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vSmartMOM: A vector matrix operator method-based radiative transfer model linearized with respect to aerosol properties

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In this paper, we build up on the scalar model smartMOM to arrive at a formalism for linearized vector radiative transfer based on the matrix operator method (vSmartMOM). Improvements have been made with respect to smartMOM in that a novel method of computing intensities for the exact viewing geometry (direct raytracing) without interpolation between quadrature points has been implemented. Also, the truncation method employed for dealing with highly peaked phase functions has been changed to a vector adaptation of Wiscombe's delta-*m* method. These changes enable speedier and more accurate radiative transfer computations by eliminating the need for a large number of quadrature points and coefficients for generalized spherical functions.

We verify our forward model against the benchmarking results of Kokhanovsky et al. (2010) [22]. All non-zero Stokes vector elements are found to show agreement up to mostly the seventh significant digit for the Rayleigh atmosphere. Intensity computations for aerosol and cloud show an agreement of well below 0.03% and 0.05% at all viewing angles except around the solar zenith angle (60°), where most radiative models demonstrate larger variances due to the strongly forward-peaked phase function.

We have for the first time linearized vector radiative transfer based on the matrix operator method with respect to aerosol optical and microphysical parameters. We demonstrate this linearization by computing Jacobian matrices for all Stokes vector elements for a multi-angular and multispectral measurement setup. We use these Jacobians to compare the aerosol information content of measurements using only the total intensity component against those using the idealized measurements of full Stokes vector $[I, Q, U, V]$ as well as the more practical use of only $[I, Q, U]$. As expected, we find for the considered example that the accuracy of the retrieved parameters improves when the full Stokes vector is used. The information content for the full Stokes vector remains practically constant for all azimuthal planes, while that associated with intensity-only measurements falls as we approach the plane perpendicular to the principal plane. The $[I, Q, U]$ vector is equivalent to the full Stokes vector in the principal plane, but its information content drops towards the perpendicular plane, albeit less sharply than I-only measurements.

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1. Introduction

Sanghavi et al. [38] demonstrated the linearization of a scalar radiative transfer model based on the matrix

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operator method. In the present work, we briefly outline the formalism for the vectorization of the matrix operator method as also shown previously by Liu and Ruprecht [24] and Hollstein and Fischer [19]. Additionally, we provide a formalism for the linearization of the vector model with respect to aerosol optical and microphysical parameters. We have named the resulting linearized vector radiative transfer model "vSmartMOM"(*v*ectorized *S*imulated *m*easurement of the *a*tmosphere using *r*adiative *t*ransfer based on the *M*atrix *O*perator *M*ethod). Other radiative transfer methods that have been used for this purpose include the method of discrete ordinates [41], the Gauss–Seidel method [18] and the Markov chain formalism [45].

While intensity-only measurements have driven early aerosol remote-sensing missions [43,7,31], it has been found that the use of only the intensity component I of the Stokes vector $\mathbf{I}=[I,Q,U,V]$ is insufficient for constraining the aerosol inverse problem. The information content of a measurement is considerably enhanced by the use of multispectral and multi-angular observation strategies. However, it has been shown that the inclusion of the Stokes vector elements Q and U (V is generally too small to measure reliably) can better constrain aerosol retrievals from remote-sensing measurements [27,4]. This has spurred new missions incorporating polarimetry in addition to multispectral and multi-angular observations [28,42] as well as new retrieval algorithms developed to take full advantage of the information content of the measurements [8,17].

Sanghavi et al. [38] were motivated by a need to find a speedy and an accurate method for computing the Jacobian matrix necessary for optimized retrieval of aerosol and surface parameters from a multi-angular, multispectral satellite instrument like the Multi-angle Imaging SpectroRadiometer (MISR) [7]. The present work develops a similar framework for the Stokes vector $\mathbf{I}$ rather than only the component I.

We present the vector radiative transfer formulation of the matrix operator method in Section 2. We use benchmark results from [22] to verify our computations, as presented in Section 3. Our vector formulation differs from our previous work, in that we adapt the delta-m truncation method [44] for vector radiative transfer instead of using the more arbitrary delta truncation method [1] that we followed in Sanghavi et al. [38]. The vector form of the delta-m method has been implemented into radiative transfer codes previously by Rozanov and Kokhanovsky [37,41,32,26], however, we attempt to provide a more complete explanation in the form of a rigorous derivation in Appendix A. Also, in order to eliminate error due to interpolation between quadrature points, we have enhanced the conventional method of direct raytracing (which uses the solar and/or viewing zenith angles as quadrature points carrying zero weight) by making use of two sets of Radau quadrature points (see Appendix B). The Jacobian matrix for the full Stokes vector is defined in Section 4. The linearization of the vector formulation of the radiative transfer equation is based on employing the chain rule of differentiation to obtain the derivative of the forward model. This has been summarized in Appendix C. We set up an aerosol-laden atmospheric scenario in Section 5.1 to demonstrate both the forward model and the results of linearization with respect to aerosol optical and microphysical parameters in Sections 5.2 and 5.3, respectively. The gain in information afforded by use of the full Stokes vector compared to using only intensity measurements is quantified in Section 5.4.

2. The matrix operator method

The matrix operator method or discrete space theory was first developed by Grant and Hunt [14,15]. It allows for an exact and a speedy computation of the radiative transfer of turbid media, especially because of its encapsulation of the infinite series of reflections into a single matrix inversion [23]

$$(\mathbf{E}-\mathbf{X})^{-1}-\mathbf{E}=\mathbf{X}+\mathbf{X}^2+\mathbf{X}^3+\cdots, \tag{1}$$

where $\mathbf{X}$ is a matrix representing a pair of consecutive reflections between two layers and $\mathbf{E}$ is the identity matrix. This eliminates the issue of slow convergence for weakly absorbing atmospheres, i.e., at high values of single scattering albedo, $\overline{\varpi}_0\rightarrow 1$, that are faced by several other methods. Also, there is minimal loss of computational speed for increasing optical thicknesses, making it suitable for simulating aerosols and clouds alike. MOM can generate the entire radiative field for a given scenario, both internal and at the boundaries of the atmosphere, for isotropic as well as anisotropic scatterers, and hence can be used for the simultaneous computation of intensities measured using different viewing geometries. This makes it ideal for the simulation of backscattered light measured by a multi-angle instrument like MISR aimed at quantifying the aerosol content of the atmosphere.

2.1. Vector formalism

For macroscopically isotropic media, the following equation describes monochromatic, one-dimensional vector radiative transfer for an infinitesimal layer in a plane–parallel atmosphere [3]:

$$\begin{aligned}\mu\frac{\mathrm{d}\mathbf{L}(\overline{\tau},\mu,\phi;\mu_0,\phi_0)}{\mathrm{d}\overline{\tau}} &= -\mathbf{L}(\overline{\tau},\mu,\phi;\mu_0,\phi_0)+(1-\overline{\varpi}_0)\mathbf{B}(T)\\ &\quad+\frac{\overline{\varpi}_0}{4\pi}\overline{\mathbf{Z}}(\mu,\phi;\mu_0,\phi_0)\mathbf{S}_0\exp(-\overline{\tau}/\mu_0)\\ &\quad+\frac{\overline{\varpi}_0}{4\pi}\int_0^{2\pi}\int_{-1}^{1}\overline{\mathbf{Z}}(\mu,\phi;\mu',\phi')\mathbf{L}\\ &\quad\times(\overline{\tau},\mu',\phi';\mu_0,\phi_0)\,\mathrm{d}\mu'\,\mathrm{d}\phi'\end{aligned} \tag{2}$$

where $\mathbf{L}(\overline{\tau},\mu,\phi;\mu_0,\phi_0)$ represents the Stokes vector of diffuse light propagating along the direction (μ,ϕ) at an optical depth $\overline{\tau}$ in an atmosphere that can have two sources of light: the incident solar flux represented by the Stokes vector $\mathbf{S}_0$ incident along the direction (μ_0,ϕ_0) and the thermal radiation $\mathbf{B}(T)=B(T)[1,0,0,0]^{\mathrm{T}}$, where $B(T)$ is Planck's function at temperature T. $\overline{\mathbf{Z}}(\mu,\phi;\mu',\phi')$ is the phase matrix which governs the scattering of the Stokes vector incident along (μ',ϕ') in the direction (μ,ϕ) with respect to the local meridian plane [20]. We compute $\overline{\mathbf{Z}}(\mu,\phi;\mu',\phi')$ using the formalism presented by Siewert [39]. (The over-score in the above equation is used to denote quantities averaged over different contributing

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