Journal of Quantitative Spectroscopy & Radiative Transfer 107 (2007) 479–507

Journal of Quantitative Spectroscopy & Radiative Transfer

www.elsevier.com/locate/jqsrt

A successive order of scattering code for solving the vector equation of transfer in the earth's atmosphere with aerosols

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Received 9 October 2006; received in revised form 14 March 2007; accepted 14 March 2007

Abstract

The paper presents in detail a code developed to solve the vector equation of radiative transfer. It is based on the successive orders of scattering and on the expansion into Fourier series of the azimuth; it includes the polarizing effects of aerosol scattering and of reflectance by water or terrestrial surfaces. The code is available from the authors upon request, and this detailed description aims at helping potential users to adapt the code to their own problem. Some examples of applications are given.

Keywords: Radiative transfer; Aerosols; Polarization; Successive scatterings

1. Introduction

In this paper, we present in some detail a radiative transfer (RT) code, developed over the years, at the Laboratoire d'Optique Atmosphérique (LOA) of Lille University. It includes a complete treatment of polarization due to aerosol scattering, and Earth's surface reflectance, and relies on the method of successive orders of scattering (OS); limited and simpler versions of the code are available and can be used.

The extraterrestrial solar radiation reaching the Earth's atmosphere is scattered by the air molecules and by the various solid and liquid particles (clouds, aerosols); it is also absorbed by gas molecules in several specific wavelength bands. The scattered radiation partly reaches the surface, and is partly reflected to space. In what follows we limit ourselves to the cloudless atmosphere, and outside the absorption bands with a line structure, as water vapor or carbon dioxide. Therefore we consider only scattering by air molecules and by aerosols; where necessary, we can easily include a continuum gas absorption like ozone absorption. We also assume the Earth's atmosphere to be plane-parallel, i.e. the characteristics vary only along the vertical direction.

The transfer of radiation inside the atmosphere is governed by the equation of transfer (ET), based on the conservation of energy, and allowing the calculation of radiance, and after angular integration, the calculation of irradiance; this so-called scalar ET remains very useful for many problems. However, as the scattering

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0022-4073/$ - see front matter
doi:10.1016/j.jqsrt.2007.03.010

process modifies the state of polarization, the scalar ET is only approximate, and can lead to errors on the radiance reaching about 10% for a molecular atmosphere. Moreover the polarization of the scattered radiation contains in itself important information on the characteristics of the scattering particles, and it is used for improving aerosol remote sensing.

Numerous methods have been developed for solving the ET, both in the scalar and in the vector forms. A description of the methods, with a large list of references up to 1985, can be found in the collective book edited by Lenoble [1] under the auspices of the Radiation Commission of IAMAS. Since then, research has remained active, generally leading to numerical codes, and there are now several radiative transfer (RT) codes freely available to the users. Among the most popular, one can mention Libradtran [2], DISORT [3], TUV [4], Adding [5]; other RT models are presented in [6,7], and this list is far from being exhaustive. Most of these codes are big modular codes, tending to be as complete as possible and covering various kinds of problems, including longwave radiation. Even trying to be users' friendly, these big codes are not always easy to implement and some users take them as black boxes, without understanding how they operate. The recent research concerns mostly more complex problems. Important progress is presently made in designing 3-D codes necessary to handle real non uniform clouds [8]; other 3-D models are developed for twilight [9], and limb [10] observations.

Our code concerns the limited and somewhat simple probem of shortwave solar radiation in 1-D cloudless atmosphere. Its objective is analyzing radiation measurements, understanding the contribution of aerosol scattering and absorption, and of Earth's surface reflectance. The code allows the simultaneous introduction of several aerosol models with different characteristics and different profiles. It also offers the choice of different reflectance laws, for land and water surfaces.

The available modular codes are certainly very useful in some cases, however we did not find them a satisfactory solution to our own problems, and this was the first reason for starting this work. We believe that for many problems, at least the simple ones, it is much more efficient to write directly a code specifically designed for the problem considered. With a good knowledge of the radiative transfer theory, i.e. of the theoretical basis of the code, and only an elementary knowledge of a programming language, this is not a too demanding task. A variant of this approach is to use a code as ours, with the information included in this paper, in order to adapt the code to the user's specific problem. Our objective is not to provide the users' community with a new big code, competing with other codes already available, but to transmit our own experience in writing a RT code.

The code described here combines the expansion of the optical properties into generalized Legendre functions, with a Fourier expansion in the azimuth. This code is flexible and easy to use; it is available in different versions in FORTRAN, and it has been used successfully, by ourselves and by some other users for different problems.

In Section 2, we recall the theoretical basis of the code with the necessary definitions in Section 2.1; the polarization is most easily characterized by the four Stokes parameters defined in Section 2.2. The phase matrix, which characterizes the single scattering (including polarization) of the molecules and particles is presented in Section 2.3, with the necessary information on the aerosol phase matrix. Section 2.4 establishes the exact vector ET, to be used for obtaining the correct value of the radiance, as well as information on the polarization characteristics; the scalar ET is a special case of this vector ET. Section 3 is devoted to the method of successive orders of scattering (OS) and Section 4 presents the development of the ET and of the phase matrix into Fourier series, as it can be used in most of the ET solution methods. Section 5 adds the possibility of a reflecting lower boundary, as snow, water, or vegetation. According to our objective, we have tried to present the basis of the code as completely as possible, even if some points are classical and can be found elsewhere. The paper is therefore expected to be self-consistent. Finally, Section 6 presents some examples of applications of the OS codes developed at LOA for different problems, as remote sensing of aerosols and analysis of surface ultraviolet spectral irradiance; detailed results are not shown, as they are available in published papers; references are given. Conclusions are presented in Section 7.

2. Theoretical basis

In this section, we present the theoretical basis necessary for understanding our code; although most of these notions are classical, we think useful for the reader to have them summarized in a complete and consistent manner.