Linearized vector spherical radiative transfer model MCC++

O.V. Postylyakov
A.M. Obuhov Institute of Atmospheric Physics, RAS, Pyzhevsky per.3, Moscow, 119017,

Abstract. Application of radiative transfer models has shown that simulation of spectral measurements, retrieval-error analysis and development of retrieval algorithms are in need of fast computation of derivatives of radiance with respect to atmospheric constituents under investigation in addition to calculation of the radiance intensity itself. The vector spherical radiative transfer model MCC++ was linearized, that allows efficiently calculating derivatives of all elements of the Stokes vector with respect to the volume absorption coefficient and surface properties simultaneously with radiance. Application of the MCC++ model may improve treating of multiple scattering in algorithms retrieving gas, aerosol and surface properties from satellite and ground-based observations of scattered solar radiation.

Introduction

Radiative transfer in the Earth atmosphere can be simulated correctly only by a model, which takes into account its sphericity (see, for example, [*Loughman et al. 2004*]) and polarization of light (see, for example, [*Postylyakov et al. 2004b*]). It requires solution of the transfer equation in unknown vector of Stokes parameters, *I, Q*, *U*, and *V*, which jointly characterize the radiance intensity, and the degree, plane and ellipticity of the radiance polarization [*Chandrasekhar 1950*].

Furthermore, experience of treatment of optical remote sensing data manifests that calculation of the Stokes vector in itself is not enough for efficient application of radiative model, because other characteristics of radiance, requiring extensive calculation, are also used in remote sensing [*Marchuk 1964*, *Rozanov et al. 1997*]. There are three typical problems in remote sensing, which require additional characteristics of radiance field.

First, modern instruments for determination of the gas contents are spectral ones, and, therefore, forward model of an experiment is in need of calculations for large arrays of slightly differing wavelengths. The second problem is analysis of errors of retrieval of atmosphere and surface properties. Third, for interpretation of remote sensing measurement, it is most convenient to linearize forward model and to solve the raising linear retrieval problem.

Evidently, that all three noted problems require directly or indirectly calculation of derivatives of the Stokes vector with respect to atmospheric and surface properties in addition to radiance [*Postylyakov 2004c*]. A model, which solves equation in derivatives of radiance simultaneously with transfer equation in radiance, is termed linearized. Gained experience proved that a simultaneous solution of these equations can be greatly faster than the traditional algorithm of the finite difference approach based on multiple runs of a radiative model with perturbed optical properties

Five linearized radiative transfer models have been developed, two of them are vector spherical Monte Carlo models, model of Marchuk et al. [*1980*] and model MCC++ and three are non-statistical scalar plane-parallel or pseudo-spherical ones: GOMETRAN/CPI [*Rozanov et al. 1997*], LIDORT and LIRA.

This paper reviews the linearized vector spherical radiative transfer model MCC++ as well as describes features of a new version of the model.

Description of the model

The radiative transfer model MCC++ [*Postylyakov 2004a*] employs Monte Carlo algorithms [*Marchuk et al. 1980*] for multiple scattering simulation and takes into account aerosol and molecular scattering, gas and aerosol absorption. The model takes into account polarization of light and treats a spherically symmetrical (spherical-shell) atmosphere.

A new version of the model was extended to take into account the bidirectional reflectance distribution function (BRDF) of surface as well as treat Lambertian surface.

The linearization of the model MCC++ allows calculation of derivative of the Stokes vector with respect to the volume absorption coefficient in all atmospheric layers simultaneously with radiance calculation [*Postylyakov 2004b, 2004c*]. Relation of the estimated Stokes-vector derivatives with other forms of radiance derivatives: the air mass factors used in the DOAS retrieval algorithms, the weighting functions determined in the inverse problems, and the efficient layer air mass factors, was shown in paper [*Postylyakov 2004c*].

The new version of the MCC++ became capable to calculate derivatives of radiance with respect to surface properties.

The developed model efficiently uses computing time [*Postylyakov 2004a, 2004c, Loughman et al. 2004*]. Computing time of the intensity by the MCC++ model is approximately the same as of radiative models treating sphericity of the atmosphere approximately and it is significantly less than time of full spherical models had taken part in comparisons. The simultaneous calculation of all derivatives (i.e. with respect to absorption in all model atmosphere layers) and the intensity is only 1.2-2 times longer than the calculation of the intensity only.

The MCC++ model has been validated against other models for different geometries, including comparisons of polarization and calculation of *derivatives [Postylyakov et al. 2001*, *Postylyakov 2004a*, *Loughman et al. 2004*]. The comparisons were overviewed in paper [Postylyakov 2004c].

Examples of calculation of derivatives

Two examples of calculation of the efficient layer air mass factors (LAMFs) (see [*Postylyakov 2004a, 2004c*]) by the vector model MCC++ are shown in Figs. 1 and 2. Measurements of a limb-viewing satellite instrument at 600 nm for the line of sight (LOS) with the tangent height equal to 40 km was modeling. Two shown cases correspond to almost completely polarized and almost completely unpolarized scattered light: the relative azimuth angles (RAA) in the LOS tangent point between direction to the Sun and direction to the instrument are equal to 89^{O} and 179^{O}, accordingly. The sphericity of the atmosphere is significant in both cases, because the solar zenith angle (SZA) at the tangent point is equal to 85^{O}. The statistical accuracy (standard variation) of the intensity calculation is 0.1%.

(a)

(b)

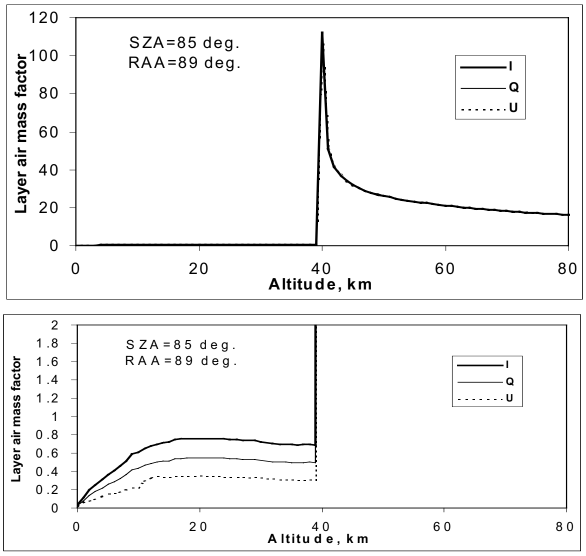

Figure 1. The efficient layer air mass factors for three Stokes parameters *I, Q*, and *U*. A limb-viewing observation at 600 nm with the LOS tangent height 40 km, SZA=85^{O} and RAA=89^{O}. The same functions are shown at different scales in (a) and (b).

(a)

(b)

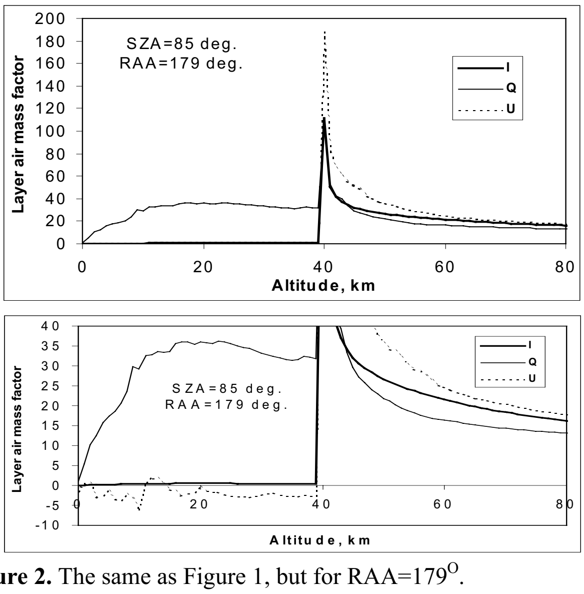

Figure 2. The same as Figure 1, but for RAA=179^{O}.

The LAMFs are significantly differing in two cases. In case of RAA=89^{O}, the LAMFs for different Stokes parameters, *I*, *Q*, and *U*, are practically coincide. They are slightly different only below the LOS, where they are completely determined by multiple scattering. In case of RAA=89^{O}, the LAMF of the intensity I is similar to the LAMF of the first case. But the LAMF of *Q* is significantly differ from the *I* ones below the LOS, and the LAMF of *U* is large at and above the LOS.

Conclusion

A new version of the MCC++ model became capable to calculate derivatives of radiance with respect to surface properties and was extended to take into account the BRDF of surface. Application of the MCC++ model may improve accuracy of multiple scattering simulation in algorithms retrieving gases and aerosol from satellite and ground-based observations of scattered solar radiation (see, for example, *Postylyakov et al.* [*2004a*], [*2004c*], *Ugolnikov et al.* [*2003*]) .

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