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# Analytical algorithm for modeling polarized solar radiation transfer through the atmosphere for application in processing complex lidar and radiometer measurements

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ABSTRACT

Inversion algorithms and program packages recently created for processing data of the ground-based radiometer spectral measurements along with lidar multi-wavelength measurements are extremely multiparametric. Therefore, it is very important to develop an efficient program module for computations of functions modeling measurements by a sun-radiometer in the inversion procedure. In this paper, we present the analytical version of such efficient algorithm and analytical code on C++ designed for performance of algorithm testing. The code computes multiple scattering of the Sun light in the atmosphere. Data output are the radiance and linear polarization parameters angular patterns at a preselected altitude. The atmosphere model with mixed aerosol and molecular scattering is given approximately as the homogeneous atmosphere model. The algorithm testing has been carried out by comparison of computed data with accurate data obtained on the base of the discrete-ordinate code. Errors of estimates of downward radiance above the Earth surface turned out to be within 10%–15%.. The analytical solution construction concept has taken from the scalar task of solar radiation transfer in the atmosphere where an approximate analytical solution was developed. Taking into account the fact that aerosol phase functions are highly forward elongated, the multi-component method of solving vector transfer equations and small-angle approximation have been used. Generalization of the scalar approach to the polarization parameters is described.

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## 1. Introduction

Necessity to process data of ground-based integrated sun-radiometer and lidar measurements requires methods and programs oriented on large data level being developed. Recently, the algorithm of consecutive inversion of spectral sun-radiometer data and multi-wavelength lidar data was elaborated [1]. A little later the synergetic inversion algorithm and code were proposed [2]. These computational tools are extremely multiparametric, especially the synergetic algorithm. The synergetic algorithm inverts data of two instruments in parallel, that is, in single iterative inversion procedure. It simultaneously estimates all unknown parameters of aerosol model including aerosol size distribution, particles shape and complex refractive index, that are retrieved from measurements by sun-radiometers [3,4] and in addition aerosol vertical profiles provided by lidars. Increase of a number of determined

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parameters entails increase many times of the volume of calculations. Taking this into account, we have initiated development of an analytical version of the program module “Direct atmospheric task” used to compute functions modeling measurements by a sun-radiometer and their derivatives in the inversion procedure. The analytical subprogram will provide saving computational resource and accelerate computer run, what is very important for automatic processing data bulk of observations in the networks [4–6].

At present, many nice codes are used to find parameters of the radiation scattered in the Earth atmosphere. They are grounded on the numerical methods of the radiative transfer problem without and with polarization inclusion and give highly accurate values of computed radiation parameters. Information about widely used numerical methods, algorithms and codes for solving the direct atmospheric task can be found, for example, in the books and surveys [7–12]. Also, the efforts to simplify a procedure of the transfer equation solution and to minimize computation time have led to development of approximate analytical approaches for determination of the radiation parameters in the atmosphere. High-usage methods are the classical ones [13–19]: the asymptotic solutions, variants of two-stream and four- stream approaches, Eddington and delta – Eddington approximations and the like.

In this paper our goal is to present results obtained while developing the analytical algorithm and code for computations of solar radiation multiple scattering in the atmosphere with mixed aerosol and molecular scattering and for simulation of radiometer measurements data. The second goal is to show results of the algorithm testing. The accuracy check has been fulfilled by means of comparison of data computed on the base of analytical code with results of computations by the discrete-ordinate code earlier developed by the research group from Laboratory of optics of the atmosphere (LOA) of Lille University 1 (France) [20].

In Section 2 of this report the principles of construction of the analytical algorithm are described at length. In Section 2.1, brief description of the used models is given; the optical parameters of homogeneous atmosphere model with mixed aerosol and molecular scattering are specified. Section 2.2 presents the equations of vector theory where the sought quantities are three Stokes parameters, or three elements of the first column of Green's matrix, which are the complete set of solar radiation parameters in the atmosphere. Use of the azimuth Fourier series and the Generalized spherical functions (GSFs) expansions is the first step in performance solutions of the vector equations. In Section 2.3 referred to as “Structure of solution” we describe cutting-off the peaks of two highly elongated forward phase functions made in accordance with the multicomponent method [21]. Reformulation of the medium optical parameters on the score of cutting-off the phase functions peaks is the subject of Section 2.6.

Section 2.4 along with Appendix A are devoted to description of solution of the transfer equation defining radiance that has the phase function without the small-angle peak. It has been built on the analytical approximation that was earlier developed within the scalar task of radiation transfer in planetary atmospheres [22,23]. Specifically, the scalar approximation has been used for the radiance zero harmonic and generalized to all others.

Note essence of the analytical solution of the scalar radiative transfer equation (RTE). It determines the first order scattering exactly and higher orders scattering approximately, by the expression obtained from the RTE with the phase function approximated by the sum of two first terms of its expansion in the Legendre polynomials. The approximate expression results from integration in $\tau$ after giving the Eddington solution for the radiance as the first approximation. The radiance angular distribution in the atmosphere, so defined, is quite acceptable if the parameter of phase function asymmetry $g \leq 0.5$.

Also note, based on this technique, in [24], processing data of laboratory measurements by a photometer of tissue samples optical properties was implemented. The computation scheme there was modified for inclusion of two flat reflecting surfaces which model walls of cuvette. This fact proves that the chosen analytical solution is suitable for processing measured data.

In Section 2.5, analogous determination of the multiple scattered parts of polarization parameters is explained. The final schemes to compute the parts of multiple scattering of the both radiance and polarization parameters are described in Section 2.6 and Appendix B. The total computation scheme that is obtained after adding the solutions parts of single scattering is given in Section 2.7. Note, very close analytical solution in the case of pure Rayleigh atmosphere was reported in [25]. The solution for Rayleigh law of scattering from [25] can be considered as a prototype of the computation scheme for mixed aerosol and Rayleigh scattering presented here. In Section 2.8 we introduce the factor earlier proposed within the scalar theory [26], which is aimed to raise the radiance estimates accuracy.

In Section 3 results of testing the algorithm are displayed. In the figures presented, the radiance angular patterns obtained from the analytical code are given in comparison with the accurate ones provided by the discrete-ordinate code [20]. Summary is given in Section 4.

Difference between vector and scalar approximate analytical solutions should be emphasized. In actual fact, the approximate approach of scalar problem, above outlined, was developed merely for the radiance zero harmonic. The first azimuth Fourier harmonic, which was also included into the scalar solution, was dealt with in the single scattering approximation. As opposed to the scalar method, the solutions of the vector equations (after cutting off the phase functions peaks) represent the sums of the zero ($j=0$), first ($j=1$), and second ($j=2$) azimuth Fourier harmonics, not only the zero and first ones. Each summand in turn is expressed through the series in the GSFs with the maximal Polynomial's number $l=2$. The allowance for the terms $l=2$ and $j=2$ provides solutions transition to the case of scattering governed by the Rayleigh matrix [25] as the aerosol optical thickness (AOT) tends to a zero.

In difference to the scalar method, in the solutions of vector equations the multiple scattering is included into all terms of Green's matrix elements. It is described by

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