

Highlights

- A radiative transfer simulator for EPIC onboard DSCOVR is developed.
- The simulator is used to perform sensitivity study of cloud remote sensing.
- The ultraviolet channel 388 nm can be used to assist cloud top height retrieval.
- The oxygen absorption bands can be used to increase the cloud masking confidence.

Cloud remote sensing with EPIC/DSCOVR observations: a sensitivity study with radiative transfer simulations

Meng Gao^a, Peng-Wang Zhai^{b,*}, Yuekui Yang^c, Yongxiang Hu^d

^aSSAI/NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Greenbelt, MD, USA

^bJCET/Department of Physics, University of Maryland Baltimore County, Baltimore, MD, 21250, USA

^cNASA Goddard Space Flight Center, Climate and Radiation Laboratory, Greenbelt, MD, USA

^dMS 475 NASA Langley Research Center, Hampton, VA 23681-2199

Abstract

The Earth Polychromatic Imaging Camera (EPIC) onboard the Deep Space Climate Observatory (DSCOVR) views nearly the whole sunlit face of the Earth with 10 spectral bands ranging from the UV to the near-infrared, including two oxygen absorbing bands centered at 764 nm (A-band) and 687.75 nm (B-band). Clouds are among the primary remote sensing targets using EPIC images because of their important impacts on the Earth's radiation budget. In order to facilitate the EPIC cloud data product development, we have built a radiative transfer simulator featuring flexible cloud microphysical parameters, gas absorptions, and the instrument line shape functions for each EPIC band. The radiative transfer simulator is used to explore the sensitivity of EPIC observations on liquid-phase cloud microphysical parameters, including optical depth, geometric thickness, and cloud top height. We found that the ratios of the reflectances in the oxygen A and B bands to their respective continuum measurements can be used to increase the confidence level of cloud masking over scenes with sun-glint. In addition, the 388 nm band can be used to differentiate low and high clouds with the uncertainty of roughly 2-3 kilometers. Combining this information with the oxygen absorp-

*Corresponding author

Email address: pwzhai@umbc.edu (Peng-Wang Zhai)

tion bands, the cloud geometric thickness can be obtained with the rough uncertainty of 3-4 km.

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1. Introduction

The Earth Polychromatic Imaging Camera (EPIC) onboard the Deep Space Climate Observatory (DSCOVR) acquires at least 9-12 images of the sunlit side of the Earth daily from the first Lagrange point (L1) of the Sun-Earth orbit, which is approximately 1.5 million km from the Earth [1]. The EPIC bands cover wavelengths from UV (317.5 nm, 325 nm, 340 nm, and 388 nm), visible (443 nm, 551 nm, 680 nm, and 687.75 nm) and near infrared (764.0 nm, and 780 nm), which have important science applications in the remote sensing of the total column ozone, aerosol index, and UV reflectance at the Earth's surface [2]; SO_2 [1], clouds [3, 4, 5, 6], vegetation [7], and detection of horizontally oriented ice plates [7].

Cloud masking is among the highest priorities of the numerous applications of the EPIC images including atmospheric correction [8], aerosol remote sensing [9], ocean color [10], just to list a few. Cloud masking over sun glint is a challenging task as sun glint is very bright and a thin cloud layer above it may reduce or increase the reflectance at the top of the atmosphere (TOA) depending on the viewing geometry. This makes simple reflectance threshold methods unreliable [11, 12]. Improvements of cloud masking have been made by using infrared bands [13], which unfortunately are not available in EPIC bands. A reliable cloud mask algorithm over sun glint is especially important for EPIC data processing because it occupies a significant portion of each image.

Cloud optical depth (COD), cloud top height (CTH), and cloud geometric thickness (CGT) are among the primary remote sensing parameters, which are critical to climate modeling [14]. It is relatively straight forward to retrieve COD from EPIC visible bands [7]. Yang et al. [3] explored the possibility of retrieving both CTH and CGT using the different photon path length distribution in the oxygen A and B bands. Davis et al. [4, 5] later demonstrated that only one variable in CTH and CGT can be retrieved from the EPIC oxygen A and B bands after considering the instrument noise.

Radiative transfer theory suggests that the strong wavelength dependence of Rayleigh scattering can be used to retrieve CTH [15]. In this sense, the UV bands are most sensitive to CTH as larger CTH decreases the amount of molecular scattering, which are prominent in this wavelength range. The possibility of retrieving CTH with the EPIC UV bands is not explored yet in the literature.

In order to facilitate the algorithm development for cloud remote sensing, we have developed a radiative transfer simulator for the EPIC measurements. The details of the simulator is described below in Sec. 2. The simulator can be used to perform sensitivity study of retrieving different parameters from the EPIC images. In particular, we have used this simulator to study the possibility of retrieving CTH using the EPIC 388 nm band, which in turn can be used as an input to the oxygen A and B band lookup tables for retrieving CGT [3]. Moreover, we have studied the possibility of performing cloud masking over sun glint using R_{abs}/R_{ref} , where R stands for reflectance measured by EPIC, and the subscript *abs* refers to the oxygen A (centered at 764 nm) or B (centered at 687.75 nm) bands, and *ref* represents the continuum band centered at 780 nm or 680 nm paired with the oxygen A or B bands, respectively. Both sensitivity studies are important for improving the cloud data products for EPIC observations [6] and have not been done before.

This paper is organized as follows. Sec. 2 describes the radiative transfer simulator for EPIC. In Sec. 3 the simulator is used to calculate the ratio of R_{764}/R_{780} for a hypothetical hydrosphere (no land surface) to explore the possibility of cloud masking using the oxygen A band. Sec. 4 shows the sensitivity of the EPIC measurement at 388 nm to the CTH variation. We summarize the results in Sec. 5.

2. Radiative transfer simulator for EPIC

The EPIC simulator is built upon a radiative transfer model, which is based on the successive order of scattering (SOS) method [16, 17, 18, 19]. The radiative transfer model solves multiple scattering of monochromatic light in the atmosphere and surface system. The formulas of the SOS method is physics based which provide more insights on how each order of scattering contributes to the total radiance field [20]. After years of development, our model has been well validated against the matrix operator method [21], Monte Carlo method [22], and Markov chain method [23]. Gas absorptions

due to ozone, oxygen, water vapor, nitrogen dioxide, methane, and carbon dioxide have been incorporated in all EPIC bands. For water vapor, oxygen, carbon dioxide, and methane, we used the atmospheric radiative transfer simulator (ARTS) [24] and the HITRAN2012 database [25] to build a hyperspectral lookup table of the gas absorption coefficients. Absorptions by ozone and nitrogen dioxide are included by interpolating the measurements in [26] and [27], respectively. In the oxygen A and B bands, we performed line-by-line simulations inside the measurement bands and then convoluted the radiance at the top of the atmosphere with the EPIC instrument line shape function. For other bands, we first calculated the average absorption coefficients within the instrument line shape function, then coupled the average absorption coefficients with the multiple scattering solution in the radiative transfer model to simulate the EPIC detector response.

The atmosphere is assumed to be a three-layer medium. The top layer is a molecule layer, which scatters according to the Rayleigh scattering matrix with the depolarization of 0.0284 [28]. The middle layer is a mixture of scattering particles and molecules. The scattering particles can be aerosols or cloud particles. In this work we have assumed the scattering particles as water cloud droplets, which follow the gamma size distribution, with the effective radius of $10 \mu\text{m}$ and the effective variance of 0.1. The influence of varying particle size distributions is not studied in this work as Fischer and Grassl [29] showed the impact of the water droplet size is minor to the reflectance in oxygen A bands. The scattering matrix of water cloud is calculated with the Lorenz-Mie theory [30]. The lowest layer again consists of molecules only. The vertical extent of the middle layer is determined by CTH and CGT. The lower boundary is an ocean surface with the surface roughness characterized by the Cox Munk model [31] with the wind speed. In this work the wind speed of 6 m/s is used for sensitivity study. CTH is measured from the ocean surface, which is always larger or equal to CGT. When CGT is equal to CTH, the bottom layer don't exist and the atmosphere becomes a two-layer system. The vertical profiles of the molecule number densities are determined by the 1976 US standard atmosphere [32].

3. Cloud masking over glint

Figure 1a shows R_{764}/R_{780} of a clear sky case(COD=0) for a typical Earth viewing geometry from EPIC, which reveals a near circular symmetrical pattern. The center circular region affected by the glint has low values

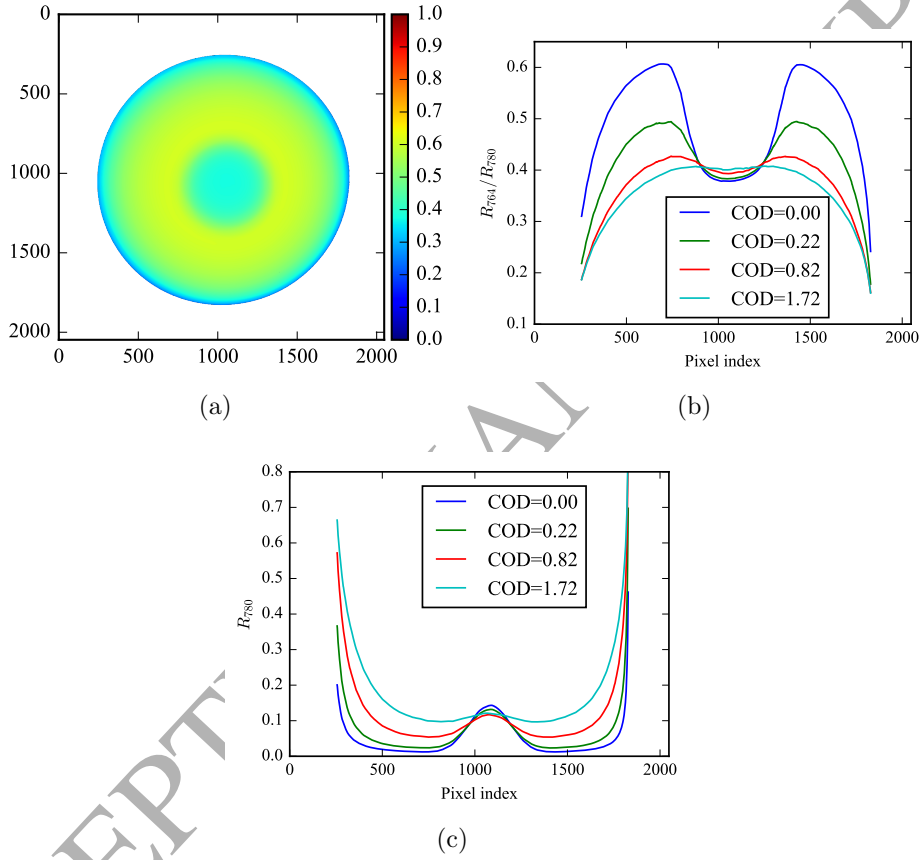


Figure 1: (a) R_{764}/R_{780} of a clear sky case (COD is 0.0) for a typical Earth viewing geometry from EPIC. (b) R_{764}/R_{780} as a function of the pixel index on the horizontal line which intercept the image at $y=1024$, where y is the vertical pixel index. CTH and CGT are 2.5 and 1 km, respectively. (c) R_{780} on the same horizontal line as in Fig. 1b

of R_{764}/R_{780} , which is due to the strong glint radiance from the reference band of 780 nm. The ratio rises up when the viewing angle moves out of the glint and the atmosphere path length is relatively stable. Around the outer ring of the Earth the ratio decreases again because the reflectance in the reference band increases significantly due to enlarged scattering path length. Due to the near circular symmetry a line of pixels across the Earth image center is enough to represent the variability over the globe. Figure 1b shows the ratio R_{764}/R_{780} for several values of COD over a horizontal line across the center of Fig. 1a. Each pixel on the line has different solar incident and viewing angles, which are used in the radiative transfer simulator to calculate the reflectance ratios. It shows that R_{764}/R_{780} decreases as COD increases outside the glint affected area. The reason is that for the cases given here, the reflectance R_{780} increases more than R_{764} as the optical depth increases due to the oxygen absorption. Inside the glint area, the impact of COD on the ratio is reversed, i.e., R_{764}/R_{780} increases if COD is larger, because R_{780} decreases as clouds block the intensity of sun glint. Figure 1c shows that R_{780} outside of the glint area increases as COD increases, which is consistent with Fig. 1b. At the center of the glint region, R_{780} decreases as COD increases when COD is relatively small (around 1). For a large value of COD (around 2), R_{780} will increase as COD increases as the glint is largely blocked out by clouds. Figures 1b and 1c show that the ratio R_{764}/R_{780} varies with COD more sensitive than R_{780} . Furthermore, we can define the spatial gradient as the slope of R_{764}/R_{780} or R_{780} as a function of pixel index. The spatial gradient of R_{764}/R_{780} in Fig. 1b for a clear sky case is the largest compare with cases with nonzero COD, which can be used to increase the confidence level of cloud masking product near the edge of the sun glint disk for EPIC images.

4. Cloud height retrieval from the UV band

EPIC measurements in the oxygen A and B bands are sensitive to CTH and CGT. As we have reviewed in the introduction, the oxygen A and B band measurements are highly correlated so that only one parameter in CTH and CGT can be obtained after considering the impacts of noise [4]. To evaluate whether the UV bands can be used to determine CTH, Fig. 2 show the spectral reflectance of EPIC images for two viewing geometries: $\theta_s = 20^\circ$, $\theta_v = 20^\circ$, $\phi_v = 170^\circ$; and $\theta_s = 30^\circ$, $\theta_v = 30^\circ$, $\phi_v = 180^\circ$, where θ_s , θ_v , and ϕ_v are the solar zenith angle (SZA), viewing zenith angle (VZA), and viewing

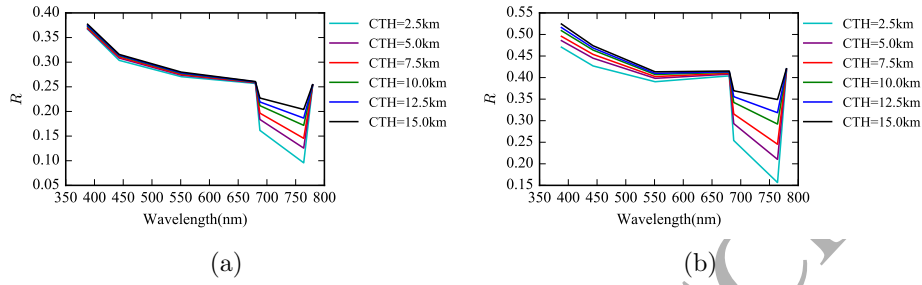


Figure 2: The reflectance as a function of wavelength for two different viewing geometries. CGT and COD are 2 km and 5.05, respectively. (a) The solar zenith angle (SZA) is 20° , which is the same as the viewing zenith angle (VZA). The relative azimuth angle (RAA) is 170° (b) SZA is 30° , which is the same as VZA. RAA is 180°

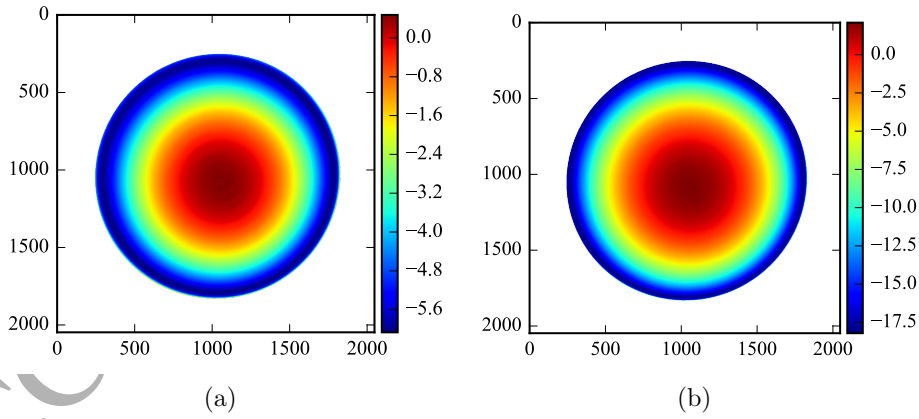


Figure 3: (a) The percentage difference of the reflectance at 388 nm between CTH = 5 km and 2.5 km for a typical Earth viewing geometry from EPIC. COD is 5.05 and CGT is 2 km. (b) the same as Fig. 3a but for the difference between CTH=10 km and 2.5 km. Note the different colorbar scales in (a) and (b).

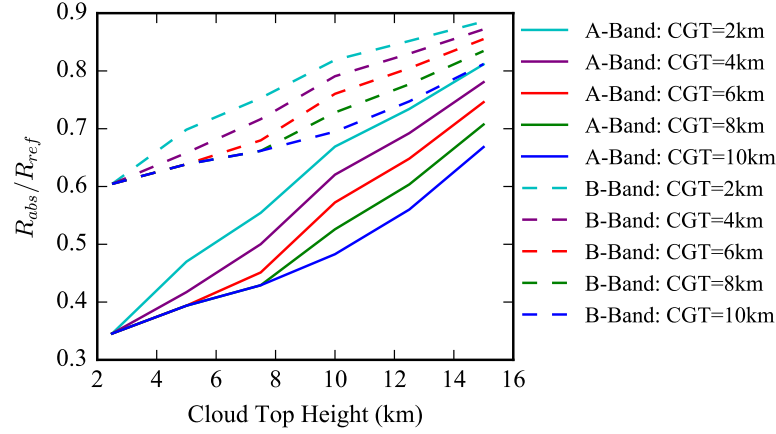


Figure 4: R_{obs}/R_{ref} as a function of CTH for both the oxygen A and B bands. A set of different CGT are used. Cloud optical depth is 5.05, and SZA is 40° , which is the same as VZA. RAA is 170°

azimuth angle relative to the solar principal plane (RAA), respectively. As expected, the oxygen A and B bands have the largest sensitivity on CTH. The reflectance at 388 nm increases as CTH increase in Fig.2b. The dependence however is not obvious for a different viewing geometry in Fig. 2a. To show the overall picture, Fig. 3a shows the percentage difference of the reflectance at 388 nm between CTH=5 km and CTH=2.5 km. CGT is 2 km, and COD is 5.05 which is large enough so that the impact of sun glint is negligible. The absolute percentage difference between CTH = 5 km and CTH = 2.5 km is smallest at the center of the Earth's disk and becomes larger towards the rim of the Earth image. Geogdzhayev and Marshak [33] showed that the calibration of EPIC images is around 3% when normalized by the green band. If we assume 3% accuracy in the EPIC radiometric calibration, the CTH change of 2.5 km is only detectable at 388 nm for a ring area outside the center red and yellow region. Fig. 3b is the percentage difference between CTH = 10 km and CTH 2.5 km, which shows similar angular pattern as Fig. 3a but with larger magnitude. Around $1/3 \sim 1/2$ of the center region the relative difference is still smaller than 3%. In summary it is difficult to use the 388 nm band to determine CTH at the center of EPIC images. However, the 388 nm band is helpful to find CTH for the outer ring region with uncertainty of 2 - 3 km, if we assume 3% as the calibration uncertainty.

To investigate the impact of the possible CTH information from the 388

nm band to the CGT retrieval, Fig. 4 shows the ratio R_{abs}/R_{ref} as a function of CTH for a set of different CGT values, where the subscripts *abs* and *ref* stand for the oxygen A/B bands and their corresponding reference continuum bands, respectively. The cloud optical depth is 5.05 and both SZA and VZA are 40° and RAA is 170°. The oxygen B band ratio shows smaller displacement between consecutive CGT values than that of the oxygen A band. If CTH is known, the ratio R_{abs}/R_{ref} can be used to search the look-up-table represented by Fig. 4 to find CGT. For example, if $R_{764}/R_{780} = 0.5$ and CTH = 8 km, Fig. 4 shows that CGT is less than but close to 6 km. A uncertainty in CTH would lead to uncertainty in CGT determination. If $R_{764}/R_{780} = 0.5$ and CTH = 10 km, an estimate of CGT would be close to 10 km from Fig. 4, so an uncertainty of 2 km in CTH would lead to an error of roughly 4 km for CGT. This estimate however depends on different R_{764}/R_{780} and CTH values as the look-up-table is not uniformly gridded.

5. Summary

In this paper we present a radiative transfer simulator for the DSCOVER/EPIC images. The radiative transfer model is based on the successive order of scattering method. Gas absorption due to ozone, oxygen, water vapor, nitrogen dioxide, methane, and carbon dioxide are included. The simulator is used to study the sensitivity of the EPIC bands to cloud parameters, including cloud masking, cloud optical depth, cloud top height, and cloud geometric thickness. The atmospheric reflectance increases as COD increases if the viewing angle is outside the sun glint region. Inside the sun glint region, the reflectance in non-absorbing bands does not have monotonic variation depending on the COD values. However, the ratio of the oxygen A/B bands to their continuum reference increases monotonically with respect to COD inside a circular region affected by the sun glint. The ratios R_{abs}/R_{ref} for the clear sky case has the largest spatial gradient which could be used to increase the cloud masking confidence level around the edge of the sun glint disk. In addition to the oxygen A and B bands, we studied the sensitivity of the reflectance at UV (388 nm) band to the CTH variation. We found that the 388 nm band has limited sensitivity in the center region of the Earth image to CTH. On the other hand, the 388 nm band is sensitive to CTH for the ring region whose inner radius is larger than half of the Earth radius. If 3% accuracy is assumed for the calibration of the 388 band, the change of 2 - 3 km in CTH could be detected by this band for the outer ring region.

This in turn leads to an uncertainty of 4 km in CGT retrieval based on the oxygen A and B bands look-up-table.

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