res.,* 102, 16989–17013, 1997.

[6] Marchuk, G.I., G.A. Mikhailov, M.N. Nazaraliev, et al. The Monte Carlo method in atmospheric optics. *Berlin-Heidelberg-New York: Springer Verlag*, 1980.

[7] Rahman, H., B. Pinty, M. Verstraete. Coupled surface atmosphere reflectance (CSAR) model: 2.Semi-empirical surface model usable with NOAA AVHRR data. *J.Geophys.Res*., 98, 20791-20801, 1993.