

## EXTRACTION OF AEROSOL PROPERTIES AND SURFACE REFLECTANCE FROM POLDER DATA OVER LAND

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### Commision VIII

**KEY WORDS:** Atmospheric Aerosols over Land, Surface Reflectance, Polarized Radiance, PARASOL/POLDER

### ABSTRACT

It is as yet very difficult to extract optical properties of atmospheric aerosols from satellite data over land. The PARASOL/ POLDER observes the reflectance and polarization of a target quasi-simultaneously in multi-viewing angles at wavelengths of 490nm, 670nm and 865nm. In this study, a new estimation method of aerosol properties using the polarized radiance effectively is described. The polarized radiance at the top of the atmosphere does not depend on the surface reflectance if the ground surface is assumed to be the uniform Lambertian reflector. First of all, the optical thickness  $\tau$ , the refractive index  $N_r$  and the size distribution  $a$  (index of Junge power-law) of aerosols is estimated from polarized radiances at 670nm received by the POLDER. In this case, it was assumed that the imaginary part of complex refractive index,  $N_i$ , is zero because there is very little absorption for dust particles at 670nm. After that, the surface reflectance  $A$  is obtained from total radiances at 670nm. Next, the  $\tau$ ,  $N_i$  (the imaginary part of complex refractive index) at 490nm are estimated from polarized radiances because the absorption of light ray by aerosols is not ignored. The surface reflectance  $A$  at 490nm is estimated at the same way as the case of 670nm. Finally, the method described here was applied to PARASOL/POLDER data over land taken on April 28, 2006. As a result, it is shown that this algorithm provides reasonable values for aerosol properties and surface reflectance.

### 1. INTRODUCTION

The Asian dust transported from desert areas in the northern China often covers over East Asia in the late winter and spring seasons. It is regarded as a main source of atmospheric aerosols over East Asia and has significant effects on the climate change. Many authors have investigated aerosol properties over ocean (Nakajima et al.,1998, Tanre et al.,1997) and over dark vegetated areas (Kaufman et al.,1997a, Kaufman et al.,1997b) by using satellite measurements. In these cases, the surface reflectance is small and the contribution of the radiance reflected by the surface to the total radiance received by a satellite sensor is small. However, in the remote sensing over land at optical wavelengths, the radiance received by the satellite sensor strongly depends on the surface reflectance. It will be, therefore, necessary to estimate optical properties of aerosols in the air and the surface reflectance simultaneously from satellite data.

The PARASOL/POLDER observes the reflectance and polarization of a target quasi-simultaneously in multi-viewing angles at wavelengths of 490nm, 670nm and 865nm, and so POLDER data provide enough information to estimate optical characteristics of atmospheric aerosols and the surface reflectance. We have developed the algorithm for estimating optical properties of aerosols and the surface reflectance simultaneously from POLDER data (Kusaka et al., 2001, 2002, 2004). However, their algorithms do not take into account absorption of light ray by aerosols at shorter wavelengths. Therefore, the improvement of the estimation process will be needed.

In this study, we describe a new method for extracting aerosol properties from POLDER data by using the polarized radiance effectively. After that, we use the estimated aerosol properties to estimate the surface reflectance from the total radiance received by the POLDER. This is because the polarized

radiance at the top of the atmosphere does not depend on the surface reflectance if the ground surface is assumed to be the uniform Lambertian reflector (Kusaka, et al., 2009). Since the ground resolution of a POLDER-measured pixel is  $5 \times 5 \text{ km}^2$  at nadir, the radiance and polarization at the top of the atmosphere are given by numerical solutions of the radiative transfer equation in a plane parallel atmosphere bounded by the uniform Lambertian reflector. We used the 6SV-1.0B code developed by Vermote et al. (Vermote et al. 2006) to compute values of Stokes parameters at the top of the atmosphere. In this case, it was assumed that the number size distribution of aerosols is represented by the Junge power-law (minimum radius:  $0.05 \mu\text{m}$ , maximum radius:  $15 \mu\text{m}$ ) and aerosol particles are spherical.

By comparing the radiance and polarization received by the POLDER with those obtained from the radiative transfer simulation, we estimate the optical thickness of aerosols,  $\tau$ , the exponent of Junge power-law,  $a$ , the complex refractive index,  $N_r$  (real part) and  $N_i$  (imaginary part), and the surface reflectance,  $A$ . The contribution of light scattering by aerosols to the total radiance in the near infrared wavelength is relatively small. In the present study, we extract aerosol properties and the surface reflectance from POLDER data acquired at 490nm and 670nm channels.

### 2. Polarized Radiances at the Top of Atmosphere

The radiance and polarization of scattering light are completely described by the Stokes parameters (I, Q, U, V), where I is the radiance and the other parameters have same dimension. We have  $V=0$  in the linear polarization. The linearly polarized radiance  $I_p$  and the polarization direction  $\chi$  can be derived from Q and U as follows (Hansen, et al., 1974):

$$I_p = \sqrt{Q^2 + U^2} \quad (1)$$

$$\tan(2\chi) = U/Q \quad (2)$$

The degree of polarization is defined as the ratio  $I_p/I$ .

The polarized radiance received by a satellite sensor does not depend on the surface reflectance because the reflected light by the Lambertian surface is depolarized. This indicates that we will be able to estimate optical properties of atmospheric aerosols inversely from the polarized radiance. Once we have found definite optical properties of aerosols in the atmosphere, we can easily determine the surface reflectance from the total radiance,  $I$ , received by a satellite sensor.

### 3. Look-up Tables for Radiance and Polarization

The values of Stokes parameters at the top of the atmosphere are obtained from the numerical computation of the radiative transfer equation in a uniform plane parallel atmosphere bounded by the uniform Lambertian reflector. We use the 6SV-1.0B code to compute values of Stokes parameters at the top of atmosphere. This code requires a set of input parameters such as geometrical conditions defined by a user, atmospheric model, user-defined aerosols model, optical and spectral conditions, spectral ground reflectance, target elevation and so on, as an input text file and outputs the values of Stokes parameters and others in a text file.

#### 3.1 Application Software for Generating Look-up Tables

In order to create a Look-up table for the radiance and polarization, we need to change various parameters in the input text file and extract information necessary from the output text files. This is a time-consuming task. We produced an application software, 6SinOut, to change values of input parameters and extract necessary information from output files. We used the Visual C++ in the .NET framework to develop the 6SinOut.

The 6SinOut consists of two components. One creates output files of computational results that correspond to various sets of input parameters into the 6SV-1.0B. The other arranges output files in an appropriate order and then extract the total radiance, the polarized radiance, the polarization direction and geometric conditions from each of output files.

#### 3.2 Construction of Look-up Tables

We computed the radiance and polarization at the top of the atmosphere in the following atmosphere-ground system.

(1) Since we focus on retrieving optical characteristic of atmospheric aerosols including Asian dust from satellite data over East Asia in the late winter and spring seasons, we adopted the midlatitude winter model as the atmospheric model.

(2) We adopted the Junge power-law as the typical number size distribution of aerosols because the difference between size distributions is represented by the exponent,  $a$ , of the Junge power-law if the range of the aerosol size is fixed.

(3) The polarized radiance at the top of the atmosphere does not depend on the Lambertian surface reflectance,  $A$ , and so we assumed  $A=0$  in the creation of Look-up tables for estimating aerosol properties from polarized radiances. We also assumed that the altitude of a target is zero.

First of all, we generated the Look-up table, LU670, available for the estimation of aerosol properties at 670nm. In this case, we assumed that there is very little absorption of light ray at 670nm by dust particles and so the imaginary part of complex refractive index,  $N_i$ , is zero. Using the 6SinOut, we computed the radiance, RAD, the polarized radiance, POL and the

polarization direction, PD, at the top of atmosphere as a function of the optical thickness of aerosols at 550nm,  $\tau(550)$ , refractive index of aerosols,  $N_r$ , and index of Junge power-law,  $a$ , under a given geometric condition such as solar zenith angle, SZA, viewing zenith angle, VZA, and relative azimuth angle, RAZ. The values of RAD, POL and PD computed for typical values of  $N_r$ ,  $a$ ,  $\tau(550)$ , SZA, VZA and RAZ were saved in the look-up table, LU670.

The measurement of the wavelength dependency for the absorption of light ray by dust particles is as yet very sparse, but the absorption of light ray by aerosols will be taken into account in the estimation of aerosol properties at 490nm. This indicates that we will need to estimate the complex refractive index of aerosols ( $N_r$ ,  $N_i$ ). Therefore, we generated the look-up table, LU490, of RAD, POL and PD for typical values of  $N_r$ ,  $N_i$ ,  $a$ ,  $\tau(550)$ , SZA, VZA and RAZ in the same way as the case at 670nm.

### 4. Estimation of Aerosol Properties and Surface Reflectance at 670nm and 490nm

The values of Stokes parameters  $I$ ,  $Q$ ,  $U$  measured in different  $N$  geometric conditions, each of which consists of a 3-tuple of (SZA, VZA, RAZ), at a pixel of POLDER data at 490nm and 670nm channels are saved. Since the values of SZA, VZA, RAZ at a target pixel measured by the POLDER are different from those given in Look-up tables, we used the 2nd-order polynomials function to interpolate the values of RAD, POL and PD against all combinations of  $N_r$ ,  $a$ ,  $\tau(550)$  in the LU670 that correspond to geometric conditions given in POLDER data, and then generated a new Look-up table, nLU670, at 670nm.

#### 4.1 Estimation of Aerosol properties at 670nm

We used the least square method to estimate aerosol properties,  $N_r$ ,  $a$ ,  $\tau(550)$  from POLDER data at 670nm. Let the  $i$ -th geometric condition at a target pixel be (SZA, VZA, RAZ) <sub>$i$</sub> , ( $i=1, \dots, N$ ). The polarized radiance,  $pI_{p_i}$ , measured by the POLDER is derived from Eq.(1) by using the measured  $Q_i$  and  $U_i$ . The sum of the square error between the measured  $pI_{p_i}$  and the  $POL_i$  in the nLU670 was defined as

$$S = \sum_{i=1}^N (pI_{p_i} - POL_i)^2 \quad (3)$$

where  $i$  represents the  $i$ -th geometric condition.

The problem is to find the values of  $N_r$ ,  $a$  and  $\tau(550)$  that correspond to the minimum of  $S$ . The optimum solution of  $N_r$ ,  $a$  and  $\tau$  was derived in the following two steps.

**Step 1:** Using the values of POL in the nLU670 that correspond to all combinations of typical values of  $N_r$ ,  $a$  and  $\tau$ , we compute all values of  $S$  and obtain 3 values of  $N_{r_k}$ ,  $a_k$  and  $\tau_k$  that correspond to  $S_k$  ( $k=1,2,3$ ) where  $S_1$  is the minimum value and we have  $S_1 < S_2 < S_3$ .

**Step 2:** Using  $N_{r_k}$ ,  $a_k$  and  $\tau_k$  obtained at the step 1 as initial values, we compute the better solution, i.e.,  $N_r$ ,  $a$ ,  $\tau$  that correspond to the local minimum in the neighborhood of  $S_k$ . To do that, the modified hill climbing algorithm adopted by Kusaka, et al. (Kusaka, et al., 2004) in which the partial derivatives of  $S$  are not used, were applied to get the new local minimum,  $nS_k$ , different from  $S_k$ . As a result, the values of  $N_r$ ,  $a$  and  $\tau$  corresponding to the minimum value of  $nS_k$  ( $k=1,2,3$ ) are chosen as the optimum solution.

#### 4.2 Estimation of Surface Reflectance at 670nm

Since aerosol properties in the atmosphere were determined in the previous section 4.1, we can easily estimate the surface reflectance,  $A$ , from the radiance,  $I$ , received by the POLDER.

We first used the 6SV-1.0B code to compute the radiances at the top of the atmosphere for typical values of the surface reflectance ( $A=0.0, 0.1, 0.2, \dots, 0.5$ ) under geometric conditions given in POLDER data. After that, we determined inversely the surface reflectance from the measured radiances by means of the same least square method as described in the section 4.1.

### 4.3 Estimation of Aerosol Properties and Surface Reflectance at 490nm

In general, the real part of complex refractive index,  $N_r$ , slightly increases as the wavelength is shorter. However, we have not so much experimental results about the wavelength dependency of  $N_r$  for various types of aerosols. In the estimation of aerosol properties at 490nm, we assumed that  $N_r$  at 490nm is the same as that at 670nm and moreover the number size distribution, i.e., the exponent of Junge power-law, is the same as that at 670nm. Aerosol properties we will estimate at 490nm are, therefore, the imaginary part of refractive index,  $N_i$  and the optical thickness of aerosols,  $\tau$ .

The values of POL and PD that correspond to geometric conditions, (SZA, VZA, RAZ), measured by the POLDER,  $N_r$  and  $a$  (exponent of Junge power-law) estimated at 670nm were interpolated from the LU490 and were saved in a new Look-up table, nLU490. We applied the nLU490 instead of nLU670 to the estimation algorithm described in the section 4.1 and determined the optimum value of  $N_i$  and  $\tau$ .

The surface reflectance at 490nm was determined from the measured radiances in the same way as described in the section 4.2.

## 5. RESULTS

The estimation method as described in the section 4. was applied to PARASOL/POLDER data (P3L1TBG1032192JD) taken on April 28, 2006. Fig. 1 shows the POLDER image over Japan (B: 490nm, G: 865nm, R: 670nm). We estimated aerosol properties and surface reflectance at target pixels in the neighbourhood of the symbol + shown in Fig. 1.

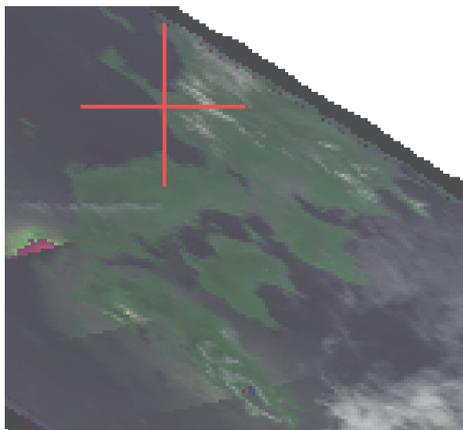


Fig.1 PARASOL/POLDER image over Japan taken on April 28, 2006

Since target pixels selected consist of the mixed area including the rice field and the suburban area, the polarized radiances

measured in the back scattering direction at 490nm and 670nm are very small. Therefore, POLDER data in which degrees of polarization ( $I_p/I$ ) are larger than 0.03 were used in this study. At the target area shown by the symbol + in Fig.1, only POLDER data acquired in 7 different geometric conditions ( $N=7$ ; see the section 4.1) were chosen. The results are shown in Table 1. In Table 1,  $\tau(550)$  is the estimation value of optical thickness of aerosols given in the 6SV-1.0B as the input parameter. As seen from Table 1, the estimated  $\tau(550)$  in the case of 670nm shows almost the same value as that in the case of 490nm. We also used the 6SV-1.0B code to compute the optical thickness of aerosols,  $\tau(670)$  at 670 nm and  $\tau(490)$  at 490nm on the basis of aerosol properties shown in Table 1. As a result, we found that we have  $\tau(670)=0.434$ , and  $\tau(490)=0.699$ . In the Hokuriku district, Japan, as shown by the symbol + in Fig.1, the end of April is in the rice-planting season and so the surface reflectance should be low because most of rice fields are covered with water. We can see from Table 1 that we have reasonable values for the surface reflectance.

Table 1 Values of aerosol properties estimated at 670nm and 490nm

		670nm		
$N_r$	$N_i$	$a$	$\tau(550)$	$A$
1.32	0	4.06	0.478	0.043
		490nm		
1.32	0.006	4.06	0.489	0.036

In this study, aerosol properties and the surface reflectance were separately estimated from the polarized radiances,  $I_p$  and the total radiance,  $I$ . Therefore, the degree of polarization ( $I_p/I$ ) was used to compare the measured Stokes parameters with the estimated ones.

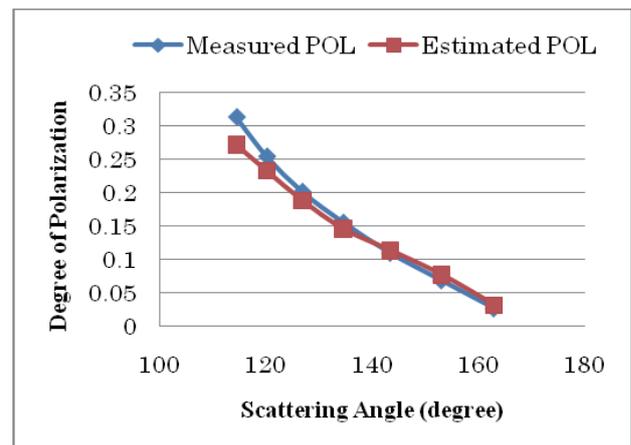


Fig.2 The measured degrees of polarization by the POLDER and the estimated ones at 670nm against scattering angles computed from geometric conditions observed by the POLDER

Fig. 2 shows degrees of polarization measured by the POLDER and those obtained from our estimation processes at 670nm. Fig.3 shows the measured degrees of polarization and the estimated ones at 490nm. As seen from Figs. 2 and 3, we have a good correspondence between the estimated values and measured ones. However, at 490nm, a variation of the estimated

degrees of polarization is slightly larger than that of the measured ones. This is due to the larger change of the estimated total radiances, as compared with that of the polarized radiances.

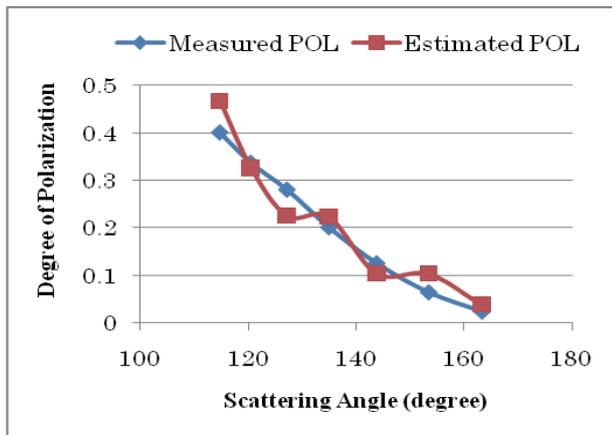


Fig.3 The measured degrees of polarization by the POLDER and the estimated ones at 490nm against scattering angles computed from geometric conditions observed by the POLDER

## 6. CONCLUSIONS

A new method for the estimation of aerosol properties over land from the polarized radiances measured at 490nm and 670nm channels by the POLDER was proposed. It was also shown that once aerosol properties in the atmosphere have been determined, the surface reflectance can be successfully estimated from total radiances received by the POLDER. As a result, it was found that the estimation method described in this study provides reasonable values for aerosol properties and the surface reflectance at 490nm and 670nm.

In practical applications of the estimation method presented in this study to land surfaces in global scales, we will be needed to take into account the difference of the altitude of the land surface because it is assumed that the altitude of a target is zero in computing the radiance and polarization at the top of the atmosphere.

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