A COMPARISON OF RADIATION TRANSFER ALGORITHMS FOR MODELING OF THE ZENITH SKY RADIANCE OBSERVATIONS USED FOR DETERMINATION OF STRATOSPHERIC TRACE GASES AND AEROSOL

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ABSTRACTS

A preliminary comparison of radiative transfer codes applicable to the algorithms of the gas and aerosol profile retrieval from skylight measurements performed at solar zenith angles of about 90^O was carried out. There are compared codes of the Monte Carlo simulation, a code of successive orders of scattering, and a code based on the Combined Differential-Integral approach involving the Picard Iterative Approximation (CDIPI). For solar zenith angles from 0^O to 93^O and wavelengths 311, 332, 450 and 800 nm, the results obtained with different codes agree with accuracy of a few percent. For solar zenith angles larger than 94^O, a qualitative agreement of three codes is obtained. For these angels agreement better than 5% between the Monte Carlo and the CDIPI codes was received in all cases for atmosphere without aerosol.

1. INTRODUCTION

Observations of the zenith-sky radiance by ground-based UV/visible spectrometers and visible polarimeters are capable of giving the vertical distributions of important trace gases and aerosol in the atmosphere. Such UV observations at solar zenith angles from 75^O to 90^O are used in the short Umkehr method for ozone profile determination [*Elansky et. al 1999*]. Measurements in the visual spectral range at solar zenith angles from 84^O to 96^O are used in the differential twilight methods for measurement of the NO2, O3, BrO, OClO stratospheric contents and profiles, as well as in the polarization twilight method for aerosol profile determination [*Postylyakov et al. 2000*]. For measurements made at high solar zenith angles a single scattering radiation transfer (RT) code can give only 30-80% of the measured radiance. So modern retrieval algorithms begin to use multiple scattering RT codes.

In this work, a preliminary comparison of different codes applicable to the algorithms of the gas and aerosol profile retrieval from skylight measurements at solar zenith angles of about 90^o is given.

2. RADIATIVE TRANSFER MODELS

The comparison involves Monte Carlo vector (noted as vP) and scalar (sP) codes (Postylyakov), a scalar code (sN&B) of successive orders of scattering (Nikolaishvili and Belikov), and a scalar code (sR) implementing CDIPI technique (Rozanov).

Monte Carlo code was developed for spherically symmetrical atmosphere. It was used in two versions [*Marchuk et al., 1980*]. The method of conjugate walk was used for calculations at angles from $z=0^O$ to $z=93^O$ at UV wavelengths and for all zenith angles at visual wavelengths. The method of double local estimation was used for UV at angles $z>93^O$, where it have better convergence. This code was developed on C++ and its earlier version used algorithms of code published in paper of *Marchuk et al.*[*1980*] and FORTRAN code of S.A. Uhinov [*Elansky et al., 1991*].

Method of successive orders of scattering was developed for a numerical solution of the radiance transfer problem in the spherical homogeneous atmosphere irradiated by a plane homogeneous flux of monochromatic light. The model is based on the numerical solution of the integral equation of radiative transfer [*Belikov et al., 2000*]. To construct a finite-difference approximation of the initial integral equation, the dependence of its solution on one of four independent variables (which can be called as an azimuth angle) is represented approximately by a trigonometric interpolation polynomial. For other independent variables the three-dimensional grid of points is formed up and a system of finite-difference equations with respect to coefficients of the trigonometric polynomial at the points of the difference grid is constructed. These equations are solved by a method of successive approximation.

The sR code used a new radiative transfer model (CDIPI) suitable to calculate the radiation field in a spherical planetary atmosphere. The suggested approach involves the Picard iterative approximation to solve the radiative transfer equation in its integral form. The radiation field calculated by solving the integro-differential radiative transfer equation in a pseudo-spherical atmosphere is used as an initial guess for the iterative scheme.[*Rozanov et al., 2001*]

3. OPTICAL MODELS OF ATMOSPHERE

Standardized optical models of the spherical-homogeneous atmosphere were developed for the comparison. The models determine integrated contents of gases, aerosol and Rayleigh in each altitude layer of the atmosphere. The vertical distributions of atmospheric components inside the layers vary from a code to another. For the vP and sP codes, spices are distributed uniformly within each layer. For the sN&B and sR codes, it was taken that spice concentrations increase linearly with height.

The comparison in the UV spectral range used optical model of the atmosphere described at [*Petropavlovskih et al., 1998*]. For comparison at zenith angles large than z=90^{O} this optical atmosphere model was expanded up to 200 km by pure Rayleigh scattering.

For visual wavelengths the distribution of aerosol microphysical characteristics was taken in accordance with the model [*WMO 1986*]: industrial aerosol below 2.5 km, continental aerosol from 2.5 km to 10 km, and stratospheric aerosol above 10 km. Thickness of the layers was equal 0.5 km below 20 km, 2 km - from 20 km to 30 km, 5 km - from 30 km to 60 km and 10 km from 60 km to 200 km. The calculations were carried out for pure Rayleigh scattering and atmosphere with background aerosol.

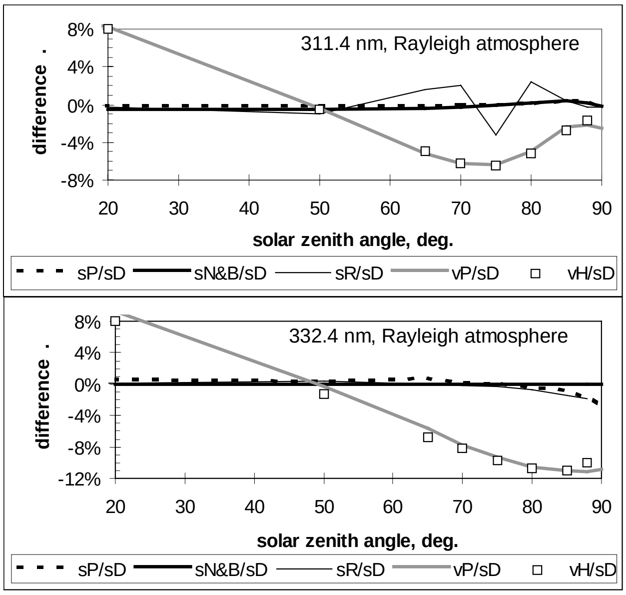

Fig.1. Relative differences between intensities of zenith-sky calculated by different RT codes. A Rayleigh scattering and ozone absorption (350 DU) are taken into account.

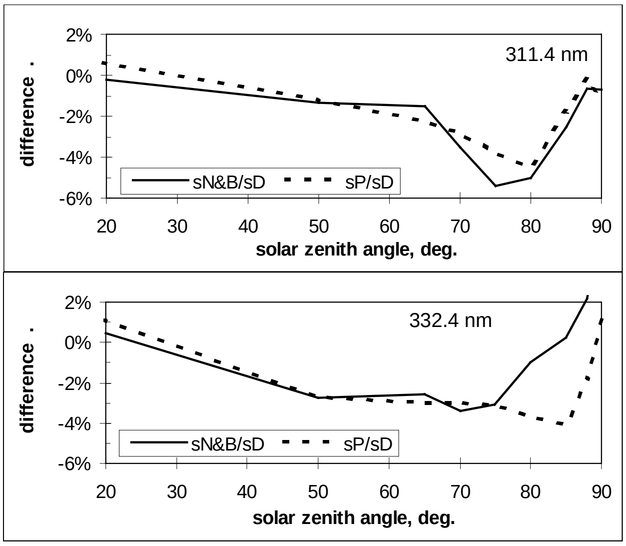

Fig.2. Relative differences between intensities of zenith-sky calculated by different RT codes. Rayleigh, aerosol and ozone (350 DU) are taken into account.

4. RESULTS AT ULTRAVIOLET WAVELENGTHS

Figures 1 and 2 present the results of computations for wavelengths of 311.4 and 332.4 nm. The figures show, analogous to comparison of *Petropavlovskih et al.*, [*1998*], the normalized difference between the computed radiation and Dave's pseudo-scalar code [*Dave, 1978*] (noted as sD): $\frac{\text{code} - \text{sD}}{\text{sD}}$. Computations performed with the improved sN&B code, with the sP and the sR codes comply well one with another and with other complete spherical codes of the previous comparison for zenith angles from 0^O to 90^O. A distinction between the vector vP code and scalar codes is characterized by features considered in the above-mentioned paper. For reference, in Figure 1, the values obtained with the vector code (vH) of *Herman*, [*1995*], which previously provided a high accuracy, are given. The deviations resulted from this code are taken from the article [*Petropavlovskih et al., 1998*].

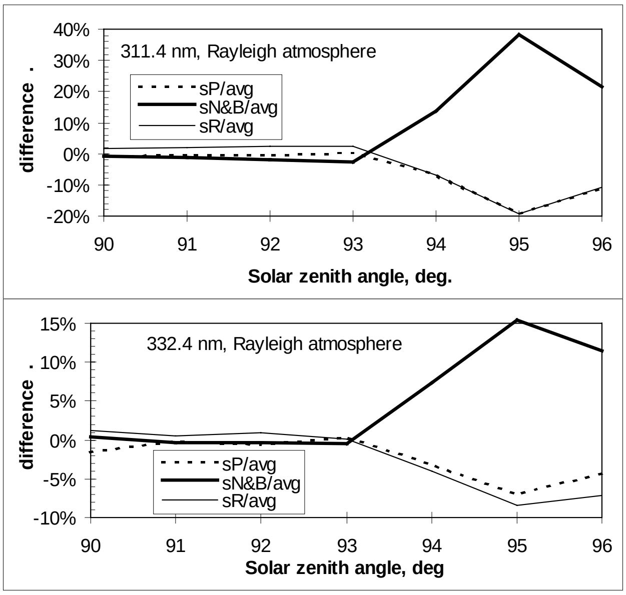

Fig.3. Relative differences between intensities of zenith-sky calculated by different RT codes. A Rayleigh scattering and ozone absorption (350 DU) are taken into account.

Figure 3 presents the relative differences between result of each code and calculation averaged over all three codes: $\frac{\text{code - avg}}{\text{avg}}$. In the angular range from 90^O to 93^O, a good correlation of all codes is obtained. For angles larger than 93^O, the differences between sN&B and two other codes increase to several tens percent.

5. RESULTS AT VISUAL WAVELENGTHS

Agreement between all models is very good at visual wavelengths for pure Rayleigh atmosphere (see Figures 4 and 5). Only at z=96^O the difference between codes reaches 4-6%. The reason of such differences could be enhanced steps for height grid above 60 km.

Figures 6 and 7 give relative differences between results of sN&B and sP codes: $\frac{\text{sN \& B - sP}}{\text{sP}}$ for atmosphere with aerosol. For solar zenith angles up to 93^O, the results obtained with these two models differ

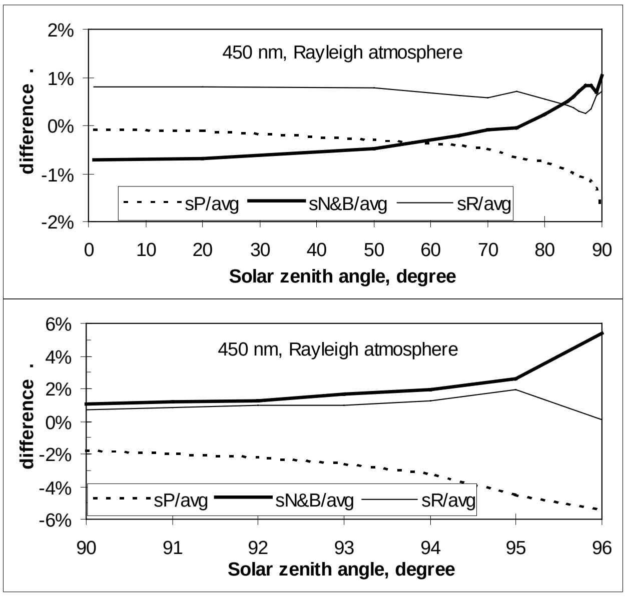

Fig.4. Relative differences between intensities of zenith-sky calculated by different RT codes at 450 nm. Rayleigh scattering is taken into account.

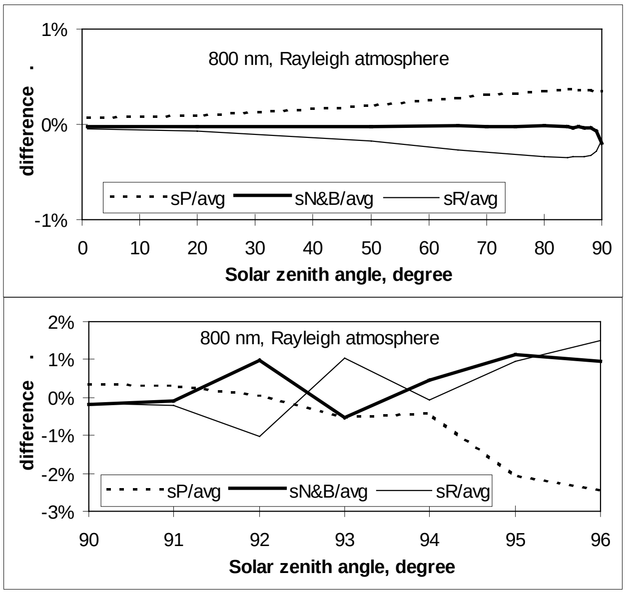

Fig.5. Same as Fig.4 but for 800 nm.

within 6%. However, this difference is somewhat greater than a similar difference obtained for the UV spectral region. This result is evidently associated with the use of another optical atmosphere model with enhanced steps for height grid above 30 km and grid of the scattering matrix corresponding to an angles near 90^O. For solar zenith angles from 94^O to 96^O, two models give results differing up to 15-20%. Two versions of sP code (the method of conjugate walk and the method of double local estimation) agree better than 0.3% for angles from 90^{O} to 96^{O}.

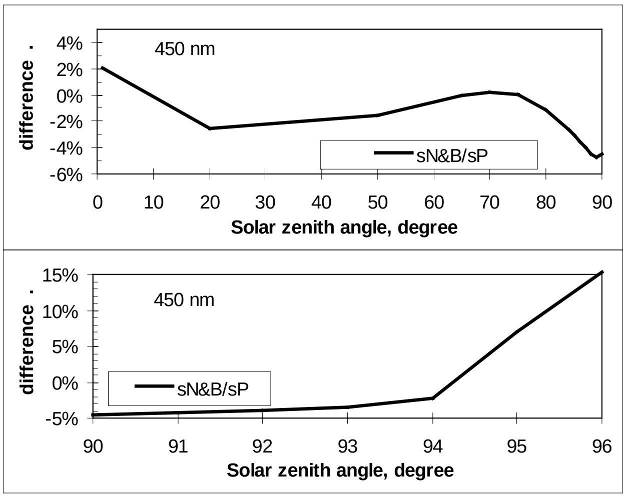

Fig.6. Relative differences between intensities of zenith-sky calculated by different RT codes at 450 nm. Rayleigh scattering and aerosol are taken into account.

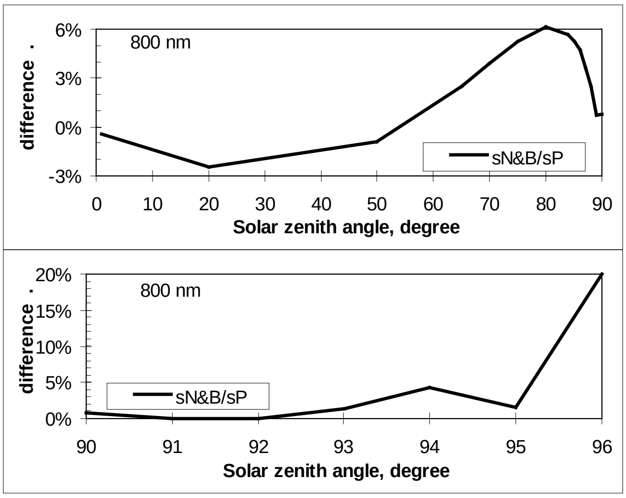

Fig.7. Same as Fig.6 but for 800 nm.

6. CONCLUSION

Compared codes of the radiance transfer show good agreement for solar zenith angles from 0^{O} to 93^{O} and wavelengths from 311 to 800 nm. As a rule, the difference does not exceed several percent and it can be evidently explained by a distinction in inside-layer spicy distributions and technique of the aerosol phase function modeling.

For solar zenith angles larger than 93^{O} agreement better than 4-6% was received between the Monte Carlo and the CDIPI codes for atmosphere without aerosol at all wavelengths. The compared code of successive orders of scattering coincides well to other codes for this optical model at visual wavelengths, but essentially differs for UV wavelengths. Since only two codes took part in the comparison for atmosphere with aerosol, it is impossible to determine conclusively what causes a discrepancy up to 15-20% at 96^{O} in this case. However, we can conclude that for the range of solar zenith angles large than 94^{O}, both models give qualitatively coincident results.

ACKNOWLEDGEMENT

This work was supported by Russian Foundation of Basic Researches, grant #98-05-64922 and by ISTC, project #1328.

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