CloudSat Project

A NASA Earth System Science Pathfinder Mission

Level 2 Cloud Optical Depth Product Process Description and Interface Control Document

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Contents

1 Introduction

This document provides an overview of the 2B-TAU cloud optical depth retrieval algorithm. The document describes the algorithm's:

- purpose,
- scientific basis,
- required inputs,
- implementation,
- outputs, and
- operator instructions.

1.1 Purpose

The primary objective of the algorithm is to produce estimates of the optical depth (τ) and its uncertainty for each radar profile determined to contain cloud. However, as shown below, to obtain accurate estimates of optical depth, τ, the effective radius, r_{eff}, must be retrieved as well (Breon et al.[1]). To appreciate the importance of retrieving r_{eff}, Fig. 1a and 1b illustrate the consequences of assuming an incorrect asymmetry factor on the retrieved optical depth.

MODIS reflectivities depend upon the observational geometry (observational, θ, and solar zenith, θ_0, angles, azimuthal angle difference, $\phi - \phi_0$) according to the geographical position of AQUA satellite. Although these angles range from nadir to about 20^o, retrievals performed at nadir would be calculated at higher speed, but would incur intolerably large errors as shown in Fg 1c. The selected algorithm allows for arbitrary viewing angles. The optical depth and effective radius are retrieved using upwelling reflectivity at the top of the atmosphere (TOA) measured by MODIS in several channels and other ancillary data (e.g., geolocation, meteorological parameters and surface albedo). The retrieved values are spectral and represent the optical depth and effective radius at the short wave. The radar reflectivity measured by the CloudSat Profiling Radar (CPR) provides information about the cloud distribution in the atmospheric column, and serves as a quantitative basis to produce cloud optical depth profiles.

2 Basis of the Algorithm

2.1 Overview

The retrieval uses a Bayesian statistical approach described by Marks and Rogers [2]. The retrieved state vector containing the optical depth and effective radius is obtained by using the MODIS reflectivity measurements to refine *a priori* information and also subjects to the uncertainties in both the *a priori* information and the measurement uncertainties. The CPR reflectivity is used to produce the *a priori* value of τ and its associated uncertainty. Another fundamental component is a forward model which provides us with the simulated TOA reflectivities for the atmospheric model described by the state vector. Comparison between the simulated and measured TOA reflectivities is used to update the state vector and allows us to converge iteratively to a solution. The forward model uses a multi-stream plane-parallel adding model (Christi and Gabriel [3]) based on methods by Benedetti et al. [4]. The next subsection contains a brief description of the retrieval algorithm components.

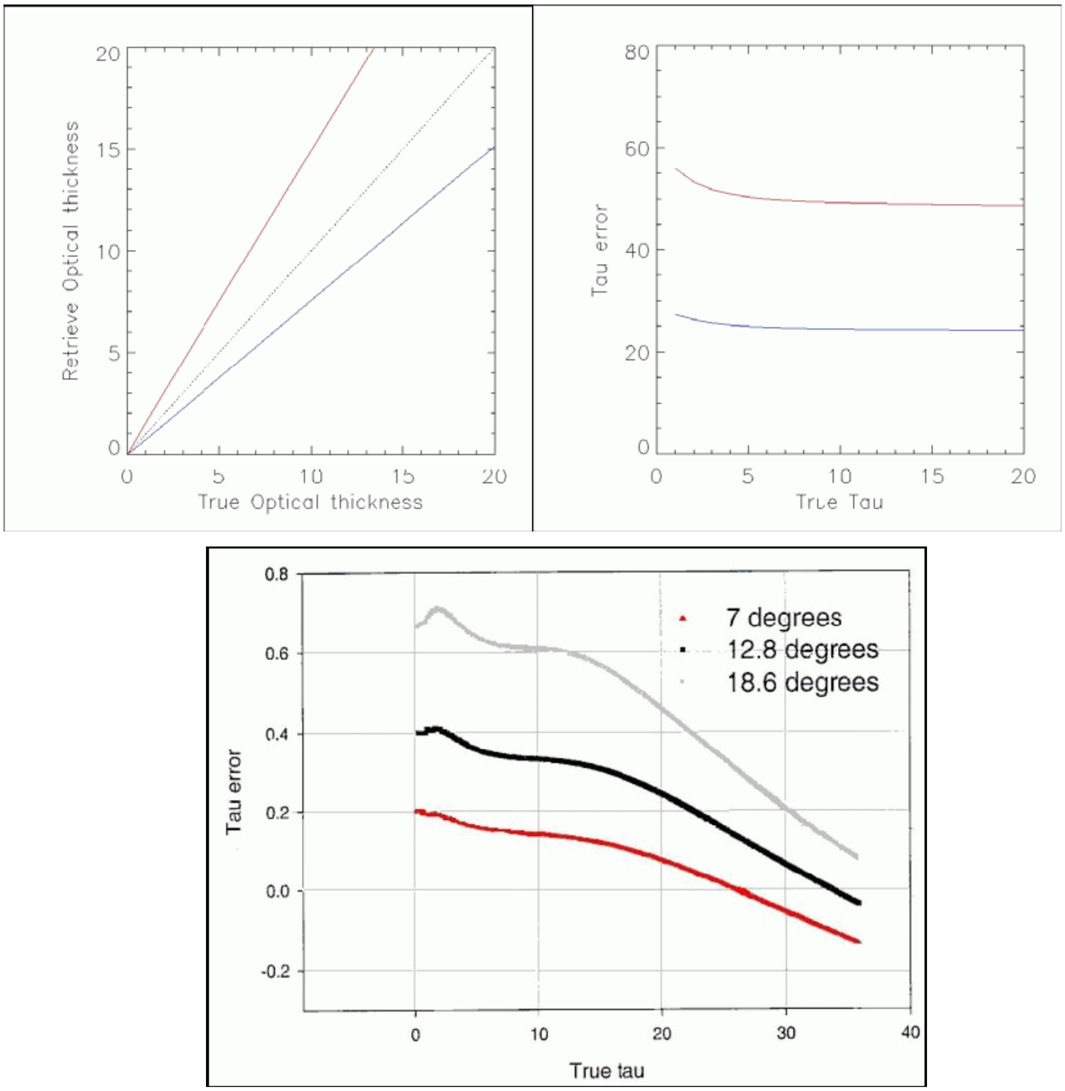

Fig. 1: a) Retrieved optical depth for different asymmetry factors (colored lines). True asymmetry factor is g=0.85. b) As in a) except that errors are shown. c) Error on retrieved optical depth due to incorrect observation angle. True exiting reflectivities at indicated angles are shown by colored lines. Retrieved optical depths computed at Nadir

2.2 Forward Radiative Transfer Model

2.2.1 Theory

The model used here incorporates a cloud layer overlying a reflecting surface. The optical properties of the cloud and surface are assumed to be horizontally homogeneous. In addition, the optical properties of the cloud are assumed to be vertically homogeneous. Given these assumptions the monochromatic 1D radiative transfer equation (RTE):

$$\mu \frac{dI(\tau,\mu,\phi)}{d\tau} = -I(\tau,\mu,\phi) + \frac{\omega}{4\pi}\int_0^{2\pi}\int_{-1}^{1} P(\mu,\phi;\mu',\phi')\, I(\tau,\mu',\phi')\, d\mu' d\phi' + S(\tau,\mu,\phi), \tag{2.1}$$

where $I(\tau,\mu,\phi)$ is the radiance observed at a height expressed by the optical depth τ in the direction given by $\mu = \cos(\theta)$ and ϕ, ω is the single scattering albedo, which is measure of the degree of absorption and spans the range between 1 and 0, with 1 and 0 meaning purely scattering and purely absorbing media, correspondingly, $P(\mu,\phi;\mu',\phi')$ is the phase function and represents the angular pattern of the scattered radiation.

The source term in Eq. (2.1) has a form

$$S(\tau,\mu,\phi) = \frac{\omega}{4\pi} F_0 P(\mu,\phi;\mu_0,\phi_0)\exp(-\tau/\mu_0) + (1-\omega)B(T), \tag{2.2}$$

where F_0 is the monochromatic solar flux at the top of the atmosphere, $\mu_0 = \cos(\theta_0)$, θ_0 and ϕ_0 are the zenith and azimuth angles at which the solar radiance illuminates the top of the atmosphere. The second term of the source function, $S(\tau,\mu,\phi)$, represents the contributions of longwave radiation which can be described by the Planck function. Since 2B-TAU algorithm uses MODIS reflectivities, we can set $F_0 = \pi$.

The solution of (2.1) is subject to the standard boundary conditions. They describe radiance interaction with the surface at the bottom of the atmosphere.

2.2.2 Method of solution of the RTE

The selected algorithm uses a multi-stream plane-parallel adding model. This method is based on a discretization of the equation of transfer so that the Eq. (2.1) is represented in a discrete ordinate form and then the adding method is applied to obtain the solution. We decompose $I(\tau,\mu',\phi')$, and $S(\tau,\mu,\phi)$ over the azimuthal coordinate ϕ using Fourier series. The functions are decomposed over the zenith coordinate μ using numerical quadrature (i.e. Gaussian). The phase function $P(\mu,\phi;\mu',\phi')$ is represented as a series of the Legendre polynomials. Our model assumes that clouds can be represented as plane-parallel entities comprised of water or ice, and hence, our atmosphere can be divided into homogeneous layers. In this case, the radiances can be calculated by employing the interaction principle repeatedly to all layers resulting in a variation of the well known adding method. The global reflection, transmission matrices and source functions required by the adding method are calculated using an eigenmatrix technique described in [3],[4]. This method differs from the doubling method in that the global operators (i.e. the reflection (R) and transmission (T) matrices) also used in the construction of the source functions can be computed for any optical depth directly using formulas that do not require iteration. By contrast, doubling procedure is initialized by an infinitesimal generator and uses thereafter repeated matrix-to-matrix multiplications to calculate the global operator associated with a given optical depth. As demonstrated by Cristi and Gabriel [3] this method is computationally efficient and stable.

2.2.3 Implementation details:

The forward model is implemented as follows:

1. Because of the solar radiance is a directional source and any value of the observation and solar illumination angles is possible, it may be required to take into account several azimuthal harmonics to achieve a required accuracy of the radiance estimation. This number generally increases when the observation and solar illumination angles become larger. Our numerical experiment shows that four harmonics are enough for most cloud scenes.
2. For the far infrared channels (wavelength grater than 3 μm), since the thermal sources are angularly isotropic, only the zeros azimuth harmonic is required regardless of the observation geometry.
3. The expansion over μ uses 8 angles up and 8 angles down. Correspondingly, the number of the expansion terms in the Legendre polynomial decomposition of the phase function is set to 16.
4. The measurement of the TOA reflectivities at two wavelengths to infer both τ and r_{ef} is necessary.
5. A Lambertian surface is assumed. The surface albedo depends on geographical location and the day of the year and obtained from a datafile.
6. The phase function dependents on the cloud constituent type. For the liquid water cloud, we assume that cloud particles have the spherical shape and their size distribution, $p(r)$, is described by the gamma distribution

   $$p(r) = r^{k-1} \frac{\exp(-r/b)}{\Gamma(k) b^k}, \tag{2.3}$$

   where $\Gamma(k)$ is the Gamma function.

   For the ice water cloud the model suggested by Yang et al [5] is used.
7. The single scattering albedo and coefficients of phase function decomposition into the Legendre polynomials are pre-calculated and organized as look up tables.

2.3 Bayesian Retrieval

The general approach of the retrieval is as shown in Figure 2, starting with process 5 (Estimate $\vec{x}_{prior}$) and ending with process 8 (Eval QC flags). In general, for each cloudy profile produced by the CPR, an *a priori* estimate of the column vector containing cloud optical and effective radius is supplied. The estimates are updated until the forward-modeled reflectivities produced by the estimates are in agreement with the observed reflectivities obtained from MODIS, subject to the uncertainties in both the *a priori* estimates and in the MODIS reflectivities.

2.3.1 *a priori* Estimates

Initial estimates (*a priori* estimates) of column cloud optical depth and effective radius are required for the retrieval. If the CPR indicates the column is cloudy, the radar reflectivity profile is used to produce the *a priori* estimate. Each radar range gate is assumed to hold liquid or ice exclusively. Using a fixed temperature defining the phase transition (253 K), the ECMWF-AUX temperature profile is used to determine the water phase contained in each range gate. The auxiliary datasets (IWC-RO-AUX and CWC-RO-AUX) are used to provide information about the liquid/ice water contents for the each range gate. The water contents are then converted to the optical depths using the anomalous diffraction theory (Mitchell and Arnott [6]). The effective radius is the same as that used in the CPR to obtain the optical depth.

If a column is indicated cloudy by the MODIS scene characterization obtained from 2B-GEOPROF but the CPR does not indicate cloud, the *a priori* optical depth and effective radius are estimated by decoding the MODIS scene characterization and assigning the values which are typical to the characterization.

2.3.2 MODIS Reflectivities and Uncertainties

A subset of MODIS reflectivities and uncertainties are obtained from the MODIS level 1B radiance product. The subset consists of a 3x5 grid of MODIS pixels for each CloudSat profile. A vector of MODIS reflectivities values (0.864 μm and 2.13 μm for day time retrieval; 3.7 μm and 11.0 μm for night time retrieval) and a vector of reflectivity uncertainties are associated with each pixel. For each CloudSat profile, a simple mean is taken of the valid reflectivity and uncertainty values over this 3x5 grid.

2.3.3 Iteration and Convergence

The framework for iteratively updating the state vector $\vec{x}$ containing the cloud optical depth and effective radius and testing for convergence is similar to that described by Marks and Rodgers [2] and by Rogers [7]. The expression for the updated value of $\vec{x}$ is given by (adapted from Eq. (5.9) of Rodgers [7]) is:

$$\vec{x}_{i+1} = \vec{x}_i + [\mathbf{S}_a^{-1} + \mathbf{K}_i^T \mathbf{S}_e^{-1} \mathbf{K}_i]^{-1} \mathbf{K}_i^T \mathbf{S}_e^{-1} [\vec{I}_e - \vec{I}(\vec{x}_i) + \mathbf{K}_i (\vec{x}_i - \vec{x}_a)] , \tag{2.4}$$

where the subscript a refers to *a priori* values, the subscript e refers to the measured values, and the subscripts i, $i+1$ refer to the iteration cycle number. In Eq. (2.4) $\vec{x}$ is the column state vector containing the optical depth and effective radius, and $\mathbf{K}$ is the Jacobian matrix:

$$\mathbf{K} = \begin{pmatrix} \left.\frac{dI}{d\tau}\right|_{\lambda_1} & \left.\frac{dI}{dr_{eff}}\right|_{\lambda_1} \\ \left.\frac{dI}{d\tau}\right|_{\lambda_2} & \left.\frac{dI}{dr_{eff}}\right|_{\lambda_2} \end{pmatrix} \tag{2.5}$$

The matrices $\mathbf{S}_a$ and $\mathbf{S}_e$ refer to uncertainties in the *a priori* state vector, $\vec{x}_a$, and MODIS reflectivities, $\vec{I}_e$, respectively, and can be written as follow:

$$\mathbf{S}_a = \begin{pmatrix} \sigma_\tau & 0 \\ 0 & \sigma_{r_{\text{eff}}} \end{pmatrix} \qquad \text{and} \qquad \mathbf{S}_e = \begin{pmatrix} \sigma_{I_{\lambda_1}} & 0 \\ 0 & \sigma_{I_{\lambda_2}} \end{pmatrix} \tag{2.6}$$

Acceptable convergence is achieved when (Eqs. (5.29, 5.31) of Rodgers [7]):

$$d = \left\{ \mathbf{K}_i \mathbf{S}_e^{-1} \left[\vec{I}_e - \vec{I}(\vec{x}) \right] - \mathbf{S}_a^{-1} \left[\vec{x}_i - \vec{x}_a \right] \right\} \ll 2 \tag{2.7}$$

The parameter d is an estimate of the χ^2 statistic for the retrieval.

In practice, the *a priori* estimate of the cloud column vector $\vec{x}_a$ is used as the starting value (i.e., $\vec{x}_0 - \vec{x}_a$). The Jacobian $\mathbf{K}$ is evaluated using a numerical forward-difference approximation. The iterations are continued until either convergence is achieved or until the maximum number of iterations is reached.

3 Algorithm Inputs

3.1 CloudSat

3.1.1 CloudSat Level 2B Geometric Profile

Specific input requirements (Table 1 and 2) are time, geolocation (latitude, longitude, elevation), radar reflectivity, likelihood of hydrometeors, CPR cloud mask, MODIS scene characterization, CPR echo top characterization, CPR data status, surface bin number, spacecraft altitude, range to first bin and ray header range bin size. The parameter "nbin" is the number of vertical bins in the CloudSat radar profile [8].

Table 1a: Inputs from 2B-GEOPROF (per profile)

Variable Name	Dimensions	Range	Units	Description
modis−scene	Scalar	0 -9		MODIS scene characterization
CPR−echotop	Scalar	0-5		CloudSat echo top characterization
CPR−cloudmask	Nbin	0,1		CloudSat cloud mask
Z_r	Nbin	0.	dBZ	CPR reflectivity
Profile_time	Scalar	0-6000	s	Time since the start of the granule
Latitude	scalar	-90 -+90	deg	latitude
Longitude	scalar	-180/+180	deg	longitude
Height	Nbin	-5000-30000	m	Height of range bin in Reflectivity/Cloud Mask above reference surface (~ mean sea level).

Table 1b: Inputs from 2B-GEOPROF common for all profiles

Variable Name	Dimensions	Range	Units	Description
TAI_start	Scalar	0-6E8	s	TAI time for the first profile
Vertical_binsize	Scalar		m	effective vertical height of the radar range bin
Data_status	Scalar			Data status flags
SurfaceHeightBin	Scalar	1-125		Location of Surface Bin as determined by 1B CPR algorithm. The value here is shifted (as Height).

3.1.2 CloudSat IWC-RO-AUX and LWC-RO-AUX

Table 2: Inputs from IWC-RO-AUX and LWC-RO-AUX (per profile)

Variable Name	Dimensions	Range	Units	Description
IO_RO_vis_extinction_coef	Nbin	0 -10	1/km	Ice-only Radar-only Visible Extinction Coefficient
IO_RO_vis_ext_coef_uncertainty	Nbin	0-250	%	Ice-only Radar-only Visible Extinction Coefficient Uncertainty
LO_RO_vis_extinction_coef	Nbin	0-90	1/km	Liqued-only Radar-only Visible Extinction Coefficient
LO_RO_vis_ext_coef_uncertainty	Nbin	0-250	%	Ice-only Radar-only Visible Extinction Coefficient Uncertainty

3.2 Ancillary (Non-CloudSat)

3.2.1 CloudSat Ancillary Albedo Dataset

Specific input requirements (Table 3) are surface albedo [9]. The parameter "nchan" is the number of channels used to retrieve τ and r_{eff} .

Table 3: Inputs from AN-ALBEDO (per profile)

Variable Name	Dimensions	Range	Units	Description
A_s	nchan	0. -1.	-	surface albedo

3.2.2 CloudSat Auxiliary MODIS Reflectivities

Specific input requirements (Table 4) are reflectivities and reflectivity uncertainty (See [10] for details). The parameter "nfoot" is the number of MODIS pixels subsetted to cover the CloudSat radar footprint.

Table 4: Inputs from MODIS-AUX (per profile)

Variable Name	Dimensions	Range	Units	Description
$\vec{I}_e$	nfoot, nchan	0. -?	$W/m^2 sr\,\mu m$	MODIS reflectivities
$\Delta\vec{I}_e$	nfoot, nchan	0. -?	$W/m^2 sr\,\mu m$	MODIS reflectivity uncertainties

3.2.3 CloudSat Auxiliary ECMWF Dataset

Specific input requirements (Table 5) are the temperature, specific humidity, and pressure profile as well as surface temperature and pressure. See [9].

Table 5: Inputs from ECMWF-AUX (per profile)

Variable Name	Dimensions	Range	Units	Description
T	nbin	0. -?	K	temperature profile
P	nbin	0. -?	Pa	pressure profile
S_u	nbin	0. -?	*Kg/Kg*	Specific humidity
P_0	scalar	0. -?	Pa	surface pressure
T_0	scalar	0. -?	K	surface temperature

3.3 Control and Calibration

TBD by 2B-TAU algorithm team.

4 Algorithm Implementation

4.1 Flowchart overview of the retrieval algorithm

See Figure 2.

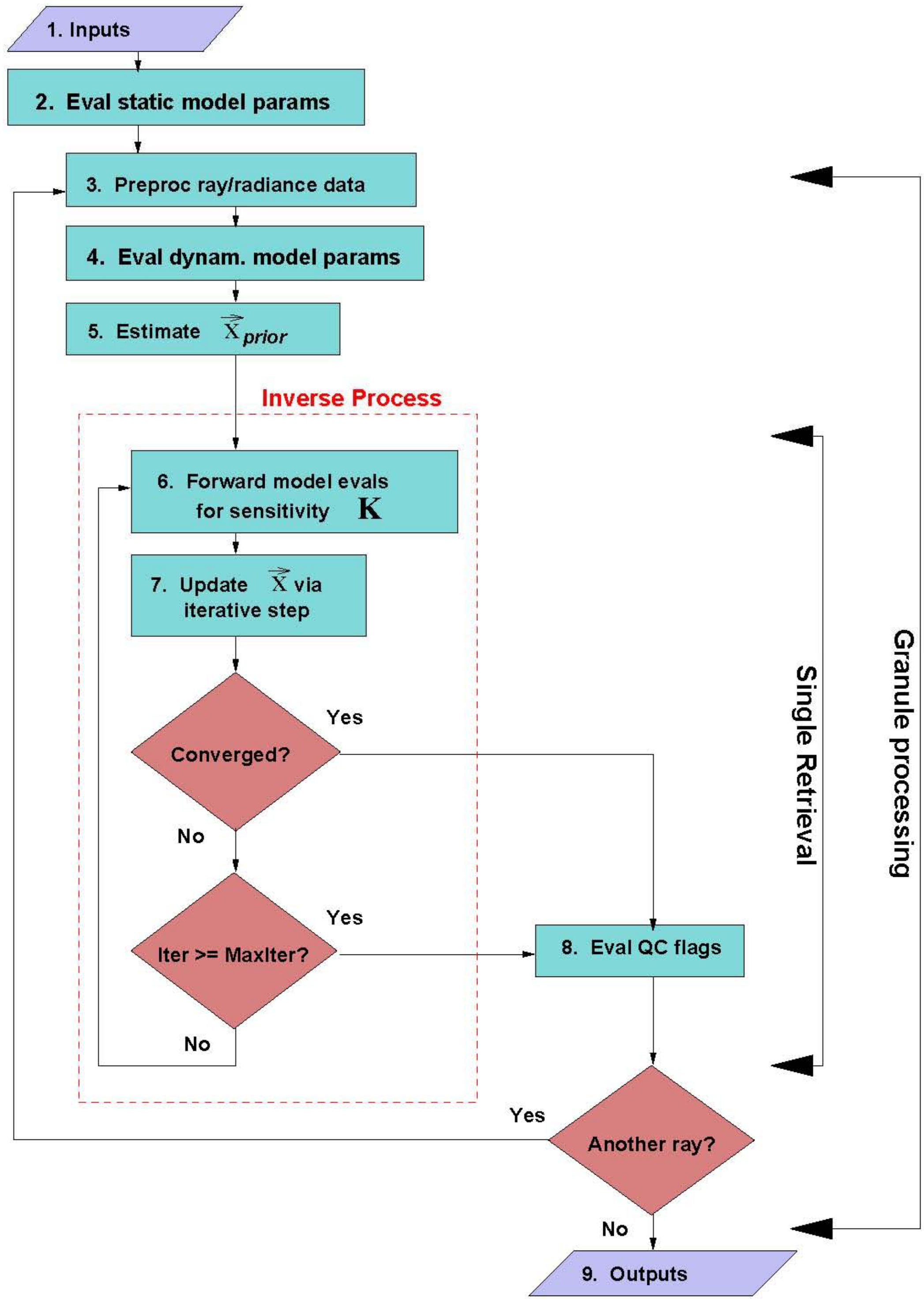

Figure 2: Retrieval process diagram

4.2 Pseudocode description

Following is a pseudocode description of the algorithm:

start 2B-TAU

open (2B-GEOPROF, 1B-CPR)

open ancillary data files (AN-ALBEDO, MODIS-AUX, ECMWF-AUX)

set TOA $F_0 = \pi$

get (solar, sensor) zenith angle (*SZA,SEZA*) (MODIS-AUX)

get (solar, sensor) azimuth angle (*SAA,SEAA*) (MODIS-AUX)

for-each 2B-GEOPROF profile

> **clear** *status*
>
> **if** ($SZA \le SZA_{\max}$) OR ($SZA > SZA_{horiz}$) perform the retrieval
>
> > **set** *status*: *daytime* or *nighttime*
> >
> > **read** MODIS scene characterization (2B-GEOPROF)
> >
> > **read** CPR echo top characterization (2B-GEOPROF)
> >
> > **eval** *status*:*scene*
> >
> > **if** *status*:*scene*=not clear
> >
> > > **compute** relative azimuth angle
> > >
> > > **read** CPR reflectivity profile
> > >
> > > **read** CPR cloud mask (2B-GEOPROF)
> > >
> > > **read** ECMWF (temperature, pressure, specific humidity and ozone) (ECMWF-AUX)
> > >
> > > **compute** gas absorption (correlated-k distribution)
> > >
> > > **eval** *status*:*phase*
> > >
> > > **set** prior effective radius (from cloud phase information) and uncertainty
> > >
> > > **read** surface albedo(AN-ALBEDO)
> > >
> > > **read** MODIS reflectivity data (MODIS-AUX)
> > >
> > > **compute** spatially-averaged MODIS reflectivity vector
> > >
> > > **read** prior optical thickness (IWC-RO-AUX and LWC-RO-AUX)
> > >
> > > **compute** $\vec{x}_a$ and $\mathbf{S}_a$
> > >
> > > **set** convergence parameter d to the initial value
> > >
> > > **set** iteration counter $i = 0$
> > >
> > > **set** $\vec{x}_i = \vec{x}_a$
> > >
> > > **while (** $d > 1$ and $i < i_{\max}$)
> > >
> > > > **compute** $\vec{I}(\vec{x}_i)$
> > > >
> > > > **compute** $\vec{I}(\tau_i + \delta\tau_i)$
> > > >
> > > > **compute** $\vec{I}(r_{eff,i} + \delta r_{eff,i})$
> > > >
> > > > **compute** $\mathbf{K}_a$

```
            compute  x⃗_i
            compute  d
            set  i = i + 1
        end-while ( d > 1 and  i < i_max )
        if  i == i_max  (failed to converge)
            set  τ = flagmissing
            set  τ(bin) = flagmissing
            set  r_eff = flagmissing
            set  σ_τ = flagmissing
            set  σ_r_eff = flagmissing
            set  d = flagmissing
            set status:no_converge
        else
            set  τ = τ_i
            compute  σ_τ (uncertainty in retrieved optical depth)
            compute  r_eff
            compute  σ_r_eff (uncertainty in retrieved effective
        radius)
            compute  τ(bin)  vertical profile of cloud optical
        depth)
            set  d = d_i
            set status:converge, status:prior
        end-if ( i == i_max )
    else (status:scene=clear)
        set  τ = flagclear
        set  τ(bin) = flagclear
        set  r_eff = flagclear
        set  σ_τ = flagclear
        set  σ_r_eff = flagclear
        set  d = flagclear
    end-if (status:scene = not clear)
else ( SZA > SZA_max ) OR ( SZA < SZA_horiz ) no retrieval
            set  τ = flagmissing
            set  τ(bin) = flagmissing
```

```
                        set r_eff =flagmissing
                        set σ_τ =flagmissing
                        set σ_r_eff =flagmissing
                        set d =flagmissing
      end-if (SZA<SZAmax)
end-for-each (2B-GEOPROF profile)
compute scaled τ, r_eff, σ_τ, σ_r_eff, τ(bin), and d
open 2B-TAU output file
write status, scaled τ, r_eff, σ_τ, σ_r_eff, τ(bin), and d
close 2B-TAU output file
close 2B-GEOPROF
close ancillary data files
stop 2B-TAU
```

4.2.1 Algorithm Parameters

See Table 6. The parameter "npara" is the dimension of the retrieved vector $\vec{x}_i$

Table 6: Algorithm Parameters (per profile)

Variable Name	Dimensions	Range	Units	Description
$SZA, SEZA$	scalar	0. - 180°	degrees	solar, sensor zenith angle
$SAA, SEAA$	scalar	-180° -180°	degrees	solar, sensor azimuth angle
$SZA_{\max}$	scalar	80°	degrees	maximum solar zenith angle
SZA_{horiz}	scalar	90°	degrees	horizon solar zenith angle
$\vec{I}_e$	nchan	0. -?	$W / m^2 sr \mu m$	vector of MODIS reflectivities
$\mathbf{S}_e$	nchan, npara	0. -?	$W / m^2 sr \mu m$	matrix of MODIS reflectivity uncertainty
$\vec{x}_a$	npara	0. -?	-	*a priori* cloud column vector
$\mathbf{S}_a$	npara, npara	0. -?	-	matrix of *a priori* cloud parameters uncertainty
i	scalar	$0 - i_{\max}$	-	iteration counter
$i_{\max}$	scalar	-	-	maximum allowed iterations
$\vec{x}_i$	npara	0. -?	-	state vector
$\vec{I}(\vec{x}_i)$	nchan	0. -?	$W / m^2 sr \mu m$	simulated reflectivities
flagmissing	scalar	-99.	-	fill value for missing results
flagclear	scalar	0.	-	fill value for clear-sky results

4.3 Timing requirements

As retrievals are to be performed in real time, the requirement on the computational speed of the algorithm is estimated from the following considerations:

- 14.6 orbits/day;
- approximately 40,000 profiles per orbit (day and night) .

This gives around 584,000 profiles to process per day and sets an upper time constraint, given no other requirements, of 0.15 seconds per retrieval. However the number of cloudy profiles should be of the order of 2/3 of the total number of profiles, i.e. around 390,000 which gives a realistic time constraint of 0.22 seconds. As other products are dependent on the optical depth retrievals, the maximum time constraint will be significantly smaller. The actual performance of the version 3 of 2B-TAU, tested on the Test Data Set 3, is around 0.2 seconds per retrieval on a Pentium 4 (3.2Ghz) computer.

5 Data Product Output Format

5.1 Data Contents

The data specifically produced by the 2B-TAU algorithm are described in Table 7.

Table 7: Algorithm Outputs (per profile)

Variable Name	Dimensions	Range	Units	Description
τ	scalar	0 .-200	-	total cloud column optical depth
r_{eff}	scalar	0 .-200	-	cloud column effective radius
σ_τ	scalar	0. -200	-	scaled standard deviation of τ
$\sigma_{r_{eff}}$	scalar	0. -200	-	scaled standard deviation of r_{eff}
d	scalar	0. -100	-	χ^2 estimate
$\tau(bin)$	nbins	0. -200	-	distributed column optical depth
status	scalar	0 -127	-	retrieval mode and status

5.2 Data Format Overview

In addition to the data specific to the 2B-TAU algorithm results, the HDF-EOS data structure may incorporate granule data/metadata (describing the characteristics of the orbit or granule) and supplementary ray data/metadata. The data structure is described in Table 8. Only those common data fields specifically required by the 2B-TAU algorithm are listed in the table and included in the descriptions in section 5.3. The entries in the "Size" column of the table represent the array size where appropriate (*e.g.*, nray), the variable type (REAL, INTEGER, CHAR) and the size in bytes of each element (*e.g.*, (4)). The parameter "nray" is the total number of profiles in the granule.

Table 8: HDF-EOS File Structure

		Structure/Data Name		Size
Data Granule		Granule Metadata		TBD
		Granule Data		TBD
	Swath Metadata	Common metadata	TBD	TBD
		2B-TAU metadata	τ offset	1*REAL(4)
			τ scale factor	1*REAL(4)
			r_{eff} *offset*	1*REAL(4)
			r_{eff} *scale factor*	1*REAL(4)
			d offset	1*REAL(4)

			d scale factor	1*REAL(4)
			$\tau(bin)$ offset	1*REAL(4)
			$\tau(bin)$ scale factor	1*REAL(4)
	Swath Data	Common data fields	frame counter	nray*INTEGER(2)
			UTC time	nray*INTEGER(10)
			status flag	nray*INTEGER(2)
			geolocation latitude	nray*REAL(4)
			geolocation longitude	nray*REAL(4)
			DEM elevation	nray*REAL(4)
		2B-TAU data fields	τ	nray*INTEGER(2)
			σ_τ	nray*INTEGER(2)
			r_{eff}	nray*INTEGER(2)
			$\sigma_{r_{eff}}$	nray*INTEGER(2)
			d	nray* INTEGER(2)
			$\tau(bin)$	nray*nbin*INTEGER(2)
			status	nray*INTEGER(1)

5.3 Data DescriptionsGranule Metadata (attributes, size TBD by CIRA)

Granule Data (attributes, size TBD by CIRA)

2B-TAU data fields:

τ (SDS, nray*INTEGER(2))

Cloud column optical depth scaled to two-byte integer

r_{eff} *(SDS, nray*INTEGER(2))*

Cloud column effective radius scaled to two-byte integer

σ_τ *(SDS, nray*INTEGER(2))*

Fractional uncertainty in cloud column optical depth scaled to two-byte integer

$\sigma_{r_{eff}}$ (SDS, nray*INTEGER(2))

Fractional uncertainty in cloud column effective radius scaled to two-byte integer

d (SDS, nray*INTEGER(2))

χ^2 estimate for retrieval of τscaled to two-byte integer

$\tau(bin)$ (SDS, nray*nbin*INTEGER(2))

Cloud layer optical depths scaled to two-byte integer

*status (SDS, nray*INTEGER(1)) A one-byte (8 bit) status flag with six bits allocated as follows and two bits unallocated (bits numbered right to left):*

status:*scenemodis*

bit 0: 0=clear, 1=cloudy-MODIS

status:*scenecloudsat*

bit 1: 0=clear, 1=cloudy-CloudSat

status:*missing*:

bit 2: 0=missing values from inputs or $SZA_{\max} < SZA < SZA_{horiz}$,

1=no missing value from inputs

status:*phase*:

bit 3: 0=liquid, 1=ice

status:*converge*:

bit 4: 0=not converged, 1=converged

status:*prior*:

bit 5: 1=retrieval dominated by *a priori* information, 0=retrieval dominated by data

.*status*:*sun*:

bit 6: 0=nightime retrieval, 1=daytime retrieval

status:*channel*:

bit 7: 0=both reflectivities available (retrieve τ and r_{eff}), 1=one reflectivity is missing (retrieve τ only)

2B-TAU metadata fields:

τ **offset** (SDS attribute, REAL(4))

The offset used to rescale τ.

τ **scale factor** (SDS attribute, REAL(4))

The scale factor used to rescale τ**.**

r_{eff} **offset** (SDS attribute, REAL(4))

The offset used to rescale r_{eff}.

r_{eff} **scale factor** (SDS attribute, REAL(4))

The scale factor used to rescale r_{eff}.

d **offset** (SDS attribute, REAL(4))

The offset used to rescale d.

d **scale factor** (SDS attribute, REAL(4))

The scale factor used to rescale d.

$\tau(bin)$ **offset** (SDS attribute, REAL(4))

The offset used to rescale $\tau(bin)$.

$\tau(bin)$ **scale factor** (SDS attribute, REAL(4))

The scale factor used to rescale $\tau(bin)$.

Common data fields:

frame counter (nray*INTEGER(2))

Sequential frame counter carried from Level 0 data

UTC time (nray*INTEGER(10)) Frame (or ray) UTC time converted from VTCW time. A multiword record containing year, month, day of month, hour, minute, second, millisecond and day of year. See Li and Durden [11] for details.

status flag (nray*INTEGER(2))

Per email with D. Reinke. Attributes TBD by CIRA, other algorithms.

geolocation longitude (nray*REAL(4))

The longitude of the center of the IFOV at the altitude of the earth ellipsoid (Li and Durden [11]).

geolocation latitude (nray*REAL(4))

The latitude of the center of the IFOV at the altitude of the earth ellipsoid (Li and Durden [10]).

DEM elevation (nray*REAL(4))

Surface elevation of the Earth at the geolocation longitude and latitude.

Common metadata_fields:

No additional metadata are specifically required by the 2B-TAU algorithm.

6 Operator Instructions

Quality assurance on the data (preliminary list):

Correlation of total optical depth versus total Z for columns where 2B-TAU retrievals are performed (scatter plot)

Frequency of occurrence/clustering of outliers of total optical depth

Frequency of occurrence/clustering of "failed to converge" flag

7 Acronym List

CIRA	Cooperative Institute for Research in the Atmosphere
CPR	Cloud Profiling Radar
EOS	Earth Observing System
HDF	Hierarchical Data Format
IFOV	Instantaneous Field of View
QC	Quality Control
MODIS	Moderate Resolution Imaging Spectrometer
SDS	Scientific Data Set
TAI	International Atomic Time: seconds since 00:00:00 Jan 1 1993

TOA Top of Atmosphere

VTCW Vehicle Time Code Word

BDRF Bidirectional Reflection Function

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