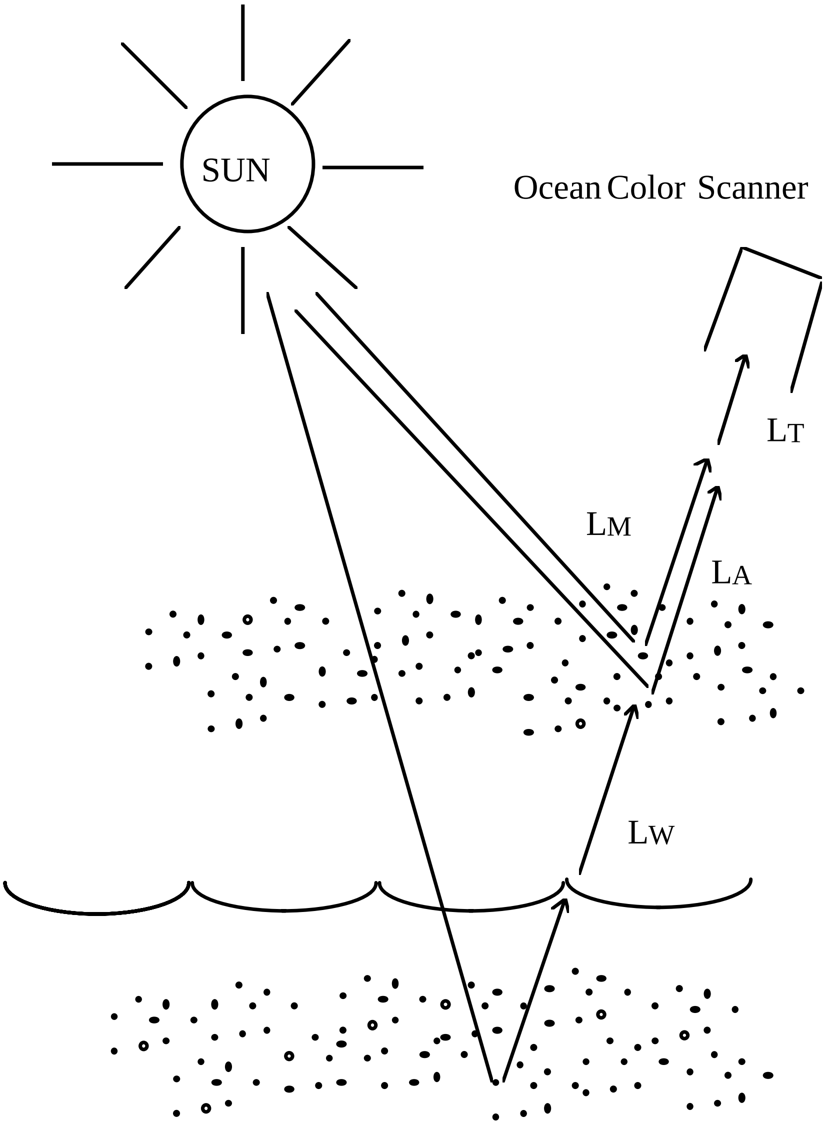
8. Atmospheric Correction

8.1 Overview

As shown in Fig. 8.1 -1, the signal from the surface of the ocean accounts for only a small part of the total radiance detected by the satellite instrument. Most of the satellite-observed radiance comes from the atmosphere and has to be removed in use of so-called atmospheric correction algorithm. In this section, the atmospheric correction algorithms for OCTS data are described.

One candidate algorithm has been developed, based on the SeaWiFS atmospheric correction algorithm proposed by Gordon and Wang (1994). Since this algorithm, or "OCTS-type" algorithm, is yet to be verified, another algorithm, called "CZCS-type" algorithm, was also implemented on the ADEOS/OCTS data processing facilities. The latter was derived from the standard CZCS atmospheric correction algorithm that has been well established and widely used.



L_T : the total radiance detected by the sensor
L_M: the radiance due to atmosphric molecular (Rayleigh) scattering
L_A : the radiance due to aerosol particle scattering
L_W: the water-leaving radiance

Fig. 8.1-1 Elements of brightness observed by satellite

8.2 Interpolation of the Earth Observation Data

The following ancillary data are required for atmospheric correction of OCTS data.

- total ozone concentration
- zonal(east-west) wind speed at the sea surface
- meridional(north-south) wind speed at the sea surface
- atmospheric pressure at the sea surface

Also, the following data is considered to be used in the future.

- relative humidity at the sea surface
- relative humidity at 700hPa
- temperature at the sea surface
- precipitable water
- sea surface temperature

Of these data, wind speed, atmospheric pressure, relative humidity and temperature are available from the objective analysis data of Japan Meteorological Agency, and the ozone data source is from ADEOS/TOMS data. These two data are stored in the Ground Truth Database in the Earth Observation Information System. If it is not possible to input these data from the database, use the temperature value in the processing system.

For sea surface temperature, the use of data from OCTS thermal infrared band is being considered.

Precipitable water is calculated by the following equations.

$$W = \frac{1}{g} * \sum_{i=1}^{9} qi\delta pi \qquad (8.2\text{-}1)$$

W: precipitable water

Each layer of atmospheric pressure is P1 : 300hPa, P2 : 400hPa
P3 : 500hPa, P4 : 600hPa
P5 : 700hPa, P6 : 850hPa
P7 : 925hPa, P8 : 1000hPa
P9 : Sea surface

In this equation, thickness of a layer δp is calculated as follows.

$$\delta pi = \left(P_{i-1} - P_i\right) / 2 \qquad \text{(i=1)}$$
$$\delta pi = \left(P_{i-1} - P_{i-1}\right) / 2 \qquad \text{(i=2 to 8)}$$
$$\delta pi = \left(P_i - P_{i-1}\right) / 2 \qquad \text{(i=9)} \qquad (8.2\text{-}2)$$

Relative humidity RH [%] is converted to specific humidity q by the following equation.

$$q = \frac{\varepsilon * RH * es(T) / 100}{p - (1 - \varepsilon) * RH * es(T) / 100} \qquad (8.2\text{-}3)$$

P : atmospheric pressure of a layer [hPa]

ε : the molecular weight ratio of dry air to water vapor.
It is equal to 0.6222.

In this equation, saturation vapor pressure es(T) [hPa] is calculated as follows.

$$\log[10]es=10.7956*(1-T1/T) - 5.02800\log[10](T/T1)$$
$$+ 1.50475*10^{-4}*\{1-10^{-8.2969(T/T1-1)}\}$$
$$+0.42873*10^{-3}*\{10^{4.76955(1-T1/T)}-1\}+0.78614 \qquad (8.2\text{-}4)$$

T1 : the triple point temperature of water. It is equal to 273.16 [K]

The ancillary data is a grid data which is located discretely in spatial and temporal. In order to use these data for atmospheric correction, an interpolation algorithm can be used to estimate the quantities required from surrounding values.
The spatial interpolation is performed by bilinear interpolation method to the longitude/latitude, since it is a data at the grid point in the equivalent longitude/latitude interval except TOMS ozone data.
Others, since TOMS ozone data (using level 2 product) are scan data, it is performed by separate interpolation (as will be seen later).
The climatological data(meteorological and ozone data) does not depend on the time, so the temporal interpolation is not required.
The meteorological data (objective analysis data) performs linear interpolation to the time, because it is a data for every fixed time period.
Since the ADEOS/TOMS ozone data are observed at the same time as OCTS data, only spatial interpolation is performed.
Interpolation processing is performed by dividing level 1B OCTS image into given sized blocks for efficient operation.
Interpolation as described above, is performed for every grid point of these blocks. Values at pixels located between the grid points are subsequently determined by linear interpolation of grid point values.

(1) Spatial Interpolation except TOMS Ozone data (Bilinear interpolation)

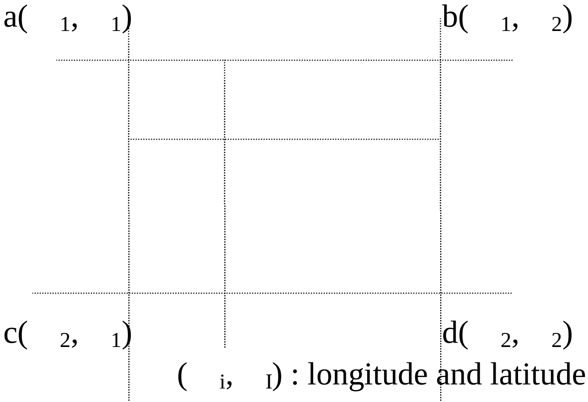
Since the ancillary data except ozone are grid data indicated in equivalent longitude/latitude, the coordinate at the grid point within the OCTS level 1 can be converted into longitude and latitude.
By this conversion, it can find four points that surrounds OCTS level 1B grid point in simple division.
The conversion from 1B coordinate to equivalent longitude and latitude, is used in F1 and F2 functions of coordinate conversion functions, shown in section 6.3.
The value at each grid point on the earth is defined as follows:
Longitude and latitude at the grid point of OCTS level 1B E($_E$, $_E$) = e
Four points that surrounds the grid point of OCTS level 1B :
A($_1$, $_1$), B($_2$, $_2$), C($_3$, $_3$), D($_4$, $_4$) = a, b, c, d

In this case, the spatial interpolation to the grid point of target “e” is calculated by the following equation. (bilinear interpolation method) :

$$e = f + (g - f) * \{(\ _E - \ _1) / (\ _2 - \ _1)\} \qquad (8.2\text{-}5)$$

where

$$\begin{aligned} f &= a + (b - a) * \{(\ _E - \ _1) / (\ _2 - \ _1)\} \\ g &= c + (d - c) * \{(\ _E - \ _1) / (\ _2 - \ _1)\} \end{aligned} \qquad (8.2\text{-}6)$$



(i, I) : longitude and latitude at the data point

a e : value at each point

Fig.8.2.1 Interval Distance of Ground Surface Observation Data

(2) Spatial interpolation for TOMS data

Since TOMS ozone data (level 2') is a scan data, spatial arrangement of each data are shaped like a distorted grid that is scanned along the ground surface.

Spatial interpolation first selects TOMS data, four points that surrounds the grid point of the interpolation point (OCTS level 1B), then performs its interpolation based on the distance from each side of the square (phase containing the geocentric) that consists of these four points.

Selection of four points that surrounds the interpolation point

Assuming that TOMS data is given four points such as A, B, C and D as in the following arrangement :

The condition that interpolation point E can exist in the block of the square that consists of these four points are as follows :

Vector from the geocentric of point A, B, C, D : $\vec{a}, \vec{b}, \vec{c}, \vec{d}$

Position vector of interpolation point : e

$$(\vec{b} \times \vec{a}) \bullet \vec{e} > 0 \text{ and } (\vec{d} \times \vec{b}) \bullet \vec{e} > 0 \text{ and } (\vec{c} \times \vec{d}) \bullet \vec{e} > 0 \text{ and } (\vec{a} \times \vec{c}) \bullet \vec{e} > 0 \qquad (8.2\text{-}7)$$

Find the block that meet this condition sequentially until obtaining the four grid points.

When the satisfied block can not be found because interpolation point is beyond the confines of TOMS data, use the nearest grid point.

Interpolation

Assuming that the plane figure contains each side of block and geocentric.
It is defined as follows in that O means geocentric.
Angle of plane ACO from the line OC : $_1$
Angle of plane BDO from the line OE : $_2$
Angle of plane ABO from the line OE : $_3$
Angle of plane CDO from the line OE : $_4$
Ozone value of each point A, B, C, D define VA, AB, AC, VD.
Ozone value VE at the point E is calculated by the following equation.

$$V_E = (1-f)*(1-g)*V_A + f*(1-g)*V_B + (1-f)*g*V_C + f*g*V_D \qquad (8.2\text{-}8)$$

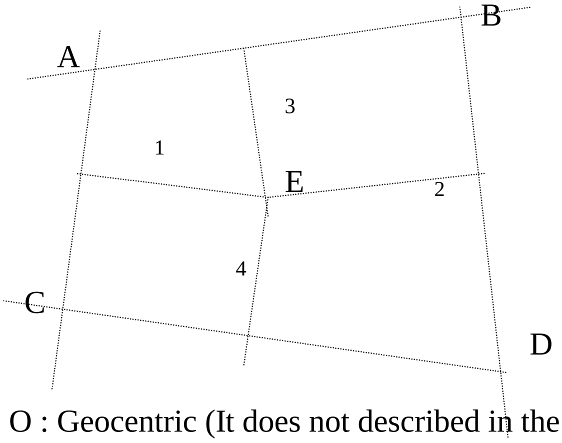
where

$$f = {}_1/({}_1 + {}_2)$$
$$g = {}_3/({}_3 + {}_4) \qquad (8.2\text{-}9)$$

If it defines $\vec{a} = \overrightarrow{OA}, \vec{c} = \overrightarrow{OC}, \vec{e} = \overrightarrow{OE}$

$$_1 = \frac{}{2} - \frac{(\vec{a}\times\vec{c})\bullet\vec{e}}{|\vec{a}\times\vec{c}||\vec{e}|} \qquad (8.2\text{-}10)$$

$_2$ $_4$ can be calculated in the same way.



O : Geocentric (It does not described in the figure)
$_1$ $_4$: Angle OE from the plane
V_A V_E : Value at each point

Fig.8.2.2 Inverse Distance for Ozone Data

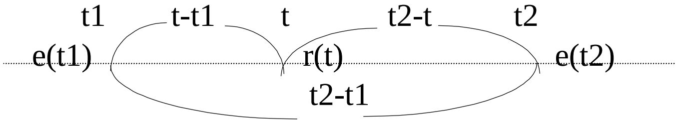
(3) Temporal interpolation of objective analysis data

Interpolation to the observation time, is calculated by the following equations using time weighting to the two ground surface observation data exist before and after on the observation time (Time weighting method).

$$e(t) = {}_1 * e(t1) + {}_2 * e(t2) \qquad (8.2\text{-}11)$$

$$
{}_1 = \frac{t2 - t}{t2 - t1} \qquad {}_2 = \frac{t - t1}{t2 - t1} \tag{8.2-12}
$$

Where, the terms are the temporal weighting factor and $_1$+ $_2$=1.



t : time of target data
t1,t2 : Observation time of ground surface observation data exists after and before t
e(t) : Values at time t

Fig.8.2.3 Time Weighting Method of Ground Surface Observation Data

(4) Interpolation within a OCTS block (Bilinear interpolation method)

Above interpolation (1) - (3) are performed to the block grid points of level 1B OCTS image. Interpolation to each pixel in a block is performed by bilinear interpolation method to the pixel address.

Namely, the interpolation value of each pixel in 1B block, expressed in each A, B, C, D are calculated by the following equation (Bilinear interpolation method).

Each pixel address at 1B grid point : $(X_1,Y_1),(X_2,Y_1),(X_1,Y_2),(X_2,Y_2)$

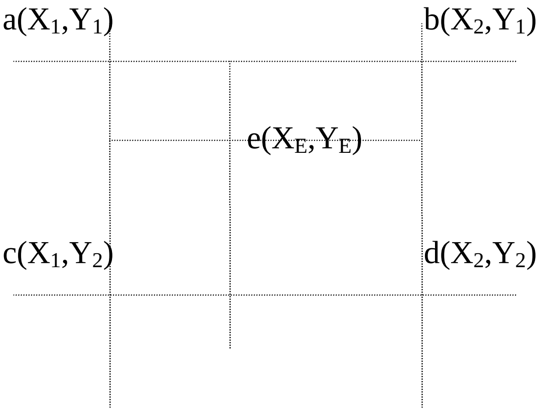
Value at each ground surface observation data : a, b, c, d

Arbitrary pixel in a block E(XE, YE) : e (spatial interpolation value)

$$
e = f + (g - f) * \{(Y_E - Y_1)/(Y_2 - Y_1)\} \tag{8.2-13}
$$

where

$$
\begin{aligned}
f &= a + (b - a) * \{(X_E - X_1)/(X_2 - X_1)\} \\
g &= c + (d - c) * \{(X_E - X_1)/(X_2 - X_1)\}
\end{aligned} \tag{8.2-14}
$$



(X,Y) : level 1B image address at data position
a e : Value at each point

Fig.8.2.4 Interpolation Method in 1B Grid Point for Ground Surface Observation Data and Ozone Data

From the above method, the value at the ground surface observation data corresponding to every pixel of level 1B image are calculated.

8.3 Calculation of the Sun-Ground-Satellite Geometry

In order to perform a atmospheric correction, the solar angle $_{0,}$ the solar azimuth angle $_0$, the satellite zenith angle , the satellite azimuth angle are required.

At first pixel are divided into blocks, then sun-satellite geometry information , $_0$, , $_0$ are calculated for every grid point by the method, indicated in section 6.6.

The sun-satellite geometry information, corresponding to the block grid point (sun-satellite-grid point geometry information) are interpolated for every pixel within a block, then, it is used in atmospheric correction.

The interpolation in block of sun-grid point information is performed using the same method (Fig. 8.2.4) with the interpolation within a block of ground surface observation data, described in section 8.2.

The interpolation within a block of satellite-grid point information divides level 1B grid point address into 1A address using the registration correction information, then, it is performed using the same method (Fig. 8.2.4) with the interpolation within a block of ancillary data, described in section 8.2.

The solar-satellite information to the arbitrary pixel within a block are calculated by the above solar-satellite grid point information.

8.4 Calculation of Solar Irradiance

In order to calculate the radiance due to atmospheric molecular (Rayleigh) scattering or aerosol scattering etc., extraterrestrial solar irradiance F_0 is required. F_0 is given by the following equaion. D is determined by the center pixel of the scene and fixed within a scene. The total day of a year(TD) is 366 for a leap year and 365 for the other year.

$$F_0 = \langle F_0 \rangle \left\{ 1 + 0.0167 \cos\left(\frac{2\pi(D-3)}{TD} \right) \right\}^2 \qquad (8.4\text{-}1)$$

$< F_0 >$: Annual average of extraterrestrial solar irradiance
The following values are stored in database.

λ $< F_0 >$	412 170.96	443 188.17	490 194.59	520 185.74
λ $< F_0 >$	565 184.49	670 153.12	765 122.61	865 98.55

Extraterrestrial solar irradiance corrected for ozone absorption F_0' is given by the following equation.

$$F_0' = F_0 \exp\left\{ -\tau_{oz} \left(\frac{1}{\cos\theta} + \frac{1}{\cos\theta_0} \right) \right\} \qquad (8.4\text{-}2)$$

θ_0 : the zenith angle of the sun
θ : the zenith angle of the satellite
τ_{oz} : the optical thickness of ozone

Optical thickness of ozone is calculated by the following equation.

$$\tau_{oz}(\lambda) = \mathrm{K}_{\mathrm{oz}}(\lambda) * DU \qquad (8.4\text{-}3)$$

$\mathrm{K}_{\mathrm{oz}}(\lambda)$: the coefficients that related optical thickness of ozone and DU.
The following values are stored in database.

λ K_{oz}	412 7.701 e^{-7}	443 3.905 e^{-6}	490 2.488 e^{-5}	520 4.724 e^{-5}
λ K_{oz}	565 1.127 e^{-4}	670 4.923 e^{-5}	765 8.146 e^{-6}	865 3.410 e^{-6}

DU : Total ozone

DU(Dobson Unit) means total ozone concentration at 0°C, 1hPa (above mean sea level) and one DU is equal to a hundredth of the ozone layer thickness. DU is expressed in mm. TOMS data is interpolated both spatially and temporally for this value.

8.5 CZCS Type Algorithm

8.5.1 Overview

In this chapter, outlines of "Toratani and Fukushima" algorithm(Fukushima and Toratani, submitted) which is based on CZCS type algorithm(Gordon et al., 1983 and 1988), is described.

This algorithm is modified to consider the Asian dust, popularly known as KOSA, based on the standard atmospheric correction algorithm by Gordon et al.

It is based on the assumption that the total radiance observed at the satellite is given as a sum of three components; the radiance due to atmosphric molecular (Rayleigh) scattering, the radiance due to aerosol particle scattering and the water-leaving radiance.

$$L_\tau(\lambda) = L_T'(\quad)*g + o = L_M(\lambda) + L_A(\lambda) + t(\lambda)\cdot L_w(\lambda) \qquad (8.5.1\text{-}1)$$

$L_\tau(\lambda)$: the total radiance observed at the satellite
$L_\tau'(\lambda)$: the adjusted radiance
g, o : radiance adjustment parameters
$L_M(\lambda)$: the radiance due to atmosphric molecular (Rayleigh) scattering
$L_A(\lambda)$: the radiance due to aerosol particle scattering
$L_w(\lambda)$: the water-leaving radiance
$t(\lambda)$: the diffuse transmittance of the atmosphere
λ: wavelength

Since the equation is established pixel by pixel, distribution of radiation brightness of upward radiation brightness from inside of the sea L_w from radiation brightness observed at a satellite L_τ is estimated through the estimation of L_M, L_A and L_w pixel by pixel.

Calculation method for L_M, L_A and t is described in articles 8.5.2 and after.

8.5.2 Calculation of the radiance due to atmospheric molecule

The radiance due to atmosphere molecule scattering is calculated by the following procedures.

(1) Calculation of the ozone optical tickness

The ozone optical thickness is calculated by the following equation.

$$\tau_{0Z}(\lambda) = K_{0Z}(\lambda) * DU \qquad (8.5.2\text{-}1)$$

$\tau_{0Z}(\lambda)$: the ozone optical thickness

$K_{0Z}(\lambda)$: the coefficients that relate the ozone optical thickness and DU. The following values are stored in database;

λ K_{0Z}	412 7.701 e^{-7}	443 3.905 e^{-6}	490 2.488 e^{-5}	520 4.724 e^{-5}
λ K_{0Z}	565 1.127 e^{-4}	670 4.923 e^{-5}	765 8.146 e^{-6}	865 3.410 e^{-6}

DU : Total ozone

DU(Dobson Unit) means total ozone concentration at 0°C, 1hPa (above mean sea level) and one DU is equal to a hundredth of the ozone layer thickness. DU is expressed in mm. TOMS data is interpolated both spatially and temporally for this value.

(2) Calculation of Rayleigh optical thickness

Rayleigh optical thickness (τ_M) is calculated by the following equation.

$$\tau_M(\lambda) = P / P_0 * \tau_{M0} \qquad (8.5.2\text{-}2)$$

P: Atmospheric pressure at each pixel (input by EOIS ground observation DB)

P_0: Standard atmospheric pressure (= 1013.25hPa)

$\tau_{M0}(\lambda)$: Rayleigh optical thickness at standard atmospheric pressure. The following values are stored in database.

λ τ_{M0}	412 0.31380	443 0.23450	490 0.15540	520 0.12640
λ τ_{M0}	565 0.085430	670 0.043870	765 0.025470	865 0.015760

(3) Calculation of extraterrestrial solar irradiance corrected for ozone absorption .

Extraterrestrial solar irradiance (F_0) is calculated by the following equation, which takes into account the effect of ozone absorption

$$F_0'(\lambda) = F_0(\lambda) * \exp\left\{-\tau_{0Z}(\lambda) * \left(1/\cos\theta(\lambda) + 1/\cos\theta_0\right)\right\} \qquad (8.5.2\text{-}3)$$

where

$$F_0(\lambda) = \left\langle F_0(\lambda)\right\rangle \left\{1 + 0.0167 * \cos\left(2\pi(D-3)/365\right)\right\}^2 \qquad (8.5.2\text{-}4)$$

$\left\langle F_0(\lambda)\right\rangle$: Annual average extraterrestrial solar irradiance

The following values are stored in database

λ	412	443	490	520
F_0	170.96	188.17	194.59	185.74
λ	565	670	765	865
F_0	184.49	153.12	122.61	98.55

D: the day of the year (D=1 on January 1 and D=365 on December 31)
π: circular constant (radian)
$\theta(\lambda)$: the zenith angle of the satellite
θ_0: the zenith angle of the sun

(4) Calculation of the radiance due to atmospheric molecular (Rayleigh) scattering

The radiance due to atmospheric molecular (Rayleigh) scattering (L_M) is calculated by the following equation.

$$L_M(\lambda) = \rho_M(\lambda) \cdot \left\{F_0(\lambda) \cdot \cos\theta_0\right\} / \pi \qquad (8.5.2\text{-}5)$$

where

$$\rho_M(\lambda) = \frac{\left\{1 - \exp\left(-\tau_M(\lambda)/\cos\theta(\lambda)\right)\right\}}{\left\{1 - \exp\left(-\tau_{M0}(\lambda)/\cos\theta(\lambda)\right)\right\}} * \exp\left\{-\tau_{oz}(\lambda) * \left(\frac{1}{\cos\theta(\lambda)} + \frac{1}{\cos\theta_0}\right)\right\} * \sum_{i=0}^{2} \rho_i\left(\lambda, \theta(\lambda), \theta_0\right) \cos\left(i * \Delta\phi(\lambda)\right) \qquad (8.5.2\text{-}6)$$

F_0: the extraterrestrial solar irradiance
τ_M: the Rayleigh optical thickness which is calculated by eq. (8.5.2-2)
τ_{M0}: the Rayleigh optical thickness at standard atmospheric pressure
τ_{oz}: the optical thickness of ozone
θ: the zenith angle of the satellite
θ_0: the zenith angle of the sun
ρ_i: Fourier Coefficients which are calculated from look-up table
$\Delta\phi$: the difference between the solar and the satellite azimuth angles

The look-up table of Fourier Coefficients ($\rho_i\left(\lambda, \theta(\lambda), \theta_0\right)$) has 41 values for satellite zenith angle (0.0°- 89.95°) and45 values for solar zenith angle in 2° increments (0.0° - 88.0°), respectively. If there is no exact Fourier Coefficients for the target pixcel in the look-up table the values needed in eq. (8.5.2-5) are interpolated by two-dimensional linear interpolation.

8.5.3 Calculation of the diffuse transmittance of the atmosphere

The diffuse transmittance of the atmosphere (t) is divided into its components; the transmittance of atmospheric molecule, ozone and aerosol.

$$t(\lambda) = t_M(\lambda) \cdot t_{0Z}(\lambda) \cdot t_A(\lambda) \qquad (8.\ 5.3\text{-}1)$$

t_M: the transmittance of atmospheric molecule

t_{0Z}: thetransmittance of ozone

t_A: the transmittance of aerosol

Assuming that a photon scattered by the aerosol will be scattered through an angle of <90°, the diffuse transmittance of atmosphere is calculated here. The actual optical thickness of atmospheric molecular is considered to be half due to symmetry of scattering phase function. For t_{0Z}, one time absorption between sea surface and the satellite should only be considered. Since optical path length is in proportion to $1/\cos\theta$ when plane parallel atmosphere is taken into consideration, the transmittance of atmosphere, ozone and aerosol are expressed as follows.

$$t_M(\lambda) = \exp\left\{\left(-\tau_M(\lambda)/2\right)/\cos\theta(\lambda)\right\} \qquad (8.5.3\text{-}2)$$

$t_M(\lambda)$: the optical thickness of atmospheric molecules

$$t_{0Z}(\lambda) = \exp\left(-\tau_{0Z}(\lambda)/\cos\theta\right) \qquad (8.5.3\text{-}3)$$

τ_{0Z}: the optical thickness of ozone layer

The transmittance of aerosol (t_A) is described in the article 8.5.4.

8.5.4 Estimation of the radiance due to aerosol scattering and the transmittance of aerosol

(1) Relationship between the radiance due to aerosol scattering and ε.

The radiance due to aerosol scattering L_A is not easily obtained because aerosol concentrations and type varies with time and space. Usually an additional parameter, $\varepsilon(\lambda)= L_A(\lambda)/ L_A(670)$, is used to express the spectral characteristic of areosol scattering. Onec $\varepsilon(\lambda)$ is known, and assumig $L_w(670)=0$, $L_w(\lambda)$ can be calculated from eq. (8.5.1-1) with $L_A(\lambda)$ obtained by eq. (8.5.4-5).

At first, the radiance due to aerosol scattering L_A is expressed as follows;

$$L_A(\lambda) = \frac{\omega_A(\lambda)\cdot\tau_A(\lambda)\cdot F_0'(\lambda)\cdot P_{Aa11}(\lambda,\theta,\theta_0,\Delta\phi)}{4\pi\cdot\cos\theta} \qquad (8.5.4\text{-}1)$$

where,

$\omega_A(\lambda)$: the single scattering albedo of aerosol

$\tau_A(\lambda)$: the aerosol scattering optical thickness

$F_0'(\lambda)$: the extraterrestrial solar irradiance corrected for ozone absorption

$$P_{Aa11}(\lambda,\theta,\theta_0,\Delta\phi)$$

$$= P_A(\lambda,\psi_-(\lambda)) + \left\{r(\theta(\lambda)) + r(\theta_0)\right\} * P_A(\lambda,\psi_+(\lambda)) \qquad (8.5.4\text{-}2)$$

$$\psi_+(\lambda) = \cos^{-1}\left\{\cos\theta(\lambda)\cdot\cos\theta_0 - \sin\theta(\lambda)\cdot\sin\theta_0\cdot\cos\Delta\phi\right\}$$

$$\psi_-(\lambda) = \cos^{-1}\left\{\cos(\psi_+(\lambda)) - 2\cdot\cos\theta(\lambda)\cdot\cos\theta_0\right\} \qquad (8.5.4\text{-}3)$$

$P_{Aa11}(\lambda,\theta,\theta_0,\Delta\phi)$: the scattering phase function including the contribution from sea surface reflectance

$P_A(\lambda,\psi)$: the scattering phase function of aerosol with scattering angle ψ

r (X) : the Fresnel reflectance of the interface for an incident angle X

where

$$r(x) = 1 - \left\{2\cdot m(\lambda)\cdot y\cdot z\right\} * \cos(x) \qquad (8.5.4\text{-}4)$$

$$x = \theta(\lambda) \text{ or } \theta_0$$

$$y = \frac{\left\{m(\lambda)^2 + (\cos(x))^2 - 1\right\}^{(1/2)}}{m(\lambda)}$$

$$z = \frac{1}{\left\{\cos(x) + y\cdot m(\lambda)\right\}^2} + \frac{1}{\left\{y + m(\lambda) * \cos(x)\right\}^2}$$

$\theta(\lambda)$: the zenith angle of the satellite

θ_0: the zenith angle of the sun

$m(\lambda)$: the refractive index for air-sea boundaly (= 1.34, for all bands)

From the above, the L_A ratio between bands is expressed as follows,

$$\frac{L_A(\lambda)}{L_A(670)} = \varepsilon(\lambda,670)\frac{F_0'(\lambda)}{F_0'(670)} \qquad (8.5.4\text{-}5)$$

where,

$$\varepsilon(\lambda,670) = \frac{\omega_A(\lambda)\tau_A(\lambda)P_{Aa11}(\lambda,\theta(\lambda),\theta_0)/\cos\theta(\lambda)}{\omega_A(670)\tau_A(670)P_{Aa11}(670,\theta(670),\theta_0)/\cos(670)'} \qquad (8.5.4\text{-}6)$$

Therefore, L_A at each band can be obtained by eq. (8.5.4-6) if ε at each band is determined.

In order to consider the absorption of the Asian dust, it is necessary to calculate the aerosol transmittance. And taking the spectral dependency of the single scattering albedo of aerosol, ε is calculated by pixel by pixcel.

The assumptions for this algorithm are as follows,

1) Normalized water-leaving radiance at 565nm is constant (nLw (565) = 0.3)
2) The scattering phase function of aerosol is approximated by a two-term Henyey-Greenstein (TTHG) function
3) $\varepsilon(565,670)$ $\omega_A(565)$ has the relationship described in (8.5.4-6)
4) $\omega_A(565)$ and $\omega_A(\lambda)$ has the following relationship (λ =412, 443, 490, 520 nm)

$$\omega_A(\lambda) = 1-(1-\omega_A(565))*S(\lambda,565) \qquad (8.5.4\text{-}7)$$

Where

S (λ , 565) : the coefficients which show wavelength dependency of the aerosol single scattering albedo.6.0, 5.0, 3.5, 3.0 are used for 412, 443, 490, 520 nm band, respectively.

5) the forward scattering probability (η) = 1.0
6) ω_A(670) = 1.0

(2) Calculation of the radiance due to aerosol scattering at 670nm

Assuming L_w (670) = 0, L_A(670) is calculated with L_M(670) which is obtained by (8.5.1-1)

$$L_A(670) = L_T(670) - L_M(670) \qquad (8.5.4\text{-}8)$$

(3) Calculation of the tentative ε (565,670)

The tentative ε (565,670), which is used for the detection of KOSA, is calculated as follows.

$$\varepsilon(565,670) = \frac{L_A(565)}{L_A(670)} * \frac{F_0'(670)}{F_0'(565)} \qquad (8.5.4\text{-}9)$$

Where

$L_A(565) = L_T(565) - L_M(565) - t(565) * L_W(565)$

$L_w(566)=t_0(565)*\cos\theta_0*nLw(565)$ (8.5.4-10)

$t(565) = \exp\left(-\left(\tau_M(565)/2 + \tau_{0Z}(565)\right)/\cos\theta(565)\right)t_a(565)$

$t_0(565) = \exp\left(-\left(\tau_M(565)/2 + \tau_{0Z}(565)\right)/\cos\theta_0\right)t_a(565)$

$nLw(565)$: the normalized water-leaving radiance at 565nm is assumed to be 0.3 (see eq. (8.5.4-20))

$t_a(565)$: the transmittance of aerosol at 565nm is assumed to be 1.

$t_0(565)$: the diffuse transmittance of atmosphere from the sea surface to the sun

If tentative $\varepsilon(565,670) < 1.0$ the steps (4)-(12) described below will be taken and if tentative $\varepsilon(565,670) >= 1.0$ the steps (13) will be taken.

(4) Calculation of the aerosol optical thickness of 670nm

$\tau_A(670)$ is calculated by a TTHG function.

$$\tau_A(670) = \frac{L_A(670)*4.0*\pi*\cos\theta(670)}{\omega_A(670)*P_{Aall}(670,\theta(670),\theta_0,\Delta\phi)*F_0'(670)} \qquad (8.5.4\text{-}11)$$

$P_{Aall}(670,\theta(670),\theta_0,\Delta\phi)$: See eq. (8.5.4-2)

$\omega_A(670) = 1.0$

TTHG function

$P_A(\psi,\lambda) = \gamma * f(\psi,g_1) + (1-\gamma) * f(\psi,g_2)$

Where

$$f(\psi,g) = \frac{(1-g^2)}{(1+g^2-2g.\cos\psi)^{2/3}} \qquad (8.5.4\text{-}12)$$

$\gamma = 0.983$

$g1 = 0.82$

$g2 = -0.55$

(5) Calculation of the aerosol optical thickness at 565nm

$A = L_T(565) - L_M(565)$

$B = P_{Aall}(565) * F_0'(565) / \left(4*\pi*\cos\theta(565)\right)$

Refer to eq. (8.5.4-2) for calculation of P_{Aall}

$C = t(565)*t_0(565)*nLw565*\cos\theta_0$

As to calculation of t(565) , t_0(565) , refer to (3).

$$D = 1/\cos\theta(565) + 1/\cos\theta_0$$

$E = 1/\tau_A(670) * X$

$X = 0$ (8.5.4-13)

The initial value for $\tau_A(566)$ is $\tau_A(670)$

$\tau_2 = \tau_A(670)$

$\tau = 0.0$

The iterative procedure is repeated until $|\tau_A(565) - \tau_2| < 0.0001$.

$$\begin{aligned}
&\tau = \tau_2 \\
&y = -A + B \cdot E \cdot \tau^2 + C \cdot \exp(-D \cdot (1 - E \cdot \tau) \cdot \tau) \\
&d\_y = 2 \cdot B \cdot E \cdot \tau + (-D + 2 \cdot D \cdot E \cdot \tau) \cdot C \cdot \exp(-D \cdot (1 - E \cdot \tau) \cdot \tau) \\
&\tau_2 = \tau - y / d\_y \\
&\tau_A(565) = \tau
\end{aligned} \tag{8.5.4-14}$$

(6) Calculation of the single scattering albedo at 565nm

$\omega_A(565)$ is calculated by the following equation.

$$\omega_A(565) = \tau_A(565) / \tau_A(670) * X \tag{8.5.4-15}$$

X : albedo parameter (assumed to be 1.0)

Then $\omega_A(\lambda)(\lambda=412, 443, 490, 520)$ is calculated from $\omega_A(565)$ using the following equation.

$$\omega_A(\lambda) = 1 - (1 - \omega_A(565)) * S(\lambda, 565) \tag{8.5.4-16}$$

Where

$S(\lambda, 565)$: the coefficients which show wavelength dependency of aerosol single scattering albedo. 6.0, 5.0, 3.5, 3.0 are used for 412, 443, 490, 520 nm, respectively.

(7) Calculation of Angstrom Exponent α

Angstrom Exponent α, which is used for calculation of L_A(412, 443, 490, 520), is calculated by the following equation.

$$\tau_A(565) / \tau_A(670) = (565/670)^{-\alpha} \tag{8.5.4-17}$$

(8) Calculation of the optical thickness (412 - 529nm) of aerosol

$\tau_A(\lambda)$ is calculated by α determined by eq. (8.5.4-17)

$$\tau_A(\lambda) = \tau_A(565) * (\lambda / 565)^{-\alpha} \tag{8.5.4-18}$$

(9) Calculation of the normalized water-leaving radiance at 412 - 520 nm

In consideration of the interaction term between Rayleigh and aerosol multiple scattering the correction coefficients β(λ) (λ = 412, 443, 490, 520, 565) are defined as follows.

β(412) = 0.9
β(443) = 0.95
β(λ) = 1.0 (λ = 490, 520, 595)

Then the water-leaving radiance $nL_W(\lambda)$ is calculated by the following equation.

$$nL_W(\lambda) = \frac{Lw(\lambda)}{t_0(\lambda) * \cos\theta_0} \tag{8.5.4-19}$$

Where

$$L_W(\lambda) = \{L_T(\lambda) - L_M(\lambda) - L_A(\lambda)\} / t(\lambda)$$

$$L_A(\lambda) = L_A(670) * \beta(\lambda) * \frac{\omega_A(\lambda)}{\omega_A(670)} * \frac{\tau_A(\lambda)}{\tau_A(670)} * \frac{P_{Aall}(\lambda)}{P_{Aall}(670)} * \frac{\cos\theta(670)}{\cos\theta(\lambda)} * \frac{F_0'(\lambda)}{F_0'(670)}$$

$$t(\lambda) = \exp\left[-\{\tau_M(\lambda)/2 + \tau_{0Z}(\lambda) + (1 - \omega_A(\lambda) * \eta) * \tau_A(\lambda)\} / \cos\theta(\lambda)\right]$$

$$t_0(\lambda) = \exp\left[-\{\tau_M(\lambda)/2 + \tau_{0Z}(\lambda) + (1 - \omega_A(\lambda) * \eta) * \tau_A(\lambda)\} / \cos\theta_0\right]$$

$$\eta = 1.0$$

Refer to (4) for calculation of P_{Aall}

(10) Calculation of the normalized water-leaving radiance at 565 nm

nLw (565) is calculated by assuming $\varepsilon(565, 670) = 1.0$

$$nL_W(565) = \frac{L_W(565)}{t_0(565) * \cos\theta_0} \tag{8.5.4-20}$$

Where

$$L_W(565) = \{L_T(565) - L_M(565) - L_A(565)\} / t(565)$$

$$L_A(565) = L_A(670) * 1.0 * \frac{F_0'(565)}{F_0'(670)}$$

Refer to (3) for $t(565), t_0(565)$.

(11) Calculation of $L_A(\lambda = 765, 865)$

$L_A(865)$ is calculated by assuming $L_w(865)=0$

$$L_A(865) = L_T(865) - L_M(865) \tag{8.5.4-21}$$

In case of λ =765nm band, $L_A(765)$ is calculated by the following equations.

$$L_A(765) = \rho_A'(765) \cdot F_0(765) \cdot \cos\theta_0 / \pi \qquad (8.5.4\text{-}22)$$

Where

$$\rho_A'(765) = \rho_T'(765) - \rho_M'(765) \qquad (8.5.4\text{-}23)$$

(Here the notation that primes represent quantities computed or measured when the O_2-absorption band is present is used.)

$\rho_A'(765)$: the reflectance due to the aerosol scattering when the O_2-absorption band is present

$\rho_T'(765)$: the adjusted reflectance that observed by the satellite when the O_2-absorption band is present

$\rho_M'(765)$: the reflectance due to Rayleigh scattering when the O_2-absorption band is present

$$\rho_M'(765) = \frac{\rho_M(765)}{1+10^{P_M(M)}} \qquad (8.5.4\text{-}24)$$

$$P_M(M) = a_{M0} + a_{M1} \cdot M + a_{M2} \cdot M^2$$

$$M = 1/\cos\theta(765) + 1/\cos\theta_0$$

$$a_{M0} = -1.3491, a_{M1} = 0.115, a_{M2} = -7.0218 * 10^{-3}$$

$\rho_M(765)$: the reflectance due to Rayleigh scattering when the O_2-absorption band is not present. It is calculated from the look-up tables.

M: Airmass

(12) Calculation of aerosol optical thickness at 865nm

$\tau_A(865)$ is calculated by assuming $\omega_A(865) = 1$.

.

$$\tau_A(865) = \frac{L_A(865) * 4 * \pi * \cos\theta(865)}{\omega_A(865) * P_{Aall}(865) * F_0'(865)} \qquad (8.5.4\text{-}25)$$

Refer to (4) for calculation of P_{Aall}

(13) Calculation of $\varepsilon(670,865)$ ε(670,865) is calculated by assuming $L_w(670)=0$ and $L_w(865) = 0$.

$$\varepsilon(670,865) = \frac{L_A(670)}{L_A(865)} * \frac{F_0'(865)}{F_0'(670)} \qquad (8.5.4\text{-}26)$$

(14) Gordon algorithm processing

If ε(565, 670) >= 1.0 $nL_w(\lambda)$ (λ=412, 443, 490, 520, 565) is calculated by assuming ε(λ,670) = 1.0 (λ = 412, 443, 490, 520, 565). And in consideration of the interaction term between Rayleigh and aerosol multiple scattering the correction coefficients β(λ) (λ = 412, 443, 490, 520, 565) are defined as follows.

β(412) = 0.9

β(443) = 0.95

$\beta(\lambda) = 1.0$ ($\lambda = 490, 520, 595$)

$nL_w(\lambda)$ is obtained by the following equations.

$$nL_W(\lambda) = \frac{L_W(\lambda)}{t_0(\lambda) * \cos\theta_0} \tag{8.5.4-27}$$

Where

$$L_W(\lambda) = \{L_T(\lambda) - L_M(\lambda) - L_A(\lambda)\} / t(\lambda)$$

$$L_A(\lambda) = L_A(670) * \beta(\lambda) * \varepsilon(\lambda) * \frac{F_0'(\lambda)}{F_0'(670)}$$

$t(\lambda), t_0(\lambda)$ is calculatedby assuming $t_A = 1.0$. Then $\tau_A(865)$ and $\varepsilon(670,865)$ are calcutaed by eq. (8.5.4-25) and eq. (8.5.4-26), respectively.

The processes from (2) to (13) mentioned above are performed for each pixel.

8.6 OCTS Type Algorithm

8.6.1 Overview

In this chapter, the OCTS type algorithm based on the SeaWiFS algorithm proposed by Gordon and Wang(1994) is discribed.

There are two major differences between the OCTS type and the SeaWiFS algorithms. First, one of the bands used for estimating aerosol type is different. In the OCTS algorithm 670nm and 865nm bands are used instead of 765nm and 865nm bands, taking the effect of O_2-A band absorption at 762nm into consideration. The second difference is the parameter to be used to determine the areosol model. While the SeaWiFS algorithm uses epsilon parameter, the OCTS algorithm uses gamma parameter, defined by

$$\gamma(\lambda_i, \lambda_j) = \tau_A(\lambda_i)/\tau_A(\lambda_j),$$

where τ_A is obtained from the precalculated tables derived from radiative transfer simulation assuming each of 10 aerosol models including Asian-dust. One advantage of using gamma is that the size of the table can be significantly reduced.

Reflectance observed by the satellite are indicated as follows:

$$\rho_T(\lambda) = \rho_M(\lambda) + \rho_A(\lambda) + \rho_{MA}(\lambda) + \rho_G(\lambda) + t(\lambda)\rho_W(\lambda) \tag{8.6.1-1}$$

$\rho_T(\lambda)$: the adjusted reflectance that observed by the satellite
$\rho_M(\lambda)$: the reflectance resulting from multiple scattering by air molecules (Rayleigh scattering) in the absence of aerosols
$\rho_A(\lambda)$: the reflectance resulting from multiple scattering by aerosols in the absence of air
$\rho_{MA}(\lambda)$: the reflectance resulting from the interaction term between molecular and aerosol scattering
$\rho_G(\lambda)$: the reflectance resulting from the specular reflectinos by the direct sun light
$\rho_W(\lambda)$: the water-leaving reflectance
$t(\lambda)$: the diffuse transmittance of the atmosphere along the viewing direction
λ: Wavelength

The ρ_G term in the above equation is generally ingored because ocean-color sensors are equipped with a provision for tilting the scan palne away from the specular image of the sun.

The purpose of atmospheric correction is to retrieve ρ_W from above equation with ρ_M which is calculated based on the look-up tables and $\rho_A+\rho_{MA}$ and t which are estimated by the satellite data.

The relationship between radiance and reflectance is as follows:

$$\rho = \pi L / \left(F_0 \cdot \cos\theta_0\right) \tag{8.6.1-2}$$

L:	the upward radiance in the given viewing direction
F_0:	the extraterrestrial solar irradiance
θ_0:	zenith angle of the sun

Where, $\rho_T = \pi(L_T * g + o) / \left(F_0 \cdot \cos\theta_0\right)$

g, o : radiance adjustment parameters

The calculation methods of $\rho_M(\lambda)$, $\rho_A(\lambda) + \rho_{MA}(\lambda)$ are described below.

8.6.2 Calculation of the reflectance due to the scatteing by air molecules

(1) Calculation of the optical thickness of ozone

The optical thickness of ozone is calculated by the following equation:

$$\tau_{0Z}(\lambda) = K_{0Z}(\lambda) * DU \qquad (8.6.2\text{-}1)$$

$K_{0Z}(\lambda)$: Coefficients which relate optical thickness of ozone and DU. The following values are stored in database.

λ	412	443	490	520
K_{0Z}	7.701 e^{-7}	3.905 e^{-6}	2.488 e^{-5}	4.724 e^{-5}
λ	565	670	765	865
K_{0Z}	1.127 e^{-4}	4.923 e^{-5}	8.146 e^{-6}	3.410 e^{-6}

DU : Total ozone. It is inputted by EOIS ground observation DB. DU(Dobson Unit) means total ozone concentration at 0°C, 1hPa (above mean sea level) and one DU is equal to a hundredth of the ozone layer thickness. DU is expressed in mm. TOMS data is interpolated both spatially and temporally for this value.

(2) Calculation of the Rayleigh optical thickness

The Rayleigh optical thickness (τ_M) is calculated by the following equation:

$$\tau_M(\lambda) = P / P_0 * \tau_{M0} \qquad (8.6.2\text{-}2)$$

P: Atmospheric pressure on the ground for each pixel. It is inputted from EOIS ground observation DB.

P_0: Standard atmospheric pressure (= 1013.25hPa)

$\tau_{M0}(\lambda)$: The Rayleigh optical thickness at standard atmospheric pressure. The following values are stored in database.

λ	412	443	490	520
τ_{M0}	0.31380	0.23450	0.15540	0.12640
λ	565	670	765	865
τ_{M0}	0.085430	0.043870	0.025470	0.015760

(3) Calculation of the extraterrestrial solar irradiance(F_0) considering ozone impact

The extraterrestrial solar irradiance (F_0') in consideration of ozone impact is calculated by the following equation using extraterrestrial solar irradiance (F_0) .

$$F_0'(\lambda) = F_0(\lambda) * \exp\left\{-\tau_{0Z}(\lambda) * \left(1/\cos\theta(\lambda) + 1/\cos\theta_0\right)\right\} \qquad (8.6.2\text{-}3)$$

Where

$$F_0(\lambda) = \langle F_0(\lambda)\rangle \left\{1 + 0.0167 * \cos\left(2\pi(D-3)/365\right)\right\}^2 \qquad (8.6.2\text{-}4)$$

$\langle F_0(\lambda)\rangle$: The annual average extraterrestrial solar irradiance(F_0)
The following values are stored in database.

λ	412	443	490	520
F_0	170.96	188.17	194.59	185.74
λ	565	670	765	865
F_0	184.49	153.12	122.61	98.55

D : the day of the year (D=1 on January 1 and D=365 on December 31)
π : Circular constant (radian)
$\theta(\lambda)$: Zenith angle of the satellite
θ_0 : Zenith angle of the sun

(4) Calculation of the reflectance due to the scattering by atmospheric molecule

The reflectance due to the scattering by atmospheric molecule(ρ_M)is calculated by the following equation:

$$\rho_M(\lambda) = \frac{\{1-\exp(-\tau_M(\lambda)/\cos\theta(\lambda))\}}{\{1-\exp(-\tau_{M0}(\lambda)/\cos\theta(\lambda))\}} * \exp\left\{-\tau_{oz}(\lambda) * \left(\frac{1}{\cos\theta(\lambda)} + \frac{1}{\cos\theta_0}\right)\right\}$$
$$* \sum_{i=0}^{2} \rho_i(\lambda, \theta(\lambda), \theta_0) \cos(i * \Delta\phi(\lambda))$$

(8.6.2-5)

τ_M : the Rayleigh optical thickness which is calculated by eq. (8.6.2-2)
τ_{M0} : the Rayleigh optical thickness at standard atmospheric pressure
τ_{oz} : the optical thickness of ozone
θ : the zenith angle of the satellite
θ_0 : the zenith angle of the sun
ρ_i : Fourier Coefficients which are calculated from look-up table
$\Delta\phi$: the difference between the solar and the satellite azimuth angles

The look-up table of Fourier Coefficients($\rho_i(\lambda,\theta(\lambda),\theta_0)$) has 41 values for satellite zenith angle (0.0° - 89.95°) and45 values for solar zenith angle in 2° increments (0.0° - 88.0°). If there is no exact Fourier Coefficients for the target pixcel in the look-up table the values needed in eq. (8.6.2-5) are interpolated by two-dimensional linear interpolation.

8.6.3 Estimation of the reflectance due to the aerosol scattering

(1) The relationship between aerosol multiple scattering and aerosol single scattering approximations

Resulting from the radiative transfer simulation, the relationship between aerosol multiple scattering and aerosol single scattering approzimation is assumed to be

$$\rho_A(\lambda) + \rho_{MA}(\lambda) = \rho_{AS}(M,\lambda) + RES(\lambda,\theta(\lambda),\theta_0,\Delta\phi,\tau_A,M) \qquad (8.6.3\text{-}1)$$

Where

$\rho_{AS}(\lambda)$: the reflectance due to the single scattering of aerosol

$$RES = a_0 + a_1 \cdot \tau_A(M,\lambda) + a_2 \cdot \tau_A(M,\lambda)^2 + a_3 \cdot \tau_A(M,\lambda)^3 \qquad (8.6.3\text{-}2)$$

M: Aerosol model

a_0: Always stays 0

$a_1,\ a_2,\ a_3$: Coefficients depending on $M,\lambda,\theta,\theta_0,\Delta\phi$. They are calculated from the look-up tables by Lagrange's interpolation method. Refer to section 8.6.7 for detail

$\rho_{AS}(\lambda)$ is written as follows:

$$\rho_{AS}(M,\lambda) = \omega_A(M,\lambda) \cdot PR_A(M,\lambda,\theta(\lambda),\theta_0,\Delta\phi) \cdot \tau_A(M,\lambda) / \left(4\cos\theta(\lambda) \cdot \cos\theta_0\right) \qquad (8.6.3\text{-}3)$$

$\omega_A(M,\lambda)$: the single scattering albedo of aerosol. It is inputed from the look-up table

$\tau_A(M,\lambda)$: the optical thickness of aerosol

$PR_A(M,\lambda,\theta(\lambda),\theta_0,\Delta\phi)$: the scattering phase function with the specular reflection

$$PR_A(M,\lambda,\theta(\lambda),\theta_0,\Delta\phi) = P_A(M,\lambda,\psi_-(\lambda)) + P_A(M,\lambda,\psi_+(\lambda)) * \left(R(\theta(\lambda)) + R(\theta_0)\right) \qquad (8.6.3\text{-}4)$$

$P_A(M,\lambda,\psi)$: the scattering phase function at scattering angle ψ. It is inputed from the look-up table

$$\psi_+(\lambda) = \cos^{-1}\left\{\cos\theta(\lambda) \cdot \cos\theta_0 - \sin\theta(\lambda) \cdot \sin\theta_0 \cdot \cos\Delta\phi\right\}$$

$$\psi_-(\lambda) = \cos^{-1}\left\{\cos(\psi_+(\lambda)) - 2 \cdot \cos\theta(\lambda) \cdot \cos\theta_0\right\} \qquad (8.6.3\text{-}5)$$

$R(x)$: the Fresnel reflectance of the interface for an incident angle x

$$R(x) = 1 - \{2\ m(\lambda)\ y\ z\} \cos(x) \qquad (8.6.3\text{-}6)$$

$x = \theta(\lambda)$ or θ_0

$$y = \frac{\left\{ m(\lambda)^2 + \left(\cos(x)\right)^2 - 1 \right\}^{(1/2)}}{m(\lambda)}$$

$$z = \frac{1}{\left\{ \cos(x) + y \cdot m(\lambda) \right\}^2} + \frac{1}{\left\{ y + \cos(x) \cdot m(\lambda) \right\}^2}$$

$m(\lambda)$: the refractive index for ari-sea boundaly(= 1.34, for all bands)

(2) Calculation of $\tau_A(M,670), \tau_A(M,865)$ for each aerosol model

By assuming $\rho_W(670) = 0, \rho_W(865) = 0$,

$$\rho_A(670) + \rho_{MA}(670) = \rho_T(670) - \rho_M(670)$$
$$\rho_A(865) + \rho_{MA}(865) = \rho_T(865) - \rho_M(865) \qquad (8.6.3\text{-}7)$$

Then τ_A(M,670) and τ_A(865) are calculated by following equation.

$$a_3 \cdot \tau_A{}^3 + a_2 \cdot \tau_A{}^2 + (a_1 + b) \cdot \tau_A - (\rho_A + \rho_{MA}) = 0 \qquad (8.6.3\text{-}8)$$

Where

$$b = \omega_A \cdot PR_A / \left(4 \cdot \cos\theta(\lambda) \cdot \cos\theta_0\right)$$

(3) Determinatin of the aerosol model

In order to select specific aerosol model from the candidate aerosol models, $\gamma'_{ave}(670,865)$ is calculated as follows:

$$\gamma'_{ave}(670,865) = \left\{ \frac{1}{NM} \sum_{M=0}^{NM} \gamma'(M,670,865) \right\} * \quad +$$

(8.6.3-9)

M: Aerosol model
NM: the number of models
 , : ’ adjustment parameters

Where,

$$\gamma'(M,670,865) = \tau_A(M,670) / \tau_A(M,865) \qquad (8.6.3\text{-}10)$$

$\gamma'(M,670,865)$: Ratio of the aerosol optical thicknesses which are calculated by eq. (8.6.3-8).
M: Aerosol model

Then the two aerosol model are selected by the following equation.

$$\gamma(A,670,865) < \gamma'_{ave}(670,865) < \gamma(B,670,865) \qquad (8.6.3\text{-}11)$$

Where

A, B : Models to be selected

$$\gamma(M,670,865) = K_{ext}(M,670) / K_{ext}(M,865) \qquad (8.6.3\text{-}12)$$

$\gamma(M,670,865)$: Ratio of the Extinction Coefficients which are inputted from the look-up table.

$K_{ext}(M,\lambda)$: Extinction Coefficient

M: Aerosol model A or B

(4) Calculation of interior division ratio

Interior division ratio used for interpolation of $\rho_A(\lambda)+\rho_{MA}(\lambda)$ is calculated by the following equation with value of γ (M,670,865) of two aerosol model (A, B) selected in (3).

$$r=\{\gamma'_{ave}(670,865)-\gamma(A,670,865)\}/\{\gamma(B,670,865)-\gamma(A,670,865)\} \tag{8.6.3-13}$$

r: Interior division ratio between aerosol model A and B

γ (M, 670,865) : Ratio of Extinction Coefficient which are inputted from the look-up table.

$\gamma'_{ave}(670,865)$: the averaged $\gamma'(M,670,865)$ calculated by eq. (8.6.3-9)

M : Selected aerosol model A or B

(5) Calculation of $\rho_A+\rho_{MA}$ in each wave length from 412 nm to 565nm.

Calculate $\rho_A(M,\lambda)+\rho_{MA}(M,\lambda)$ for two models selected in (3) and determine $\rho_A(\lambda)+\rho_{MA}(\lambda)$ for each wave length using interior division ratio determined in (4).

From eq. (8.6.3-8)

$$\rho_A(M,\lambda)+\rho_{MA}(M,\lambda)=a_3\cdot\tau_A(M,\lambda)^3+a_2\cdot\tau_A(M,\lambda)^2+(a_1+b)\cdot\tau_A(M,\lambda)$$

Where,

$$b=\omega_A(M,\lambda)\cdot PR_A/(4\cdot\cos\theta(\lambda)\cdot\cos\theta_0)$$

$$\tau_A(M,\lambda)=\{K_{ext}(M,\lambda)/K_{ext}(M,865)\}\cdot\tau_A(M,865) \tag{8.6.3-14}$$

M: Selected aerosol model A or B

a_1,a_2,a_3: Coefficients dependent on $\lambda,\theta(\lambda),\theta_0,\Delta\phi$. Refer to section 8.6.7 for detail.

$\omega_A(M,\lambda)$: the single scattering albedo of aerosol. It is inputed from the look-up table

PR_A: the scattering phase function with the specular reflection

K_{ext}: Extinction CoefFicient

By the interior division ratio determined in (4),

$$\rho_A(\lambda)+\rho_{MA}(\lambda)$$
$$=(1-r)\cdot\{\rho_A(A,\lambda)+\rho_{MA}(A,\lambda)\}+r\cdot\{\rho_A(B,\lambda)+\rho_{MA}(B,\lambda)\} \tag{8.6.3-15}$$

8.6.4 Calculation of the diffuse transmittance of the atmosphere

The diffusion transmittance(t) of the atmosphere is expressed by transmittance of three elements, molecules, ozone and aerosol in atmosphere as indicated as follows:

$$t(\lambda) = t_M(\lambda) \cdot t_{0Z}(\lambda) \cdot t_A(\lambda) \qquad (8.6.4\text{-}1)$$

t_M : the transmittance of molecules in atmosphere

t_{0Z} : the transmittance of ozone

t_A : the transmittance of aerosol

Assuming that a photon scattered by the aerosol will be scattered through an angle of <90°, the diffuse transmittance of atmosphere is calculated here. The actual optical thickness of atmospheric molecular is considered to be half due to symmetry of scattering phase function. For t_{0Z}, one time absorption between sea surface and the satellite should only be considered. Since optical path length is in proportion to $1/\cos\theta$ when plane parallel atmosphere is taken in to consideration, the transmittance of atmosphere, ozone and aerosol are expressed as follows.

$$t_M(\lambda) = \exp\left\{\left(-\tau_M(\lambda)/2\right)/\cos\theta(\lambda)\right\} \qquad (8.6.4\text{-}2)$$

$\tau_M(\lambda)$: the optical thickness of molecules in atmosphere

$$t_{0Z}(\lambda) = \exp\left(-\tau_{OZ}(\lambda)/\cos\theta(\lambda)\right) \qquad (8.6.4\text{-}3)$$

$\tau_{OZ}(\lambda)$: the optical thickness of ozone

$$t_A(\lambda) = \left\{-f(\lambda)/\cos\theta\right\}$$

Where

$$f(\lambda) = (1-r) \cdot \left\{1 - \omega_A(A,\lambda) \cdot \eta(A,\lambda)\right\} \cdot \tau_A(A,\lambda)$$
$$+ r \cdot \left\{1 - \omega_A(B,\lambda) \cdot \eta(B,\lambda)\right\} \cdot \tau_A(B,\lambda) \qquad (8.6.4\text{-}5)$$

A, B : the selected models

$\omega_A(M,\lambda)$: the single scattering albedo of aerosol (refer to the table)

$\eta(M,\lambda)$: the forward scattering probability of aerosol is assumed to be 1.0

r : Interior division ratio between aerosol model A and B

8.6.5 Calculation of the water-leaving reflectance

$\rho_W(\lambda)$ for λ = 412,443,490,520,565nm band are calculated by following equation:

$$\rho_W(\lambda) = \left\{\rho_T(\lambda) - \rho_M(\lambda) - \left(\rho_A(\lambda) + \rho_{MA}(\lambda)\right)\right\} / t(\lambda) \qquad (8.6.5\text{-}1)$$

8.6.6 Calculation of $nL_w(\lambda)$, $L_A(\lambda)$, $\tau_A(865)$, $\varepsilon(670, 865)$

(1) Calculation of $nL_W(\lambda)$ at 412. 443, 490, 520, 565nm band

$nL_W(\lambda)$ is calculated by the following equation:

$$nL_W(\lambda) = L_W(\lambda)/(\cos\theta_0 \cdot t_0) \qquad (8.6.6\text{-}1)$$
$$= \rho_W(\lambda) \cdot F_0(\lambda)/(\pi \cdot t_0)$$

$nL_W(\lambda)$: the normalized water-leaving radiance

$L_W(\lambda)$: the water-leaving radiance

t_0: the diffuse transmittance of atmosphere from the sea surface to the sun

(2) $L_A(\lambda = 670,765,865)$

In case of λ =670 or 865nm band $L_A(\lambda)$ is calculated by the following equation:

$$L_A(\lambda) = L_T(\lambda) - L_M(\lambda) \qquad (8.6.6\text{-}2)$$
$$= \{\rho_T(\lambda) - \rho_M(\lambda)\} \cdot \{F_0(\lambda) \cdot \cos\theta_0\}/\pi$$

In case of λ =765nm band, $L_A(765)$ is calculated by the following equations.

$$L_A(765) = \rho_A'(765) \cdot F_0(765) \cdot \cos\theta_0 / \pi \qquad (8.6.6\text{-}3)$$

Where

$$\rho_A'(765) = \rho_T'(765) - \rho_M'(765) \qquad (8.6.6\text{-}4)$$

(Here the notation that primes represent quantities computed or measured when the O_2-absorption band is present is used.)

$\rho_A'(765)$: the reflectance due to the aerosol scattering when the O_2-absorption band is present

$\rho_T'(765)$: the adjusted reflectance that observed by the satellite when the O_2-absorption band is present

$\rho_M'(765)$: the reflectance due to Rayleigh scattering when the O_2-absorption band is present

$$\rho_M'(765) = \frac{\rho_M(765)}{1+10^{P_M(M)}} \qquad (8.6.6\text{-}5)$$

$$P_M(M) = a_{M0} + a_{M1} \cdot M + a_{M2} \cdot M^2$$

$$M = 1/\cos\theta(765) + 1/\cos\theta_0$$

$$a_{M0} = -1.3491, a_{M1} = 0.115, a_{M2} = -7.0218*10^{-3}$$

$\rho_M(765)$: the reflectance due to Rayleigh scattering when the O_2-absorption band is not present. It is calculated from the look-up tables.

M: Airmass

(3) Calculation of $\tau_A(865)$

τ_A (865) is calculated with τ_A (M, 865) obtained by eq. (8.6.3-8) and the interior division ratio obtained by eq. (8.6.3-13).

$$\tau_A(865) = (1-r)\cdot\tau_A(A{,}865) + r\cdot\tau_A(B{,}865) \qquad (8.6.6\text{-}6)$$

A, *B* : the selected two models
r : the interior division ratio between aerosol model A and B

(4) Calculation of $\varepsilon(670{,}865)$

ε(670,865) is calculated from ε(A,670,865) and ε(B,670,865) using interior division ratio calculated by eq. (8.6.3-13).

$$\varepsilon(M{,}670{,}865) = \frac{\omega_A(M{,}670)\cdot PR_A\left(M{,}670{,}\theta(670){,}\theta_0{,}\Delta\phi(670)\right)\cdot\tau_A(M{,}670)/\cos\theta(670)}{\omega_A(M{,}865)\cdot PR_A\left(M{,}865{,}\theta(865){,}\theta_0{,}\Delta\phi(865)\right)\cdot\tau_A(M{,}865)/\cos\theta(865)} \qquad (8.6.6\text{-}7)$$

Where,

M:	Selected model *A* or *B*
$\omega_A(M,\lambda)$:	Single scattering albedo of aerosol (see table)
PR_A:	Refer to eq. (8.6.3-4)
$\tau_A(M,\lambda)$:	the optical thickness of aerosol which is calculated by eq. (8.6.3-8)

ε(670,865) = (1-r) ∗ε(A,670,865) + r∗ε(B,670,865)

8.6.7 Interpolation of a1, a2 and a3

Coefficients a_n(n = 1,2,3) used in eq.(8.6.3-2) are calculated from the look-up tables by Lagrange's interpolation method. There are 10 look-up tables corresponding different aerosol models[Tropospheric model (RH50%,80%,90%), Coastal model (RH50%,80%,99%), Maritime model (RH50%,80%,99%) and Yellow dust] for each band. Each look-up table has 24values for the satellite and the solar zenith angles in 3.5° increments(0°- 80.5°) and 46values for the difference between the solar and the satellite azimuth angles in 4° increments(0° - 180°). When $\theta \leq 60° \; and \; \theta_0 \leq 60°$ one degree Lagrange's interpolation is used to obtain a_n. And when $\theta_0 > 60° \; or \; \theta_0 > 60°$ two degree Lagrange's interpolation is used.

(1) Calculation formula for one degree Lagrange's interpolation (when $\theta \leq 60° \; and \; \theta_0 \leq 60°$)

$$a_n(\theta, \theta_0, \Delta\phi) = \sum_{i=u}^{u+1} \sum_{j=v}^{v+1} \sum_{k=w}^{w+1} A_{n,ijk} \cdot L_i(\theta) \cdot M_j(\theta_0) \cdot N_k(\Delta\phi) \qquad (8.6.7\text{-}2)$$

The condition of the grid point numbers, *u*, *v* and *w*, are as follows.

$u < \theta < u + 1$

$v < \theta_0 < v + 1$

$w < \Delta\phi < w + 1$

where

$0 \leq u \leq 22, 0 \leq v \leq 22, 0 \leq w \leq 44$

$A_{n,ijk}$: values in grid points i, j, k. It's obtained from the look-up table.

θ: the zenith angle of the satellite. 0 - 80.5°, 3.5° increments, 24 data, i = 0,....., 23

θ_0: the zenith angle of the sun. 0 - 80.5°, 3.5° increments, 24 data, j = 0,....., 23

$\Delta\phi$: the difference between the solar and the satellite azimuth angles. 0 - 180.0° , 4.0° increments, 46 data, k = 0,....., 45

$$L_u(\theta) = \frac{(\theta - \theta_{u+1})}{(\theta_u - \theta_{u+1})}$$

$$L_{u+1}(\theta) = \frac{(\theta - \theta_u)}{(\theta_{u+1} - \theta_u)}$$

The shape of equations $M_j(\theta_0)$ and $N_k(\Delta\phi)$ are the same as those of $L_i(\theta)$.

(2) Calculation formula for two degree Lagrange's interpolation (when $\theta_0 > 60° \; or \; \theta_0 > 60°$)

$$a_n(\theta, \theta_0, \Delta\phi) = \sum_{i=u}^{u+2} \sum_{j=v}^{v+2} \sum_{k=w}^{w+2} A_{n,ijk} \cdot L_i(\theta) \cdot M_j(\theta_0) \cdot N_k(\Delta\phi) \qquad (8.6.7\text{-}3)$$

u+1, v+1, w+1 : grid points closest to $\theta, \theta_0, \Delta\phi$

where

$0 \le u \le 21, 0 \le v \le 21, 0 \le w \le 43$

$A_{n,\,ijk}$: values at grid point i, j, k. It's obtained from the look-up table.

θ: the zenith angle of the satellite. 0 - 80.5°, 3.5° increments, 24 data, i = 0,....., 23

θ_0: the zenith angle of the sun. 0 - 80.5°, 3.5° increments, 24 data, j = 0,....., 23

$\Delta\phi$: the difference between the solar and the satellite azimuth angles.
0 - 180.0°, 4.0° increments, 46 data, k = 0,....., 45

$$L_u(\theta) = \frac{(\theta - \theta_{u+1})(\theta - \theta_{u+2})}{(\theta_u - \theta_{u+1})(\theta_u - \theta_{u+2})}$$

$$L_{u+1}(\theta) = \frac{(\theta - \theta_u)(\theta - \theta_{u+2})}{(\theta_{u+1} - \theta_u)(\theta_{u+1} - \theta_{u+2})}$$

$$L_{u+2}(\theta) = \frac{(\theta - \theta_u)(\theta - \theta_{u+1})}{(\theta_{u+2} - \theta_u)(\theta_{u+2} - \theta_{u+1})}$$

The shape of equations $M_j(\theta_0)$ and $N_k(\Delta\phi)$ are the same as those of $L_i(\theta)$.

8.7 OCTS Level-2 Masks/Flags

8.7.1 OCTS Level-2 Masks/Flags

In the atmospheric correction, the masks and flags shown below are judged for each pixel. A pixel with flag means that a bit plane of the pixel is swithed on but data of the pixel is still processed to level-2. A pixel with mask means that a bit plane of the pixel is switched on and the level-2 process is skipped. If a pixel is masked the level-1 radiance is assigned to nL_w and L_A products and zero to the other products.

-Absorptive Aerosol
-Low $L_w(565)$
-High $\tau_A(865)$
-Solar Zenith Angle
-Cloud/Ice
-Incomplete Band Set
-Negative L_w
-Bathymetry
- Space Craft Zenith Angle
-Bright Target
-Glint
-Near Cloud
-Land
-Atmospeheic Correction Fails

This quality control information is created by the following procedures.

(1) Absorptive Aerosol (flag)
The pixel which the absorptive aerosol model was applied.
CZCS type algorithm : $\varepsilon(565, 670)<1.0$
OCTS type algorithm : $\varepsilon(670, 865)<\varepsilon_{maritime}(670, 865)$

(2) Low $L_w(565)$ (flag)
When $nL_w(565) < 0.21[\mu W/cm^2/sr/nm]$, a flag is placed.

(3) High $\tau_A(865)$ (flag)
When $\tau_A(865)>1.0$, a flag is placed.

(4) Solar Zenith Angle (flag)
When solar zenith angle > 70°, a flag is placed.

(5) Cloud / Ice (mask)

Calculate $nL_A(865)$ by the following equation and when $nL_A(865)>0.97$, place a flag and perform masking.

$$nL_A(865) = \frac{L_A(865)}{tCl(\theta_0,865) * tCL(\theta,865)} \qquad (8.7\text{-}1)$$

Where

$$tCL(\beta,865) = \exp\left\{\left(-\frac{\tau_M(865)}{4} + \tau_{0Z}(865)\right) / \cos\beta\right\}$$

$$\tau_M(865) = (P / P_0) * \tau_{M0}(865)$$

$$\beta = \theta_0 \text{ or } \theta$$

(6) Incomplete Band Set (mask)

The pixel that misses observation at some bands due to the registration correction near the scan edge. It's judged during the band to band registration process.

(7) Negative L_w (mask)

The pixel having negative L_w in one or more bands.

(8) Bathymetry (flag)

When water depth is less than 30m, flag is placed by referring to external database.

(9) Space Craft Zenith Angle (flag)

The pixel having large space craft zenith angle.

$\theta(\text{Band1})>45°$

(10) Bright Target (flag)

The pixel which the measured radiance is affected by cross-talk, under-shoot or over-shoot. The pixels with Transient Response flag in level-1B image are judged as Bright Target.

(11) Glint (mask)

The pixel contaminated by sun-glint. It's judged by $L_G(865)$ which is calculated by Cox and Munk(1954). If $L_G(865)>0.005 * F_0(865)$, a flag is placed and masking is performed.

(12) Near Cloud (flag)

When saturated rate of band1 in the square area >= 10[%], a flag is placed. The square size is 49*49 pixels in full resolution.

(13) Land (mask)

By referring to external database, flag is placed on land and masking is performed.

(14) Atmospheric Correction Fails (mask)

Place a flag when the following criteria is satisfied.

CZCS type algorithm : ε (670, 865)>2.0

OCTS type algorithm : $\gamma_{\min}$ (670, 865)< γ'_{ave} (670, 865) < $\gamma_{\max}$ (670, 865)

Where

$$\gamma(670, 865) = K_{ext}(670) / K_{ext}(865)$$

$$\gamma'(670, 865) = \tau_A(670) / \tau_A(865)$$

8.8 References

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