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Cloud top pressure retrieval with DSCOVR-EPIC oxygen A and B bands observation

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Abstract

An analytic transfer model for Earth Polychromatic Imaging Camera (EPIC) observation was proposed to retrieve the cloud top pressure (CTP) with considering in-cloud photon penetration. In this model, an analytic equation was developed to represent the reflection at top of atmosphere (TOA) from above cloud, in-cloud and below-cloud. The coefficients of this analytic equation can be derived from a series of EPIC simulations under different atmospheric conditions using a non-linear regression algorithm. With estimated cloud pressure thickness, the CTP can be retrieved from EPIC observation data by solving the analytic equation. To simulate the EPIC measurements, a program package using the double-*k* approach was developed, which can calculate high-accuracy results with a one-hundred-fold time reduction. During the retrieval processes, two kinds of retrieval results, i.e., baseline CTP and retrieved CTP, are provided. The baseline CTP is derived without considering in-cloud photon penetration, and the retrieved CTP is derived by solving the analytic equation, taking into consideration the in-cloud and below-cloud interactions. The retrieved CTP for the oxygen A and B bands are smaller than their related baseline CTP. At the same time, both baseline CTP and retrieved CTP at the oxygen B-band are obviously larger than those at the oxygen A-band. Compared to the difference of baseline CTP between the B-band and A-band, the difference of retrieved CTP between these two bands is generally reduced.

1. Introduction

The Deep-Space Climate Observatory (DSCOVR) satellite is an observation platform orbiting within the first Sun-Earth Lagrange point (L1), 1.5 million km from the Earth, carrying a suite of instruments oriented both Earthward and sunward. One of the Earthward instruments is the Earth Polychromatic Imaging Camera (EPIC) sensor. The EPIC continuously monitors the entire sunlit Earth for backscatter from sunrise to sunset with 10 narrowband filters: 317, 325, 340, 388, 443, 552, 680, 688, 764 and 779 nm (*Marshak et al., 2018*). Of the 10 narrow-band channels, there are two oxygen absorption and reference pairs, 764nm versus 779.5nm and 680nm versus 687.75nm, for oxygen A and B bands. The cloud top pressure (CTP) or cloud top

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height (CTH) is an important cloud property for climate and weather studies. Based on differential oxygen absorption, both EPIC oxygen A-band and B-band pairs can be used to retrieve CTP. It is worth noting that although CTP and CTH reference the same characteristic of clouds, the conversion between the two depends on their atmospheric profiles.

Although the theory of using oxygen absorption bands to retrieve CTP was proposed decades ago, it is still very challenging to do the retrieval accurately due to the complicated in-cloud penetration effect (*Yang et al., 2019, 2013; Davis et al., 2018a, 2018b; Schuessler et al., 2013; Kuze and Chance, 1994; O'brien and Mitchell, 1992; Fischer and Grassl, 1991; and etc.*). Many approaches are designed to retrieve clouds' effective top pressures without considering their in-cloud photon penetration, and therefore derive effective top pressures higher than CTP. Currently, the Atmospheric Science Data Center (ASDC) at National Aeronautics and Space Administration (NASA) Langley Research Center archives both calibrated EPIC reflectance ratio data and processed Level 2 cloud retrieval products, including cloud cover, cloud optical depth, cloud effective top pressure at oxygen A and B bands (*Yang et al., 2019*).

In this paper, to address the issue of in-cloud penetration, we proposed an analytic method to retrieve the CTP by using DSCOVR EPIC oxygen A- and B-band observation The structure of this paper is as follows: section 2 describes the absorption optical depth spectrum at oxygen A and B bands with their related DSCOVR EPIC filters, section 3 states the theory of CTP retrieval based on EPIC oxygen A-band and B-band observation, section 4 describes the retrieval algorithms in detail with case studies and examples of global observation data retrieval, and section 5 states the conclusions of this study.

2. DSCOVR EPIC oxygen A and B bands filters

EPIC filters at 764 nm and 779 nm cover the oxygen A-band absorption and reference band, respectively (Figure 1a). In this wavelength range, the O3 absorption is very weak (O3 optical depth < 0.003) and there are no other gas absorptions. The background aerosol and Rayleigh scattering optical depth vary smoothly within the A-band range; the differences between in-band and reference band are negligible. EPIC filters at 688 nm and 680 nm cover the oxygen B-band absorption and reference band, respectively (Figure 1b). Compared to the oxygen A-band, O3 absorption is slightly stronger in the oxygen B-band range, with an O3 optical depth around 0.01. Any water vapor absorption in the B-band range is negligible. In the standard atmospheric model, from the oxygen B-band reference band to the absorption band, the O3 absorption and Rayleigh scattering optical depth decreased by approximately 0.0002 and 0.002, respectively. This may have some impacts on the CTP retrieval from the oxygen B-band (more discussion in the later sections).

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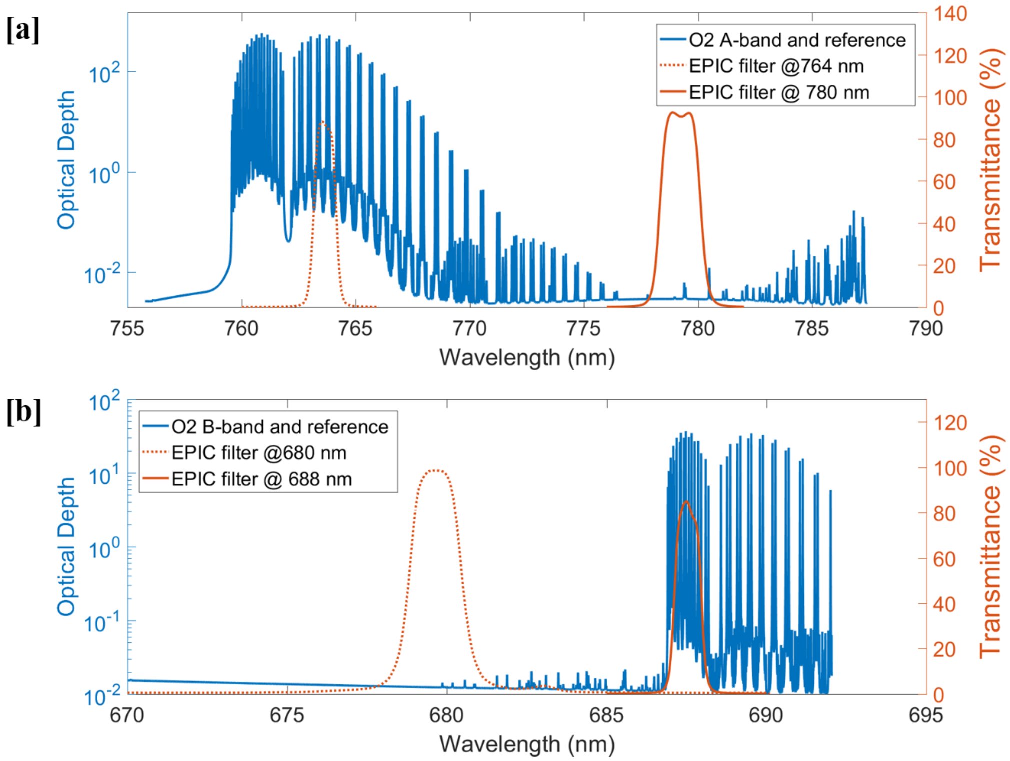

Figure 1: High resolution calculated absorption optical depth spectrum at oxygen A-band (a) and B-band (b) with DSCOVR EPIC oxygen A and B bands in-band and reference filters.

In general, if we use the pair of oxygen A and B absorption and reference bands together, the impact of other absorption lines, background Rayleigh scattering, and aerosol optical depth are very limited. At the same time, as a well-mixed major atmospheric component, the vertical distribution of oxygen in the atmosphere is very stable under varying atmospheric conditions. Thus, we can use the ratio of reflected radiance (or reflectance) at the top of atmosphere (TOA) of oxygen absorption and reference bands to study the photon path length distribution and derive the cloud information. Also, the ratios of absorption/reference are less impacted by the instrument calibration and other measurement error.

3. Theory of CTP retrieval based on EPIC oxygen A- and B- band observation

In our study, we tried two methods to retrieve the CTP based on EPIC oxygen A-band and B-band measurements: (1) Build a lookup table (LUT) for various atmospheric conditions and do the retrieval by searching the LUT; (2) Develop an analytic transfer model for EPIC observations and calculate the related coefficients based on a series of simulated values, then use this analytic transfer model to retrieve the CTP. In this paper, we mainly focus on the second method.

3.1 Method 1: LUT based approach

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One commonly used method of retrieval for satellite observation is through the building and usage of LUTs. For DSCOVR EPIC observations, we can build a LUT by simulating the EPIC measurements under various atmospheric conditions, such as different surface albedo, solar zenith and viewing angles, cloud optical depth, CTP and cloud pressure thickness. During the retrieval process, the EPIC measurements (e.g., reflectance at oxygen A and B bands) with related solar zenith and viewing angles can be obtained from the EPIC level 1B data; cloud optical depth information (retrieved from other EPIC channels) can be obtained from EPIC level 2 data. At the same time, we can get surface albedo from Global Ozone Monitoring Experiment 2 (GOME-2) Surface Lambertian-equivalent reflectivity (LER) data (*Tilstra et al., 2017*). At this point the CTP and cloud pressure thickness are the only unknown variables. Cloud pressure thickness can be estimated with cloud optical thickness using statistical rules. A multi-variable LUT searching method can then be used to interpolate and obtain the CTP. It is worth noting that certain variables will have a non-linear effect on EPIC observations, however, these variations occur smoothly. With a relatively high-resolution simulated table, we can use a localized linear interpolation method to estimate the proper values. Multiple interpolations are needed for this method to decrease the number of LUT dimensions, which will cost more time than the analytic transfer model method. The retrieval error of this method is determined by the resolution of the LUT. In physics, the retrieval accuracy is impacted by two main uncertainty sources: (1) the limited ability of EPIC in identifying cloud thermodynamic phase, which will affect the accuracy of cloud optical thickness retrieval, and 2) the uncertainty in estimating Cloud pressure.

3.2 Method 2: Analytic transfer model

For a long time, various efforts have been devoted to the study of radiative transfer in the atmosphere, including scattering, absorption, emission, and etc. (*Chandrasekhar, 1960; Irvine 1964; Ivanov and Gutshabash 1974; van de Hulst 1980, 2012; Ishimaru,1999*; *Thomas and Stamnes, 2002; Davis and Marshak, 2002; Kokhanovsky et al., 2003; Marshak and Davis, 2005; Pandey et al., 2012*; *and etc.*). In this study, we are trying to develop an analytic radiative transfer equation to analyze the radiative transfer at oxygen A and B bands. Through solving the analytic equation, we can retrieve the CTP information directly. The theory of CTP retrieval is similar for EPIC oxygen A-band and B-band observation. Here we use oxygen A-band as an example to study the radiative transfer model. For oxygen A-band, photon path length distribution is capable of describing vital information related to a variety of cloud and atmospheric characteristics.

$$I_\nu(\mu,\varphi;\mu_0,\varphi_0) = I_0(\mu,\varphi;\mu_0,\varphi_0)\int_0^\infty p(l,\mu,\varphi;\mu_0,\varphi_0)e^{-\kappa_\nu l}dl \qquad (1)$$

Where, $p(l)$ is photon path length distribution, κ_ν is the gaseous absorption coefficient, $\mu = cos(\theta), \mu_0 = cos(\theta_0)$, $(\theta,\varphi;\theta_0,\varphi_0)$ are zenith and azimuth angles for solar and sensor view respectively, I_0 and I_ν are incident solar radiation and sensor measured solar radiation, respectively.

When clouds exist, the incident solar radiation is reflected to outer space in three primary ways. First, incident solar radiation is reflected by cloud top layer directly as a result of single scattering. Second, the incident solar radiation will penetrate into the cloud and be reflected back to TOA through cloud top via multiple scattering. Third, the incident solar radiation will pass

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through the cloud and arrive at the surface, after that it is reflected back into the cloud and finally scattered back to TOA through the cloud top. Due to the position of the EPIC instrument and the long distance between EPIC and Earth, we can consider that solar zenith angle and sensor view angle are nearly reverse. At oxygen A-band, the reflected solar radiation will be reduced due to oxygen absorption depending on photon path length distributions. Absorption is negligible in oxygen A-band's reference band. For solar radiation at oxygen A-band and its reference band, they are also attenuated by airmass and aerosol that located above or below cloud through Rayleigh scattering and aerosol extinction. However, their attenuations from Rayleigh scattering and aerosol extinction are close to each other. Thus, we can use the ratio of EPIC measured reflectance at oxygen A-band and its reference band to derive the photon path length distribution, and then retrieve cloud information such as CTP.

To simplify the analytic transfer model for EPIC observation, we made a series of assumptions, e.g., isotropic component, a plane-parallel assumption with quasi-Lambertian reflecting surfaces, and etc. In this model, μ and μ_0 are the same as in Equation 1, φ is the relative azimuth angle between solar and satellite sensors; A_{surf} is the surface albedo; t_{O2}^{Top} , t_{O2}^{Base}, and $t_{O2}^{Surface}$ are oxygen A-band absorption optical depth from TOA to cloud top layer, cloud bottom layer, and surface, respectively; $\Delta t_{O2}^{Above-Cld}$, Δt_{O2}^{In-Cld} and $\Delta t_{O2}^{Below-Cld}$ are layerd oxygen A-band absorption optical depth above cloud, in cloud, and below-cloud, respectively; functions f mean their contribution to the ratio of measured reflectance at oxygen A-band (R_A) and refrence band (R_f). The detailed analysis of EPIC analytic transfer model is shown as follows:

(1) **Above Cloud**: the reflected solar radiation is determined by the oxygen absorption optical depth above the cloud and air mass directly.

$$f\left(\Delta t_{O2}^{Above-Cld}, \mu_0, \mu, \varphi\right) = f\left(\Delta t_{O2}^{Above-Cld}\right) f\left(\mu_0, \mu, \varphi\right)$$
$$= t_{O2}^{Top}\left(\frac{1}{\mu} + \frac{1}{\mu_0}\right) \quad (2)$$

(2) **Within Cloud**: the reflected solar radiation is not only determined by oxygen absorption optical depth above cloud and in-cloud, but also by penetration related factors, e.g., cloud optical depth. Due to photon penetration, oxygen parameter t_{O2}^{Top} influences the enhanced path length absorption:

$$\Delta t_{O2}^{In-Cld} = t_{O2}^{Base} - t_{O2}^{Top} \quad (3)$$

Equivalence theorem (*Irvine,1964; Ivanov and Gutshabash,1974; van de Hulst 1980*) is used to separate absorption from scattering:

$$f(t_{O2}^{Top}, \Delta t_{O2}^{In-Cld}, \mu_0, \mu, \varphi) = f(t_{O2}^{Top}, \Delta t_{O2}^{In-Cloud}) f(\mu_0, \mu, \varphi)$$
$$= f(t_{O2}^{Top}) f_1(\mu_0, \mu, \varphi) + f(\Delta t_{O2}^{In-Cloud}) f_2(\mu_0, \mu, \varphi) \quad (4)$$

$f\left(t_{O2}^{Top}\right)$ is determined by two absorption dependences: strong (~ $\sqrt{t_{O2}^{Top}}$) and weak (~ t_{O2}^{Top}).

$$f(t_{O2}^{Top}) = a_1 \sqrt{t_{O2}^{Top}} + b_1(t_{O2}^{Top}) \quad (5)$$

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Based on asymptotic approximation (*Kokhanovsky et al., 2003; Pandey et al., 2012*), the reflection of a cloud without considering below cloud interaction is given by Equation 6:

$$\begin{aligned} R(t,\mu,\mu_0,T) &= R_0^{\infty}(t,\mu,\mu_0) - TK(\mu)K(\mu_0) \\ &= R_0^{\infty}(t,\ f_1(\mu,\mu_0)) \ - Tf_2(\mu,\mu_0) \end{aligned} \qquad (6)$$

Here, R_0^{∞} is the reflectance of a semi-infinite cloud, $K(\mu)$ is the escape function of μ, T is global transmittance of a cloud. T can be estimated by Equation 7, with the cloud optical thickness τ_{cld}, the asymmetry parameter g , and α = 1.07 a numerical constant.

$$T = \frac{1}{0.75\tau_{cld}(1-g)+\alpha} \qquad (7)$$

f_1 and f_2 functions have a quadratic form as follows:

$$f_{i-1} = a_i T + b_i(\mu+\mu_0) + c_i T(\mu+\mu_0) + d_i\mu\mu_0,\ i = 2{,}3 \qquad (8)$$

Combining Equations 4, 5 and 8, we can get the equation 9:

$$\begin{aligned} f(t_{O2}^{Top}, \Delta t_{O2}^{Cld}, \mu_0, \mu, \varphi) = {} & \left(a_1\sqrt{t_{O2}^{Top}} + b_1(t_{O2}^{Top})\right)(a_2 T + b_2(\mu+\mu_0) + c_2 T(\mu+\mu_0) + d_2\mu\mu_0) \\ & + \Delta t_{O2}^{In-Cloud}(a_3 T + b_3(\mu+\mu_0) + c_3 T(\mu+\mu_0) + d_3\mu\mu_0) \end{aligned} \qquad (9)$$

(3) **Below Cloud**: The equivalence theorem used for below cloud is similar to within cloud (*Kokhanovsky et al., 2003; Pandey et al., 2012*).

$$\begin{aligned} f(\Delta t_{O2}^{Below-Cld},\ \mu_0, \mu, \varphi) = {} & T\ t_{O2}^{Surface} \frac{A_{Surf}}{1+(e_4 * T + f_4) * A_{Surf}} \\ & * \ (a_4 T + b_4(\mu+\mu_0) + c_4 T(\mu+\mu_0) + d_4\mu\mu_0) \end{aligned} \qquad (10)$$

Combining Equations 2, 9 and 10, we can get the total EPIC analytic transfer equation as follows:

$$-log\left(\frac{R_A}{R_f}\right) = f(\Delta t_{O2}^{Above-Cld},\ \mu_0, \mu, \varphi) + f(t_{O2}^{Top}, \Delta t_{O2}^{Cld}, \mu_0, \mu, \varphi) + f(\Delta t_{O2}^{Below-Cld},\ \mu_0, \mu, \varphi) \qquad (11)$$

In this total analytic equation, there are 16 coefficients (a_1, b_1, a_2, … d_4, e_4, f_4), which can be calculated through nonlinear regression algorithm according to a series of simulated values for different atmospheric conditions. Based on Equation 11, we can finally obtain a quadratic equation, $\mathbf{A}\sqrt{t_{O2}^{Top}}^{\mathbf{2}} + \boldsymbol{B}\sqrt{t_{O2}^{Top}} + \boldsymbol{C} = \mathbf{0}$, where the parameters A, B and C (not shown here) can be derived from Equation 11 directly. When these parameters (i.e., A, B and C) are obtained from EPIC observation data and other data source, we can easily solve the quadratic equation to retrieve cloud top O2 absorption depth, and then CTP.

4. Detailed retrieval algorithm

As previously stated, in method 2, the analytic EPIC equation (i.e., Equation 11) is key for the CTP retrieval. To derive the coefficients of Equation 11, a series of model simulations for

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various atmospheric conditions are needed. Thus, developing a radiative transfer model to simulate the EPIC measurements at A- and B-bands and their reference bands is the first thing we need to complete.

4.1 Oxygen A- and B-band absorption coefficients calculation

To simulate the EPIC measurements, one of the most important steps is calculating oxygen absorption coefficients at oxygen A-band and B-band. In this step, the latest HITRAN database (*Gordon et al., 2017*) is used to provide the absorption parameters, and the LBLRTM package (*Clough et al., 2005*) is used to calculate oxygen absorption coefficients layer by layer. In our algorithm, the whole Earth atmosphere is divided by 63 layers.

Since oxygen absorption coefficients are pressure (or pressure-squared) and temperature dependent, and the lines are well fitted as Lorentzian in the lower atmosphere, the relationship can be written as follows:

$$k_i = \frac{S_i}{\pi}\frac{\alpha_i}{(v-v_i)^2+\alpha_i^2} \tag{12}$$

$$\alpha_i = \alpha_i^0 \frac{p}{p_0}\left(\frac{T_0}{T}\right)^{\frac{1}{2}},\ S_i = S(T_0)\frac{T_0}{T}\exp\left[1.439E\left(\frac{1}{T_0}-\frac{1}{T}\right)\right] \tag{13}$$

Where S_i is the line intensity, v_i and α_i are the line center wave number and half width, respectively; p_0 and T_0 are standard atmospheric pressure and temperature, respectively.

An unfortunate result of this is that cloud levels at a given pressure-weighted oxygen absorption depth can have drastically different heights depending on the atmospheric profile in use. We have used the LBLRTM package to calculate oxygen parameters for each pressure/temperature profile; a time-consuming process. Our goal has been to find a simple and fast conversion function from pressure to altitude for different atmospheric profiles. Using a polynomial fitting function, fitting coefficients can be determined for oxygen absorption and applied to any given atmosphere [*Min et al., 2014; Chou and Kouvaris,1986*].

$$A_{vLM} = [a_0(v,P) + a_1(v,P)\times(T_{LM}-T_{mL}) + a_2(v,P)\times(T_{LM}-T_{mL})^2]\times\rho_{O_2} \tag{14}$$

Where A_{vLM} is optical depths for layer L, spectral point v, and atmosphere model M; ρ_{O_2} is molecular column density ($\frac{molecules}{cm^2}\times 10^{-23}$); T_{LM} is the average temperature for layer L for a given atmosphere; and T_{mL} is average temperature over all atmospheres (M1to M6) for layer L.

4.2 Fast radiative transfer model for simulating high-resolution oxygen A- and B-bands

We cannot simply calculate narrowband mean optical depth and then calculate the radiation for various atmospheric conditions when simulating EPIC narrowband measurements. The correct way is described as follows: firstly, simulate the solar radiation spectrum $S(k(\lambda))$ under specific atmospheric conditions, then integrate the spectrum with EPIC narrowband filter $R(k(\lambda))$ to obtain simulated narrowband measurements (Equation 15).

$$R(\lambda) = \int S(k(\lambda))R(k(\lambda))d\lambda \neq R(\overline{k(\lambda)}) \tag{15}$$

With the high spectrum resolution oxygen absorption coefficient data, we can simulate the high resolution upward diffuse oxygen A-band or B-band spectrum through DISORT code

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(*Stamnes et al., 1988*) for any given atmospheric condition, which has various surface albedo, SZA, cloud optical depth, cloud top height (pressure), and cloud geometric (pressure) thickness. However, due to the high spectrum resolution, it is very time-consuming when performing line by line (LBL) calculations. Thus, developing a fast radiative transfer model for simulating high resolution oxygen A-band and B-band spectrum is necessary.

In this project, the double-*k* approach is used to develop a fast radiative transfer model for oxygen A-band and B-band respectively. [*Min and Harrison 2004; Duan et al, 2005*] proposed a fast radiative transfer model. In their approach, the radiation from absorption and scattering processes of cloud and aerosol are split into the single- and multiple-scattering components: The single scattering component is computed line-by-line (LBL), while multiple scattering (second order and higher) radiance is approximated.

$$
\begin{aligned}
I &= I^{ss}(\lambda) + I^{ms}(\lambda) \\
&\approx I^{ss}[Z^h(p,t), P^h, \lambda] + I^{ms}[Z^h(p,t), P^h, \lambda] \\
&\approx I^{ss}[Z^h(p,t), P^h, \lambda] + I^{ms}[Z^l(p,t), P^l, \lambda] \\
&\approx I^{ss}[Z^h(p,t), P^h, \lambda] + I^{ms}\{F[Z^l(p,t), P^l, k(\lambda_i)]\} \qquad (16)
\end{aligned}
$$

Equation 16 is from Equation 1 in Duan et al. (2005): *ss* and *ms* mean single and multiple scattering, respectively. Z is the optical properties of the atmosphere as a function of pressure *p* and temperature *t*, with P being the phase function of that layer. H and l represent higher and lower number of layers and streams, respectively. F is the transform function between wave number space and k space, defined from a finite set of $k(\lambda_i)$.

The application of Double-*k* approach in oxygen A-band has been presented in detail in Duan et al. 2005. Here we take oxygen B-band as an example. The detailed fast radiative transfer model for simulating high-resolution oxygen B-band is as follows: The first order scattering radiance is calculated accurately by using a higher number of layers and streams for all required wavenumber grid points. The multiple-scattering component is extrapolated and/or interpolated from a finite set of calculations in the space of two integrated gaseous absorption optical depths to the wavenumber grids: a double-*k* approach. The double-*k* approach substantially reduces the error due to the uncorrelated nature of overlapping absorption lines. More importantly, these finite multiple-scattering radiances at specific *k* values are computed with a reduced number of layers and/or streams in the forward radiative transfer model. To simulate an oxygen B-band spectrum with high accuracy, 33 *k* values and 99 calculations of radiative transfer are chosen in our program. This results in around a hundred-fold time reduction with respect to the standard forward radiative transfer calculation.

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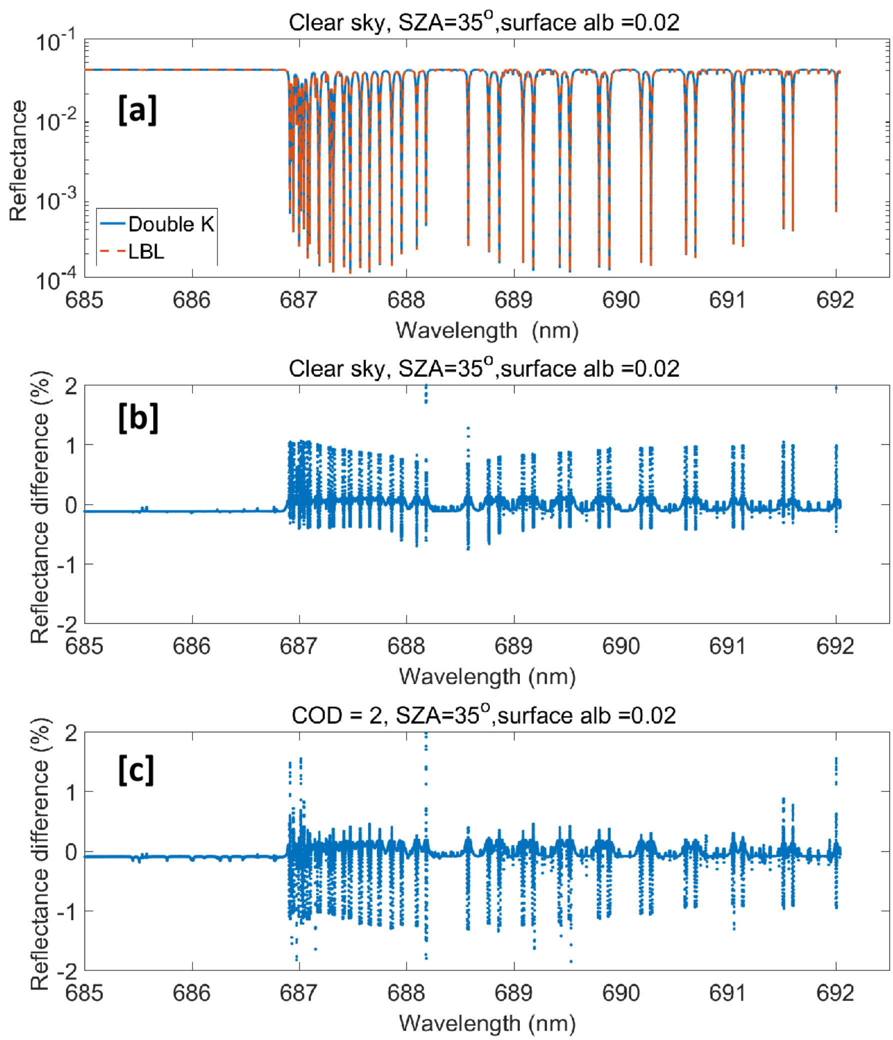

Figure 2. [a] High resolution reflectance at EPIC O2 B-Band simulated by fast radiative model (double-k) and benchmark (LBL); Difference between simulated reflectance by double-k and LBL for a clear sky case [b] and a cirrus cloud case with COD=2 [c]. Here SZA and view angle =35^o, surface albedo = 0.02.

As shown in Figure 2, under clear sky and thin cloud situations, the simulated high resolution upward diffuse oxygen B-band spectra from LBL calculation and double-k approach are compared. The spectrum difference between LBL calculation and double-k approach is very small and hard to tell directly (Figure 2a). Under both situations, most of the relative difference between these two methods are under 0.5%. The obvious relative difference (>1%) occurs only in the wavelength range with high absorption optical depth, which has little contribution to the integrated solar radiation. Therefore, for the simulated narrowband measurements at EPIC oxygen B-band, the relative difference between LBL and double-k approach is much smaller

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than that of the high resolution spectrum, which is less than 0.1% for both clear day and cloud situations (shown in Table 1). For optically thick cloud situations, the accuracy of the double-k approach is similar to that of thin cloud situations.

Table 1. Comparison of simulated narrowband measurement at EPIC B-Band channel

Case	Line by line	Double-k	Difference
Clear day	0.026963	0.026985	+0.08%
Thin Cloud	0.084046	0.084033	-0.02%

4.3 Simulation of oxygen A- and B-bands for different atmospheric conditions

Using the EPIC measurement simulation package, we made a series of simulations with different settings for surface albedo, solar zenith angle, cloud optical depth, cloud top height (pressure), and cloud geometric (pressure) thickness (or cloud bottom height). The results of these simulations consist of a data table, which can be used not only to calculate the coefficients for the analytic equation, but also to study the sensibility of every variant.

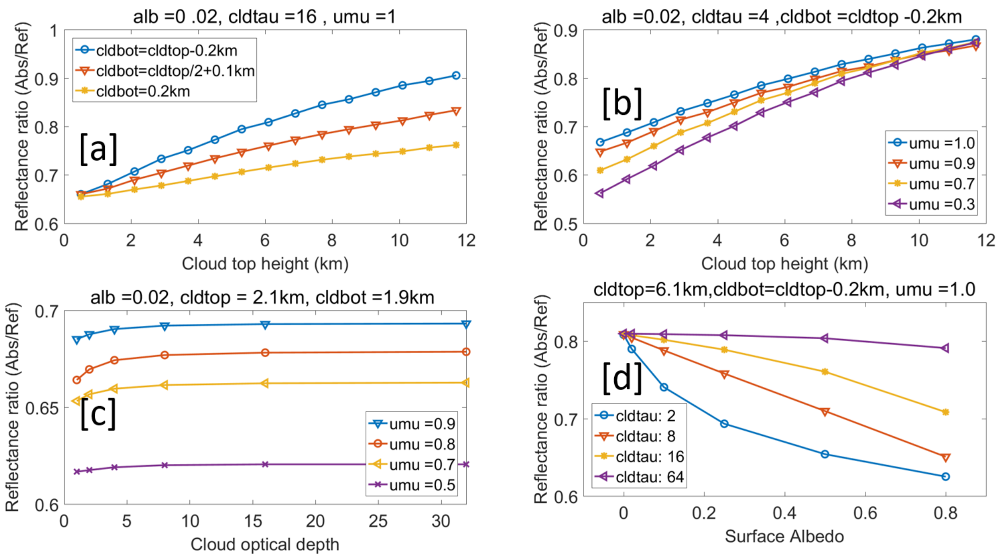

Figure 3. Ratio of simulated reflectance measurements for EPIC B-band to B-band reference with different surface albedo, cloud optical depth, solar zenith angle, cloud top height and cloud bottom height.

According to the previous theory study, the ratio of reflectance radiance (i.e., absorption to the reference) at TOA is determined by the photon path length distribution at oxygen A/B bands: the larger the mean photon path length, the stronger the absorption, and the smaller the reflectance ratio. To make the figures easy to view and understand, we use cloud top and bottom geometric height to represent cloud top pressure and thickness information in Figure 3. As shown in Figure 3a, the ratio of upward diffuse at oxygen B-band and its reference band is sensitive to the cloud top height (pressure). The higher the cloud top height, the larger the ratio. At the same time, this ratio is affected by the cloud bottom height (or cloud geometric thickness)

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when the other cloud parameters are fixed, the lower the cloud bottom (or the larger the cloud geometric thickness), the smaller the ratio. It is consistent with the theory analysis: (1) the higher the cloud top height, the shorter the mean photon path length, and the weaker the absorption; (2) when the cloud optical depth is given, larger cloud geometric thickness means smaller cloud density, then the sunlight can penetrate deeper into the cloud, which results in a longer mean photon path length. In Figure 3b, for clouds with given cloud top height, cloud optical depth and geometric thickness, the ratio decreases with the solar and view angles. This is easy to understand: the larger the solar and view angles, the longer the mean photon pathlength, and the stronger the absorption. In Figure 3c, for clouds with given cloud top height and geometric thickness, when the cloud optical depth is small (e.g., COD <5), the reflectance ratio increases with cloud optical depth. However, when cloud optical depth is larger than 16, the effect of cloud optical depth is small. This is because the larger the cloud optical depth, the shallower the sunlight penetration, and the shorter the mean photon pathlength. In Figure 3d, for clouds with given cloud optical depth, CTP, and geometric thickness, the ratio decreases with surface albedo. The smaller the cloud optical depth, the stronger the impact of the surface albedo. This is because the heavy cloud prevents the incident sunlight from passing through it to reach the surface, and also prevents the reflected light from going back to the TOA.

For oxygen A-band, the ratio of upward diffuse at absorption and reference bands shows similar characteristics as oxygen B-band. Compared to oxygen B-band, under the same atmospheric conditions, the oxygen absorption at A-band is stronger, and the ratio of A-band to its reference band has smaller values.

4.4 Case studies of cloud top pressure retrieval

In our retrieval algorithm, we have two kinds of retrieval results: baseline CTP and retrieved CTP. The baseline CTP is used as a reference for the retrieved CTP. It is similar to the effective CTP in Yang et al., (2013), which does not consider cloud penetration. The retrieved CTP is calculated by the analytic equation, which considers the in-cloud and below-cloud interaction.

During the baseline CTP calculation, the impact of penetration in-cloud is ignorable, and the incident light reached cloud top is assumed reflected back directly. As shown in Equation 15, the baseline absorption optical depth τ_{base} is derived from the ratio of upward diffuse at absorption bands and their reference bands directly. According to the model calculated oxygen A and B bands absorption optical depth profile at the specific solar zenith angle, the baseline CTP can be derived directly.

$$\tau_{base} = \log\left(-\frac{R_{abs}}{R_{ref}}\right)/\left(\frac{1}{\cos(\theta_{sza})} + \frac{1}{\cos(\theta_{view})}\right) \quad (15)$$

As shown in Figure 4, the baseline CTP value at A-band is slightly higher than the effective CTP from NASA ASDC L2 data. But the baseline CTP value at B-band is substantially higher than the effective CTP from NASA ASDC L2 data. The difference may be mainly from the calculation of oxygen A and B bands absorption coefficients or the absorption optical depth profile.

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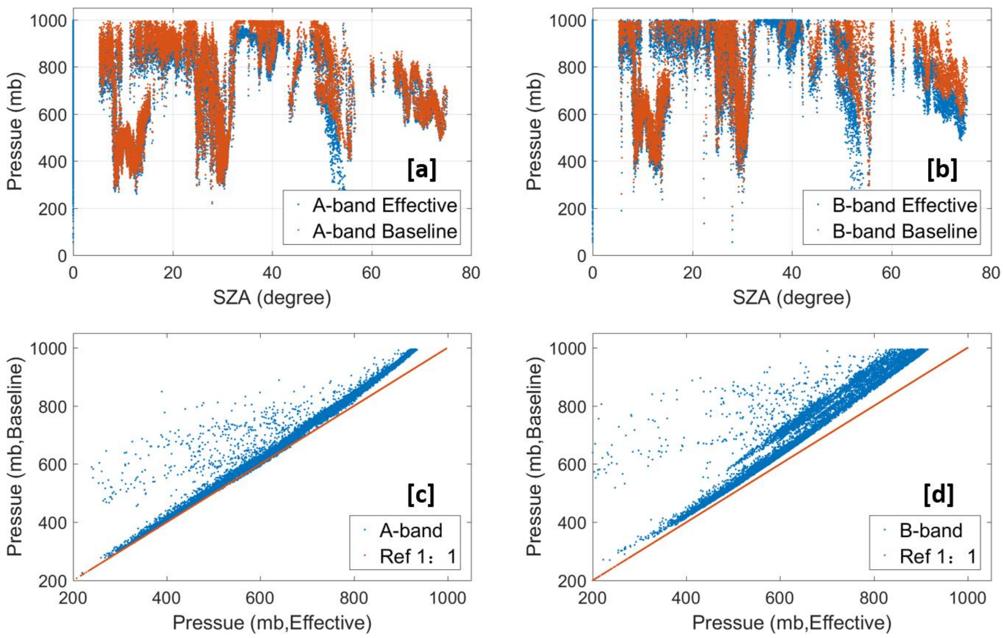

Figure 4. The comparison of effective CTP (reference from NASA ASDC data) and baseline values from our retrieval algorithm for EPIC A and B bands.

Based on the simulated reflectance ratio under different atmospheric conditions, we can calculate the coefficients for the analytic radiative transfer equations by using a nonlinear fitting algorithm. The coefficients for different SZA's are calculated individually to reduce the fitting error. Based on the calculated coefficients, we can retrieve the CTP with DISCOVR EPIC observation data at oxygen A and B bands.

During the CTP retrieval, with the exception of the previously mentioned analytic equation coefficients, we can get the surface albedo data from GOME, obtain reflectance data, solar zenith and view angles, cloud optical depth, etc. from the NASA ASDC data file. Another very important step in the retrieval processing is the acquisition of cloud pressure thickness data, which has a substantial impact on the retrieval results. We currently use a statistical approach (i.e., cloud pressure thickness (mb) = 2.5* cloud optical depth +26) to estimate the cloud pressure thickness based on cloud optical depth. As shown in Figure 5a and 5b, the retrieved CTP when considering cloud penetration is smaller than baseline CTP. For this case, the mean difference between baseline CTP and retrieved CTP for oxygen A-band and B-bands are around 57 mb and 85 mb, respectively, which is consistent with theoretical expectations. For clouds with a given CTP, the mean photon path length will increase substantially when considering cloud penetration and interaction. A decrease in retrieved CTP will result in order to match the measurement ratio of absorption to reference. Compared to the O2 A-band, both baseline CTP and retrieved CTP for the O2 B-band are larger (Figure 5c and 5d). This is because the absorption of solar radiation in the O2 B-band is weaker than that of the O2 A-band, and the incident light at oxygen B-band can penetrate deeper into the cloud, allowing more light to pass

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through. The difference in retrieved CTP between B band and A band (approx. 101 mb) is generally reduced in comparison to baseline B band and A band (approx. 129 mb). This indicates, as expected, more photon penetration correction for B-band than A-band.

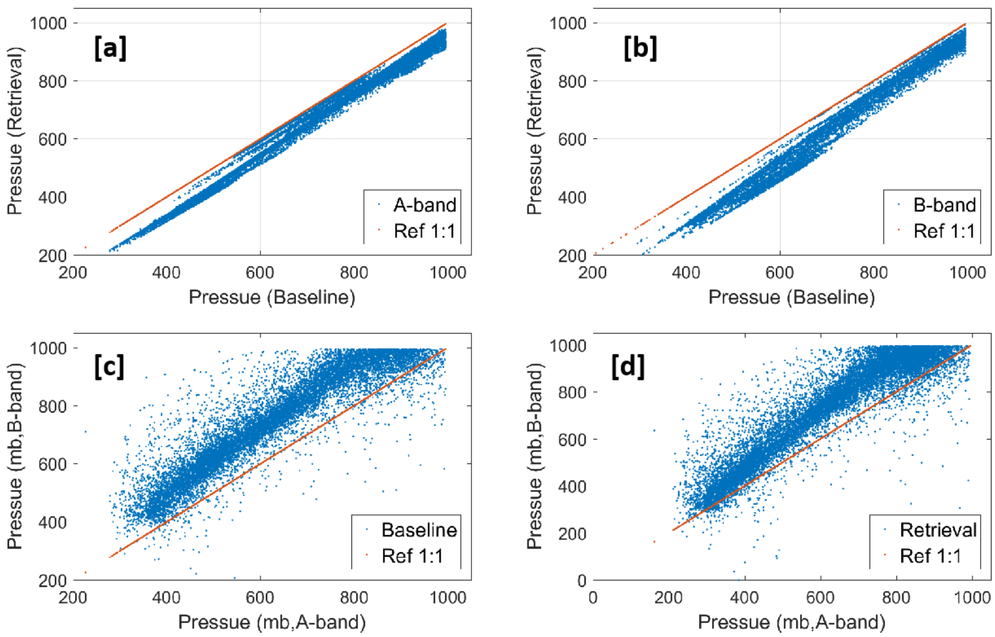

Figure 5. (a and b) The comparison of retrieved CTP and baseline values for EPIC A and B bands; (c and d) the comparison of retrieved CTP and baseline values between EPIC A- and B-bands.

We also used the LUT based method to do the retrieval for the same observation data, because both methods share the same EPIC simulation package and the same simulated data table, the results of which are similar.

4.5 Retrieval of global observation

We applied our retrieval algorithm on the global DISCOVR EPIC measurement data at oxygen A and B bands. During the retrieval, only pixels with total cloud covering (i.e., cloud mask index of 4), surface albedo < 0.25, and cloud optical depth >= 3 are considered. To make the picture easy to visualize, we set all invalid values to 1013; same as the background sea level pressure.

Figure 6a shows the synthesized RGB picture of EPIC measurements at GMT time 00:17:51 on July 25, 2016. At this point in time the sun light covers most of the Pacific Ocean. In this figure, the white pixels represent cloud cover. Figure 6d shows the global cloud optical depth (NASA ASDC L2 data), which highlights areas consistent with the RGB image. Figure 6b and 6c show the baseline and retrieved CTP at A-band, respectively, which also highlights areas (white to brown) consistent with the RGB image. Figure 6e and 6f show the baseline and retrieved CTP in B-band respectively, which are similar to, but greater than the A-band. Because

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we use the cloud optical depth to estimate the cloud pressure thickness in our retrieval, part of the retrieval error is from the cloud optical depth and the equation for cloud pressure thickness estimation.

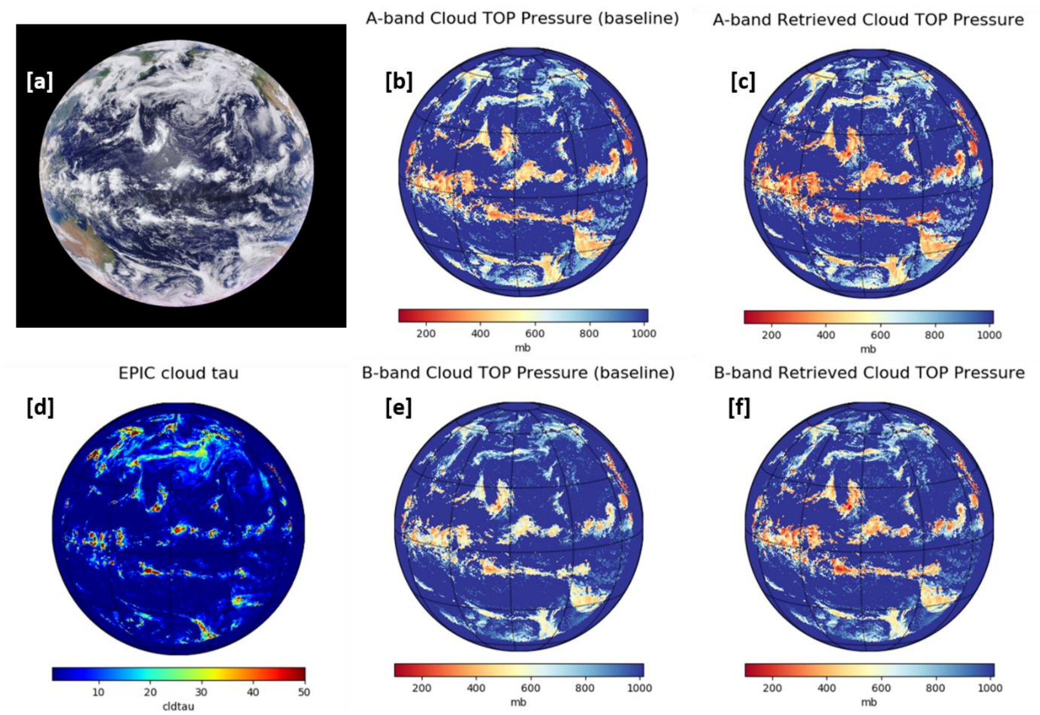

Figure 6. (a) RGB image from DSCOVR EPIC measurement at GMT time 00:17:51 on July 25, 2016; (b) and (c) Baseline and retrieved CTP derived from EPIC A-band measurement. (d) Cloud optical depth (liquid assumption) from EPIC L2 products; (e) and (f) Baseline and retrieved CTP derived from EPIC B-band measurement.

5 Conclusion

The in-cloud photon penetration has significant impacts on the CTP retrieval when using DSCOVR EPIC oxygen A- and B- band measurements. To address this issue, we proposed two methods, (1) the LUT based method and (2) the analytic transfer model method for CTP retrieval with consideration of in-cloud photon penetration. In the analytic transfer model method, we build an analytic equation that represents the reflection at TOA from above cloud, in-cloud, and below-cloud, respectively. The coefficients of this analytic equation can be derived from a series of EPIC simulations under different atmospheric conditions using a non-linear regression algorithm. With EPIC observation data, the related solar zenith and sensor view angle, surface albedo data, cloud optical depth, and estimated cloud pressure thickness, we can retrieve the CTP by solving the analytic equation.

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We developed a package for the DSCOVR EPIC measurement simulation. The high resolution radiation spectrum must be simulated first and then integrated with the EPIC filter function in order to accurately simulate EPIC measurements. Because this process is highly time-consuming, a polynomial fitting function is used when calculating the oxygen absorption coefficients under different atmospheric conditions. At the same time, the double-k approach is applied to do the high-resolution spectrum simulation to further reduce time-costs, which can obtain high accuracy results with hundred-fold time reduction. The results of the EPIC simulation measurements are consistent with theoretical analysis.

Based on the EPIC simulation measurements, we derived a series of coefficients from various solar zenith angles for the analytic EPIC equations. Using these coefficients, we performed CTP retrieval for real EPIC observation data. We have two kinds of retrieval results: baseline CTP and retrieved CTP. The baseline CTP is similar to the effective CTP in Yuekui et al., (2012), which does not consider cloud penetration. The retrieved CTP is derived by solving the analytic equation, with consideration of the in-cloud and below-cloud interactions. Compared to the effective CTP provided by NASA ASDC L2 data, the baseline CTP value at A-band is slightly higher, but the baseline CTP value at B-band is substantially higher. The retrieved CTP for both oxygen A- and B- bands is smaller than the related baseline CTP. At the same time, compared to the oxygen A-band, both baseline CTP and retrieved CTP at oxygen B-band is obviously larger.

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Reference

Chandrasekhar, S.: Radiative transfer. Dover, New York, 1960.

Chou, M.D. and Kouvaris, L.: Monochromatic calculations of atmospheric radiative transfer due to molecular line absorption. *Journal of Geophysical Research: Atmospheres*, *91*(D3), pp.4047-4055, 1986.

Clough, S. A., Shephard, M. W., Mlawer, E. J., Delamere, J. S., Iacono, M. J., Cady-Pereira, K., Boukabara, S., and Brown, P.D.: Atmospheric radiative transfer modeling: a summary of the AER codes, Short Communication, *J. Quant. Spectrosc. Ra.*, 91,233–244, 2005.

Daniel, J.S., Solomon, S., Miller, H.L., Langford, A.O., Portmann, R.W. and Eubank, C.S.: Retrieving cloud information from passive measurements of solar radiation absorbed by molecular oxygen and O2-O2. *Journal of Geophysical Research: Atmospheres*, *108*(D16), 2003.

https://doi.org/10.5194/amt-2019-373
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Atmospheric Measurement Techniques Discussions

Davis, A.B., Merlin, G., Cornet, C., Labonnote, L.C., Riédi, J., Ferlay, N., Dubuisson, P., Min, Q., Yang, Y. and Marshak, A.: Cloud information content in EPIC/DSCOVR's oxygen A-and B-band channels: An optimal estimation approach. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *216*, pp.6-16, 2018a.

Davis, A.B., Ferlay, N., Libois, Q., Marshak, A., Yang, Y. and Min, Q.: Cloud information content in EPIC/DSCOVR's oxygen A-and B-band channels: A physics-based approach. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *220*, pp.84-96, 2018b.

Davis, A.B. and Marshak, A.: Space–time characteristics of light transmitted through dense clouds: A Green's function analysis. *Journal of the atmospheric sciences*, *59*(18), pp.2713-2727, 2002.

Duan, M., Min, Q. and Li, J.: A fast radiative transfer model for simulating high-resolution absorption bands. *Journal of Geophysical Research: Atmospheres*, *110*(D15), 2005.

Ferlay, N., Thieuleux, F., Cornet, C., Davis, A.B., Dubuisson, P., Ducos, F., Parol, F., Riédi, J. and Vanbauce, C.: Toward new inferences about cloud structures from multidirectional measurements in the oxygen A band: middle-of-cloud pressure and cloud geometrical thickness from POLDER-3/PARASOL. *Journal of Applied Meteorology and Climatology*, *49*(12), pp.2492-2507, 2010.

Fischer, J. and Grassl, H.: Detection of cloud-top height from backscattered radiances within the oxygen A band. Part 1: Theoretical study. *Journal of Applied Meteorology*, *30*(9), pp.1245-1259, 1991.

Gordon, I.E., Rothman, L.S., Hill, C., Kochanov, R.V., Tan, Y., Bernath, P.F., Birk, M., Boudon, V., Campargue, A., Chance, K.V. and Drouin, B.J.: The HITRAN2016 molecular spectroscopic database. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *203*, pp.3-69, 2017.

Holdaway, D. and Yang, Y.: Study of the effect of temporal sampling frequency on DSCOVR observations using the GEOS-5 nature run results (Part II): Cloud Coverage. *Remote Sensing*, *8*(5), p.431, 2016.

Ishimaru, A.: Wave propagation and scattering in random media. Wiley-IEEE-Press, New York, 1999.

Irvine, W. M: The formation of absorption bands and the distribution of photon optical paths in a scattering atmosphere. Bull. Astron. Inst. Neth., 17, 266–279, 1964.

Ivanov, V. V., and S. D. Gutshabash, 1974: Propagation of brightness wave in an optically thick atmosphere. *Phys. Atmos. Okeana*, **10,** 851–863.

Koelemeijer, R.B.A., Stammes, P., Hovenier, J.W. and Haan, J.D.: A fast method for retrieval of cloud parameters using oxygen A band measurements from the Global Ozone Monitoring Experiment. *Journal of Geophysical Research: Atmospheres*, *106*(D4), pp.3475-3490, 2001.

Kokhanovsky, A. A., Rozanov, V. V., Zege, E. P., Bovesmann, H., and Burrows, J. P.: A semi analytical cloud retrieval algorithm usinfg backscattered radiation in 0.4–2.4 μm spectral region, J.Geophys. Res., 108, 4008, doi:10.1029/2001JD001543, 2003.

https://doi.org/10.5194/amt-2019-373
Preprint. Discussion started: 4 February 2020

Kuze, A. and Chance, K.V.: Analysis of cloud top height and cloud coverage from satellites using the O2 A and B bands. *Journal of Geophysical Research: Atmospheres*, *99*(D7), pp.14481-14491, 1994.

Marshak, A., and Davis, A. (Eds.).: 3D radiative transfer in cloudy atmospheres. Springer Science & Business Media, 2005.

Marshak, A., Herman, J., Adam, S., Carn, S., Cede, A., Geogdzhayev, I., Huang, D., Huang, L.K., Knyazikhin, Y., Kowalewski, M. and Krotkov, N.: Earth observations from DSCOVR EPIC instrument. *Bulletin of the American Meteorological Society*, *99*(9), pp.1829-1850, 2018.

Meyer, K., Yang, Y. and Platnick, S.: Uncertainties in cloud phase and optical thickness retrievals from the Earth Polychromatic Imaging Camera (EPIC). *Atmospheric measurement techniques*, *9*(4), p.1785, 2016.

Min, Q.L., Harrison, L.C., Kiedron, P., Berndt, J. and Joseph, E.: A high-resolution oxygen A-band and water vapor band spectrometer. *Journal of Geophysical Research: Atmospheres*, *109*(D2), 2004.

Min, Q., Yin, B., Li, S., Berndt, J., Harrison, L., Joseph, E., Duan, M. and Kiedron, P.: A high-resolution oxygen A-band spectrometer (HABS) and its radiation closure. *Atmospheric Measurement Techniques*, *7*(6), pp.1711-1722, 2014.

O'brien, D.M. and Mitchell, R.M.: Error estimates for retrieval of cloud-top pressure using absorption in the A band of oxygen. *Journal of Applied Meteorology*, *31*(10), pp.1179-1192, 1992.

Pandey, P., Ridder, K.D., Gillotay, D. and Van Lipzig, N.P.M.: Estimating cloud optical thickness and associated surface UV irradiance from SEVIRI by implementing a semi-analytical cloud retrieval algorithm. *Atmospheric Chemistry and Physics*, *12*(17), pp.7961-7975, 2012.

Schuessler, O., Rodriguez, D.G.L., Doicu, A. and Spurr, R.: Information Content in the Oxygen A-Band for the Retrieval of Macrophysical Cloud Parameters. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(6), pp.3246-3255, 2013.

Stamnes, K., Tsay, S.C., Wiscombe, W. and Jayaweera, K.: Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. *Applied optics*, *27*(12), pp.2502-2509, 1988.

Thomas, G. E., and Stamnes, K.: Radiative transfer in the atmosphere and ocean. Cambridge University Press, Cambridge, 2002.

Tilstra, L.G., Wang, P. and Stammes, P.: Surface reflectivity climatologies from UV to NIR determined from Earth observations by GOME-2 and SCIAMACHY. *Journal of Geophysical Research: Atmospheres*, *122*(7), pp.4084-4111, 2017.

Van de Hulst, H. C.: Multiple Light Scattering: Tables, Formulas, and Applications. Academic Press, 299 pp, 1980.

Van de Hulst HC.: Multiple light scattering: tables, formulas, and applications. Elsevier; 2012.

https://doi.org/10.5194/amt-2019-373
Preprint. Discussion started: 4 February 2020

Yang, Y., Marshak, A., Mao, J., Lyapustin, A. and Herman, J.: A method of retrieving cloud top height and cloud geometrical thickness with oxygen A and B bands for the Deep Space Climate Observatory (DSCOVR) mission: Radiative transfer simulations. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *122*, pp.141-149, 2013.

Yang, Y., Meyer, K., Wind, G., Zhou, Y., Marshak, A., Platnick, S., Min, Q., Davis, A.B., Joiner, J., Vasilkov, A. and Duda, D.: Cloud products from the Earth Polychromatic Imaging Camera (EPIC): algorithms and initial evaluation. *Atmospheric Measurement Techniques*, *12*(3), 2019.