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Microwave radiative transfer intercomparison study for 3-D dichroic media

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Abstract

Three different numerical methods capable of solving the radiative transfer of microwave radiation within 3-D dichroic media are compared. A case study, represented by an intense rain shaft populated by perfectly oriented oblate raindrops, is analysed in detail, including a discussion of the behaviour of all four Stokes components.

Results demonstrate an acceptable agreement between all Monte Carlo methods. The method based on a discrete ordinates scheme agrees only qualitatively with the Monte Carlo outputs. Because of its lower computational cost the backward Monte Carlo technique based on importance sampling represents the most efficient way to face passive microwave radiative transfer problems related to optically thick 3-D structured clouds including non-spherical preferentially oriented hydrometeors.

Keywords: Microwave radiative transfer; 3-Deffects; Dichroic media; Polarization

1. Introduction

The interaction of microwave radiation with clouds and precipitation has been studied for decades. The physical process is adequately described by the vector radiative transfer equation (*VRTE* hereafter) (for details see [1,2]), that can be solved with many different methodologies, a review of which is provided by Mätzler [3]. Only very recently techniques have been developed to numerically solve the radiative transfer equation for the full Stokes vector in 3-D environment in the presence of non-isotropic media [4–7]. The latter condition frequently occurs in nature because large atmospheric hydrometeors like falling raindrops, snow and other ice crystals, tend to have non-spherical shapes and prefer horizontal orientations. Thus falling precipitation represents a dichroic medium and polarization effects can play an important role. Moreover the combination of scattering effects, the large spatial variation of the precipitating hydrometeors in the atmosphere (compared to sensor footprints) and the partly reflecting properties of the surface puts weight on the consideration of

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three dimensional effects in microwave radiative transfer as well (for an overview of 3-D issues in the *MW* region see [8]).

Although many benchmark results are available for RT within multilayered 1-D media (see [9–12]) or 3-D [4,7,13–16], up to now there are no benchmark results for 3-D scenes in presence of dichroic material, and no intercomparison studies have been carried out among codes that have these capabilities.

In this work, we consider a single 3-D scenario involving non-spherical hydrometeors perfectly oriented in the horizontal plane. The *RT* computations in the *MW* region are performed by different models and the outputs are compared and discussed.

2. Methods to solve the vector radiative transfer equation

The VRTE for monochromatic or quasi-monochromatic radiative transfer is generally written in its integro-differential form as:

$$\frac{\mathrm{d}\mathbf{I}(\vec{r},\hat{s})}{\mathrm{d}r} = -\langle \mathbf{K}(\vec{r},\hat{s})\rangle \mathbf{I}(\vec{r},\hat{s}) + \langle \mathbf{a}(\vec{r},-\hat{s})\rangle B[T(\vec{r})] + \int \mathrm{d}\Omega' \langle \mathbf{Z}(\vec{r},\hat{s},\hat{s}')\rangle \mathbf{I}(\vec{r},\hat{s}'), \tag{1}$$

where $\mathbf{I}(\vec{r},\hat{s}) = [I,\ Q,\ U,\ V]^{\mathrm{T}}$ is the four element column vector of radiances (Stokes vector) evaluated at position $\vec{r}$ in direction $\hat{s}$, $\langle \mathbf{K}\rangle$ is the total extinction matrix, $\langle \mathbf{a}\rangle$ is the total absorption vector, B is the Planck function, $\langle \mathbf{Z}\rangle$ is the total phase matrix, T is the temperature of the medium and dr is a path-length increment. All quantities implicitly depend on the frequency v of the radiation. Eq. (1) can also be expressed in the integral form:

$$\mathbf{I}(\vec{r}_1,\hat{s}) = \mathcal{O}(\vec{r}_0,\vec{r}_1)\mathbf{I}(\vec{r}_0,\hat{s}) + \int_{\vec{r}_0}^{\vec{r}_1} \mathcal{O}(\vec{r},\vec{r}_1) \left[\underbrace{\langle \mathbf{a}(\vec{r},-\hat{s})\rangle B[T(\vec{r})]}_{\text{emission}} + \underbrace{\int \mathrm{d}\Omega' \langle \mathbf{Z}(\vec{r},\hat{s},\hat{s}')\rangle \mathbf{I}(\vec{r},\hat{s}')}_{\text{scattering}} \right] \mathrm{d}r, \tag{2}$$

where $\mathcal{O}(\vec{r}_0,\vec{r}_1)$ is the evolution operator from point $\vec{r}_0$ to point $\vec{r}_1$. For a homogeneous path it is given by

$$\mathcal{O}(\vec{r}_0,\vec{r}_1) = \exp[-\langle \mathbf{K}(\hat{s})\rangle \Delta r], \tag{3}$$

where $\hat{s}$ is the direction specified by $\vec{r}_0 - \vec{r}_1$, and $\Delta r = |\vec{r}_0 - \vec{r}_1|$.

Several methods for numerically solving the *VRTE* for a scattering and emitting atmosphere as required for the *MW* region, are extensively described in the literature in books like Liou [17]; Chandrasekhar [18]; Thomas and Stamnes [19]; Tsang et al. [1,20]; Lenoble [21]; Goody and Young [22] or in reviews like Haferman [2]; Gasiewski [23]; Mätzler [3]. In this work, we consider three techniques of solving the 3-D *VRTE*: a backward Monte Carlo, a forward Monte Carlo (with importance sampling), and a discrete ordinate iterative model. A brief description of the three methodologies is provided hereafter together with the essential references.

2.1. Backward Monte Carlo (ARTS-MC)

The ARTS Monte Carlo (ARTS-MC) scattering module offers an efficient method for polarized radiative transfer calculations in arbitrarily complex 3-D cloudy cases. The ARTS-MC algorithm is described in detail in Davis et al. [6]. The algorithm solves the integral form of the VRTE, given in Eq. (2), by applying Monte Carlo integration with importance sampling (MCI). The algorithm may be pictured as tracing a large number of photons backwards from sensor, in randomly selected multiply scattered propagation paths to either their point of emission, or entry into the scattering domain. Davis et al. [6] gives a full description of the probability density functions used to determine these propagation paths. This physical picture is identical to the backward–forward Monte Carlo (BFMC) algorithm described by Liu et al. [16]. However, BFMC does not account for dichroism, which is correctly accounted for in ARTS-MC by importance sampling, where every Stokes vector contribution is properly weighted according to its probability density. ARTS-MC also utilizes MCI for convolving the simulated Stokes vector with a 2-D antenna response function, for the detailed simulation of remote sensing observations.