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Radiative transfer models for retrieval of cloud parameters from EPIC/DSCOVR measurements

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ABSTRACT

In this paper we analyze the accuracy and efficiency of several radiative transfer models for inferring cloud parameters from radiances measured by the Earth Polychromatic Imaging Camera (EPIC) on board the Deep Space Climate Observatory (DSCOVR). The radiative transfer models are the exact discrete ordinate and matrix operator methods with matrix exponential, and the approximate asymptotic and equivalent Lambertian cloud models. To deal with the computationally expensive radiative transfer calculations, several acceleration techniques such as, for example, the telescoping technique, the method of false discrete ordinate, the correlated *k*-distribution method and the principal component analysis (PCA) are used. We found that, for the EPIC oxygen A-band absorption channel at 764 nm, the exact models using the correlated *k*-distribution in conjunction with PCA yield an accuracy better than 1.5% and a computation time of 18 s for radiance calculations at 5 viewing zenith angles.

1. Introduction

The Earth Polychromatic Imaging Camera (EPIC) on board the Deep Space Climate Observatory (DSCOVR) was designed to measure the atmosphere and surface properties over the whole sunlit face of the Earth from the Lagrange point L_1 (a gravity-neutral position at 1.5×10^6 km away from the Earth). DSCOVR is placed in a Lissajous orbit around the L_1 point, and provides a unique angular perspective at almost backward direction with scattering angles approximately between 168° and 176° (Fig. 1). EPIC scans the entire sunlit face of the Earth at a 2048×2048 pixel resolution, with a pixel size of 12×12 km^2 at the image center. The instrument has 10 spectral channels ranging from the ultraviolet to the near-infrared. Four of them are located in the oxygen A- and B-bands: two absorption channels centered at 688 nm and 764 nm with bandwidths of 0.8 nm and 1.0 nm, respectively, and two continuum channels centered at 680 nm and 780 nm with bandwidths of 3.0 nm and 2.0 nm (Table 1). These channels are used for monitoring the vegetation condition [1], the aerosol layer height and optical depth [2], and the cloud height [3].

The radiative transfer for retrieval of cloud parameters involves, in addition to cloud scattering and absorption, gas absorption and molecular Rayleigh scattering. Usually, it is necessary to consider spectral regions containing several overlapping lines with intensities varying over many orders of magnitude. An accurate method for computing the radiative transfer in a molecular atmosphere relies on line-by-line (LBL) calculations. However, LBL calculations are in most cases too computationally expensive to be used directly in online and even sometimes in offline retrieval algorithms. This prompts us to use exact or approximate radiative transfer models endowed with acceleration techniques. As approximate models, asymptotic [4–6] and equivalent Lambertian cloud models [7–9] are frequently used. In the category of acceleration techniques we include here the correlated *k*-distribution method [10,11], the radiance sampling method [12], the optimal spectral mapping method [13] and dimensionality reduction techniques. In the latter case, principal component analysis (PCA) is used to map the spectral radiances into a lower-dimensional subspace in which the inversion is performed [14,15], or to reduce the dimensionality of the optical properties [16–18]. In addition, the telescoping technique [19,20] and the method of false discrete ordinate [21–24] can be used to speed up radiative transfer calculations.

For the EPIC instrument, the retrieval is more challenging due to the singular geometry of the radiative transfer problem. Given a particle with a certain size, the scattering phase function shows considerable structure and resonances. When averaged over a size distribution of an ensemble of particles, these features are almost smoothed out, but they are still present in the backward and forward glories, at scattering angles around 180° and 0°, and in the rainbow region, at around 140° [25]. For an accurate description of the specific features of the single scattering properties in the back-

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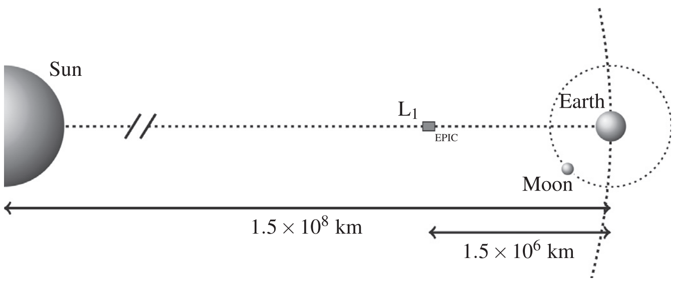

Fig. 1. Illustration of EPIC / DSCOVR geometry (distances are not to scale).

Table 1
Description of EPIC channels, adapted from EPIC's main website (https://epic.gsfc.nasa.gov/epic).

Channel	Central wavelength / nm	Full width / nm	Primary application
1	317.5 ± 0.1	1.0 ± 0.2	Ozone, sulfur dioxide
2	325.0 ± 0.1	2.0 ± 0.2	Ozone
3	340.0 ± 0.3	3.0 ± 0.6	Ozone, aerosols
4	388.0 ± 0.3	3.0 ± 0.6	Aerosols, clouds
5	443.0 ± 1.0	3.0 ± 0.6	Aerosols, clouds
6	551.0 ± 1.0	3.0 ± 0.6	Aerosols
7	680.0 ± 0.2	3.0 ± 0.6	Aerosols, clouds, vegetation
8	687.75 ± 0.20	0.80 ± 0.20	Aerosols, clouds, vegetation
9	764.0 ± 0.2	1.0 ± 0.2	Cloud height
10	779.5 ± 0.3	2.0 ± 0.4	Clouds, vegetation

ward direction, a large number of discrete ordinates is required, even when the delta-M method [26] is used.

The aim of this paper is to analyze the accuracy and efficiency of several radiative transfer models in regard to their applicability to the retrieval of cloud parameters from EPIC measurements. The radiative transfer models, relying on the matrix exponential formalism and endowed with acceleration techniques, include the exact discrete ordinate and matrix operator methods, as well as the approximate asymptotic and equivalent Lambertian cloud models. By "exact" methods, we mean those models used as the starting point to design approximate models by imposing further assumptions.

The paper is organized as follows. In Section 2 we present the exact and approximate radiative transfer models. In Section 3 we summarize the acceleration techniques, focusing on the description of a combined method incorporating the correlated k-distribution and PCA. In Section 4 we analyze the accuracy and efficiency of the radiative transfer models for simulated EPIC measurements in the oxygen A-band absorption channel. Conclusions are formulated in Section 5. Some specific features of the radiative transfer models are outlined in the appendices. Here, we give the main computation formulas of the discrete ordinate and matrix operator methods with matrix exponential, justify the equivalent Lambertian cloud model, and describe the telescoping technique.

2. Radiative transfer models

The radiative transfer equation for the diffuse radiance $I(r, \mathbf{\Omega})$ at point r and in the direction $\mathbf{\Omega} = (\mu, \varphi)$ reads as

$$\mu\frac{\mathrm{d}I}{\mathrm{d}r}(r,\mathbf{\Omega}) = -\sigma_{\mathrm{ext}}(r)I(r,\mathbf{\Omega}) + F_0\frac{\sigma_{\mathrm{sct}}(r)}{4\pi}P(r,\mathbf{\Omega},\mathbf{\Omega}_0)\mathrm{e}^{-\tau_{\mathrm{ext}}^0(|\mathbf{r}-\mathbf{r}_{\mathrm{TOA}}|)} + \frac{\sigma_{\mathrm{sct}}(r)}{4\pi}\int_{4\pi}P(r,\mathbf{\Omega},\mathbf{\Omega}')I(r,\mathbf{\Omega}')\,\mathrm{d}\Omega', \tag{1}$$

where σ_{ext} and σ_{sct} are the extinction and scattering coefficients, respectively, F_0 is the incident solar flux, P the scattering phase function, $\mathbf{\Omega}_0 = (-\mu_0, \varphi_0)$ with $\mu_0 > 0$ the incident solar direction, and $\tau_{\mathrm{ext}}^0(|\mathbf{r}-\mathbf{r}_{\mathrm{TOA}}|)$ the solar optical depth between a generic point $\mathbf{r}$ and the characteristic point at the top of the atmosphere $\mathbf{r}_{\mathrm{TOA}}$ in a spherical atmosphere. The formalism is pseudo-spherical, i.e. the multiple-scattering is treated in a plane–parallel atmosphere, while the solar-beam attenuation is computed in a spherical atmosphere [27]. For the phase function P, we consider the conventional expansion in terms of normalized Legendre polynomials P_n, i.e.

$$P(r,\mathbf{\Omega},\mathbf{\Omega}') = P(r,\cos\Theta) = \sum_{n=0}^{\infty} c_n\chi_n(r)P_n(\cos\Theta), \tag{2}$$

where $c_n = \sqrt{(2n+1)/2}$ and $\cos\Theta = \mathbf{\Omega}\cdot\mathbf{\Omega}'$. The radiative transfer equation (1) is subject to the top-of-atmosphere boundary condition ($r = r_{\mathrm{TOA}}$),

$$I(r_{\mathrm{TOA}},\mathbf{\Omega}^-) = 0, \tag{3}$$

and the surface boundary condition ($r = r_{\mathrm{s}}$),

$$I(r_{\mathrm{s}},\mathbf{\Omega}^+) = F_0\frac{A}{\pi}\mu_0\rho(\mathbf{\Omega}^+,\mathbf{\Omega}_0)\mathrm{e}^{-\tau_{\mathrm{ext}}^0(|\mathbf{r}_{\mathrm{s}}-\mathbf{r}_{\mathrm{TOA}}|)} + \frac{A}{\pi}\int_{2\pi}I(r_{\mathrm{s}},\mathbf{\Omega}^-)|\mu^-|\rho(\mathbf{\Omega}^+,\mathbf{\Omega}^-)\,\mathrm{d}\Omega^-, \tag{4}$$

where A and ρ are the surface albedo and the normalized bi-directional reflection function, respectively, and the notations $\mathbf{\Omega}^+$ and $\mathbf{\Omega}^-$ stand for upward and downward directions, respectively.

In the discrete ordinate method, we assume a cosine–azimuthal expansion of the diffuse radiance ($\varphi_0 = 0$),

$$I(r,\mathbf{\Omega}) = \sum_{m=0}^{\infty} I_m(r,\mu)\cos m\varphi, \tag{5}$$

and for each azimuthal component $I_m(r, \mu)$ we discretize the radiative transfer equation in the angular domain by considering a set of Gauss–Legendre quadrature points and weights $\{\mu_k, w_k\}_{k=1}^{M}$ in the interval (0, 1); thus, M is the number of discrete ordinates per hemisphere. The atmosphere is discretized in N levels: $r_1 = r_{\mathrm{TOA}} > r_2 > \cdots > r_N = r_{\mathrm{s}}$, and a layer j, bounded above by the level r_j and below by the level r_{j+1}, has the geometrical thickness $\triangle r_j = r_j - r_{j+1}$. The extinction and scattering coefficients as well as the phase function coefficients are assumed to be constant within each layer; their average values in layer j are $\sigma_{\mathrm{ext}j}$, $\sigma_{\mathrm{sct}j}$ and χ_{nj}, respectively. Also, we must require the intensity to be continuous across the layer interfaces. In layer j, we are led to the linear system of differential equations

$$\frac{\mathrm{d}\mathbf{i}_m}{\mathrm{d}r}(r) = \mathbf{A}_{mj}\mathbf{i}_m(r) + \mathrm{e}^{-\tau_{\mathrm{ext}}^0(|\mathbf{r}-\mathbf{r}_{\mathrm{TOA}}|)}\mathbf{b}_{mj}, \quad r_{j+1} \le r \le r_j, \tag{6}$$

where (the abbreviation "not" stands for a notation definition)

$$\mathbf{i}_m(r) = \begin{bmatrix}\mathbf{i}_m^+(r)\\ \mathbf{i}_m^-(r)\end{bmatrix} \overset{\text{not}}{=} [\mathbf{i}_m^+(r);\mathbf{i}_m^-(r)]^{\mathsf{T}} \tag{7}$$

is the radiance vector in the discrete-ordinate space, and $[\mathbf{i}_m^{\pm}(r)]_k = I_m(r, \pm\mu_k)$, $k = 1, \ldots, M$. The layer matrix $\mathbf{A}_{mj}$ has a block structure

$$\mathbf{A}_{mj} = \begin{bmatrix}\mathbf{A}_{mj}^{11} & \mathbf{A}_{mj}^{12}\\ -\mathbf{A}_{mj}^{12} & -\mathbf{A}_{mj}^{11}\end{bmatrix}, \tag{8}$$

with entries

$$[\mathbf{A}_{mj}^{11}]_{kl} = \frac{1}{2\mu_k}\left[w_l\sigma_{\mathrm{sct}j}p_{mj}(\mu_k,\mu_l) - 2\sigma_{\mathrm{ext}j}\delta_{kl}\right], \tag{9}$$

$$[\mathbf{A}_{mj}^{12}]_{kl} = \frac{1}{2\mu_k}w_l\sigma_{\mathrm{sct}j}p_{mj}(\mu_k,-\mu_l), \tag{10}$$

while the entries of the layer vector $\mathbf{b}_{mj} = [\mathbf{b}_{mj}^+;\mathbf{b}_{mj}^-]^{\mathsf{T}}$ are given by

$$[\mathbf{b}_{mj}^{\pm}]_k = \pm\frac{1}{\mu_k}(2-\delta_{m0})\frac{F_0}{4\pi}\sigma_{\mathrm{sct}j}p_{mj}(\pm\mu_k,-\mu_0), \tag{11}$$