NEW RETRIEVAL METHOD FOR AEROSOL OPTICAL PARAMETERS USING DIRECTIONAL REFLECTANCE AND POLARIZATION DATA BY POLDER ON BOARD ADEOS

YOSHIYUKI KAWATA AND TOSHIAKI IZUMIYA
Environ. Information Research Lab., Kanazawa Inst. Of Technology
Ogigaoka 7-1, Nonoichi, Ishikawa 921-8501, Japan

Abstract:
We proposed a new retrieval method for aerosol's real part of refractive index, optical thickness, and Angstrom exponent, using POLDER's directional reflectance and polarization data. We showed that aerosol's real part of refractive index can be retrieved systematically using multi-directional P-R(polarization and reflectance) diagrams in a single infrared band by our algorithm for the first time. We examined the retrieved results, by comparing with the simultaneously measured sky observation data at the study site and we obtained a reasonable agreement between them.

1. THEORETICAL BACKGROUND

The incident solar flux vector in Stokes vector representation is given by Eq.(1).

$$\pi \mathbf{F}=\pi[f\ 0\ 0\ 0]^t \qquad (1)$$

where a superscript represents the matrix transposition. In this notation we assume an incident solar flux vector $\pi\mathbf{F}$ illuminates a plane parallel atmosphere with the optical thickness of τ_{at} in the direction of (μ_0,ϕ_0), where μ_0 and ϕ_0 are the cosine of solar zenith angle θ_0 and the solar azimuth angle ϕ_0, respectively. In Eq.(1) πf equals to the extraterrestrial irradiance per unit area normal to the direction of solar rays, E_s[W/m^2]. Then, the upwelling Stokes vector at the top of the atmosphere (TOA) in the direction of (μ, ϕ), $\mathbf{I}(\tau_{at}, \mu, \mu_0, \phi-\phi_0) = [\ I\ \ Q\ \ U\ \ V\ ]^t$ can be expressed by Eq.(2) in terms of the reflection matrix of the atmosphere-ocean system $\mathbf{R}_{at+sf}$.

$$\mathbf{I}(\tau_{at},\mu,\mu_0,\phi-\phi_0)=\mu_0\mathbf{R}_{at+sf}(\tau_{at},\mu,\mu_0,\phi-\phi_0)\,\mathbf{F} \qquad (2)$$

As for the components of Stokes vector, I is the radiance, Q is related to the linear polarization, U to the plane of polarization, and V to the circular polarization. By using the adding method[Hansen and Travis, 1974], $\mathbf{R}_{at+sf}$ can be expressed in terms of the reflection matrix, the transmission matrix, of the atmosphere and the reflection matrix of the sea surface, $\mathbf{R}_{at}$, $\mathbf{T}_{at}$, and $\mathbf{R}_{sf}$, respectively. For the basic formulations of these matrices for a single atmospheric layer with a Gaussian type ocean surface (Cox-Munk model [Cox and Munk, 1954]), refer to our previous paper [Kawata and Yamazaki,1998].

Space reflectance R and the degree of linear polarization P in the reflected radiation are given by Eq.(3) and Eq.(4), respectively.

$$R=\pi I/\mu_0 E_s \qquad (3)$$

$$P=(Q^2+U^2)^{1/2}/I \qquad (4)$$

Since space reflectance is the reflectance at the top of atmosphere, we shall call it simply the reflectance. For simplicity, the degree of linear polarization is referred to the polarization in this paper.

2. AEROSOL MODELS

As for aerosol size distribution models, Junge type power law model[Junge, 1960] was only considered for simplicity and it is given by Eq.(5).

$$n(r)=\begin{cases} c\cdot 10^{\nu} & 0.02\mu m\le r\le 0.1\mu m \\ c\cdot 10^{-(\nu+1)} & 0.1\mu m\le r\le 10\mu m \\ 0 & r<0.02\mu m, r>10\mu m \end{cases} \quad (5)$$

where n(r) is the number density whose particle size is between r and r+dr. C is a constant which is determined to satisy

$$\int_{r_{min}}^{r_{max}} n(r)dr=1 \quad (6)$$

where r_{min}=0.02 [μm]and r_{max}=10.0[μm]. The index ν in Eq.(5) can be used as a measure of the size of aerosol particles.

As a measure of aerosol optical thickness, we shall use the aerosol optical thickness τ_{500} at 500[nm] in this study. The aerosol optical thickness τ_{λ} at any wavelength λ [nm] can be expressed by Eq. (7) in terms of τ_{500}.

$$\tau_{\lambda}=\tau_{500}\left(\frac{\lambda}{500}\right)^{-\alpha} \quad (7)$$

where α is Angstrom exponent and it is related to Junge's index ν as follows: α = ν - 2. Since Angstrom exponent is commonly used, we shall use α as a measure of the size of aerosol particles, hereinafter, instead of ν. In other words, we considered here 5 different cases of α , namely, α = 0.5, 1.0, 1.5, 2.0 and 2.5. The small and large values of α correspond to large and small aerosol particle size cases, respectively. As for aerosol refractive index($m=N_r-iN_i$), we considered 8 cases of real part of refractive index, i.e., N_r =1.30, 1.33 ,1.35, 1.40, 1.45, 1.5, 1.55 and 1.60, where we considered only non-absorbing aerosol case, i.e., N_I=0.0. In addition, we used the optical thicknesses of Rayleigh molecules, computed by the formulae in [Hansen and Travis,1974]. We computed Look Up Tables (LUTs) of the space reflectance and polarization for a given aerosol model with 11 different parameterized aerosol optical thicknesses of τ_{500} from τ_{500} = 0.0 to 1.0 with an increment of $\Delta\tau_{500}$= 0.1, for 33 different zenith angles of the incident and viewing directions and 72 different azimuthal angles of $\phi-\phi_0$. The LUTs were computed at 670 and 865[nm] by the adding and doubling radiative transfer code, including polarization, for 40 aerosol models (5 cases of α x 8 cases of m). In the computation, we assumed a homogeneous atmosphere(mixture of aerosol and Rayleigh particles) bounded by an isotropic Gaussian type ocean surface with a wind speed of V=5.0 [m/s]. The adoption of such a ocean wind speed is based on the fact that European Center for Medium-Range Weather Forecasts(ECMWF) data base indicates the wind speeds for the study scene at near ADEOS observation time in the range of 4.5[m/s] < V < 5.7[m/s].

3. VALIDATION DATA

As for the validation of aerosol optical parameter retrieval, the simultaneous sky observation experiment was made by the skyradiometer (POM-01: PREDE made) with 4 wavelength channels of 400, 500, 870, and 1040[nm] at Uchinada Agricultural Experiment Center in Ishikawa Prefecture in Japan, about 50[km] away from the study site A in Fig.1. Interpolated aerosol optical thicknesses at 500, 670, and 865[nm], based on the direct attenuation measurements of the sunlight, were $\tau_{500}[obs]=0.248, \tau_{670}[obs]=0.142, \tau_{865}[obs]=0.0875$, respectively. Angstrom exponent deduced from these measurements was $\alpha[obs] = 1.90$ at ADEOS observation time.

3. RETRIEVAL METHODS

Three methods for retrieving aerosol optical parameters were examined, using POLDER's directional reflectance and polarization data in 670 and 865[nm] bands acquired on April 26, 1997(Pass No.55; Level-1data with corrected for in-flight gain factors[Hagolle,1999]). We used sequential POLDER scenes from No.31 to No.48 in this study(see Fig.1). The retrieval methods which we examined are as follows:
(1) Method-I using parameterized reflectance diagram in two band space, originally proposed by [Stowe et al.,1997] in the analysis of NOAA/AVHRR data, (2) Method-II using parameterized directional polarization diagrams, originally proposed by [Masuda and Takashima,1999], and (3) Method-III using parameterized directional P-R(Polarization-Reflectance) diagrams in single infrared band, originally proposed by us. Since detailed analysis on these three methods suggested that Method III is the best one among these methods[Kawata et al., 1999], retrieval results based on Method-III were presented in this paper.

4. USE OF DIRECTIONAL P-R DIAGRAM

This is our proposed method which uses directional P-R (Polarization-Reflectance) diagram in a single infrared band. Fig.2 is such a example of parametrized P-R diagram(theoretically plotted using LUT) in 865[nm] at the study site A under a particular viewing condition of (θ_0=29.14, θ=55.87,$\phi-\phi_0$=88.25; scattering angle Θ=118.5) in scene 35 for N_r =1.40. From the diagram, we can find easily an appropriate solution from a location point (marked by X) with observed reflectance and polarization values in the diagram, i.e., (τ_{500} =0.290, α =1.62) in thecase of N_r =1.40. The study site A was observed by POLDER with 12 viewing conditions in a range of $118<\Theta<164$ and we selected 4 viewing conditions out of them,roughly correspond to Θ=118,124,136, and 143. We found that only three cases of N_r =1.40, 1.45, and 1.50 have solutions for all 4 viewing conditions. After taking an average over solutions in 4 viewing directions, appropriate aerosol parameter values were found to be (τ_{500} =0.300, α =1.66), (τ_{500} =0.298, α =2.03), and (τ_{500} =0.302, α =2.30) for N_r =1.40, 1.45, and 1.50, respectively. Other refractive index values were rejected, because they did not satisfy directional reflectance and polarization constraints. The most appropriate aerosol parameters was found to be (τ_{500} =0.297, α =1.66, N_r =1.40) which minimized the sum of relative differences between the theoretical and measured directional reflectance and polarization values by POLDER at site A(see Fig. 3). Compared with sky validation data($\tau_{500}[obs]$=0.248 and $\alpha[obs]$ =1.90), The retrieved values of τ_{500} and α are in a reasonable agreement with the sky observation data($\tau_{500}[obs]$=0.248 and $\alpha[obs]$ =1.90) at the study site A, with accuracies of about 17% and 13%, respectively, considering that the site A was about 50[km] away from the sky observation site. Because this validation results were based on a single day and a single site data, it is certain that further studies on other POLDER data sets and validation data, taken on different dates are necessary to establish our proposed new retrieval algorithm for aerosol's three optical parameters. However, we should point out strongly that aerosol's real part of refractive index can be retrieved systematically using POLDER's directional data by our algorithm for the first time.

5. RETRIEVED PARAMETER MAPS

Retrieved distribution maps for N_r, τ_{500} and α by Method-III, allowing for multi-directional viewing conditions on April 26, 1997 were constructed. In the retrieval scheme incident and viewing directions at every pixel were searched from POLDER's successive scenes and the total number of viewing directions is up to n = 12-14. The actual total number depends on the pixel location and cloud mask conditions. We will not present them here, because of difficulty in seeing in black-and white printing. They will be shown in the meeting.

6. CONCLUSIONS

Conclusions of this study can be summarized as follows:

(1) We applied our new retrieval method for aerosol's real part of refractive index, optical thickness and Angstrom exponent, based on multi-directional P-R (polarization and reflectance) diagrams in 865[nm] band, to ADEOS/POLDER data. The resulting distribution maps for aerosol's three optical parameters were constructed. We should point out that the distribution map of aerosol's real part of refractive index was made for the first time by this study.

(2) Further studies are needed to establish our proposed retrieval method.

ACKNOWLEDGMENTS

We thank very much Drs. A. Yamazaki at MRI for helpful discussions and suggestions. This study is supported by NASDA Research Contract, NASDA-PSPC-21409. The results were obtained from CNES's POLDER on board NASDA's ADEOS.

REFERENCES

[1]Cox,C. and Munk,W., 1954. Measurement of the roughness of the sea surface from photographs of the sun ' s glitter. J. Opt. Soc. Amer. 44, No.11, pp. 838-850.

[2]Hagolle, O. , 1999. POLDER in-flight absolute calibration. Proc. of ALPS'99 by CNES, Jan. 18-22, Meribel, France, WK2-P-11, pp.1-4.

[3]Hansen,J.E. and Travis,L.D., 1974. Light scattering in planetary atmospheres. Space Sci. Rev., 13, pp. 527-610.

[4]Junge,T., 1960. Aerosols. in Handbook of Geophysics.(Eds. Campen, et al.), Macmillan, New York.

[5]Kawata,Y. and Yamazaki,A., 1998. Multiple scattering analysis of airborne POLDER image data over the sea. IEEE Trans. GRS., vol.36, No.1, pp.51-60.

[6]Kawata,Y. , Izumiya, T., and Yamazaki,A., 1999. The estimation of aerosol optical parameters from ADEOS/POLDER data. Appl. Math. And Computation, Elsevier Sci.(Accepted).

[7]Masuda, K. and Takashima, T., 1999. Retrieval of the optical thickness and Angstrom coefficient of the aerosols over the ocean from polarization measurements by POLDER on board ADEOS satellite. J. of Remote Sensing Society of Japan (To appear).

[8]Stowe, L. L., Ignatov, A.M. and Singh,R R., 1997. Development, validation, and potential enhancements to the second-generation operational aerosol product at the National Environmental Satellite, Data and Information

Service of the National Oceanic and Atmospheric Administration. J. of Geophysical Research, Vol. 102, No. D14, pp. 16,923-16,934.

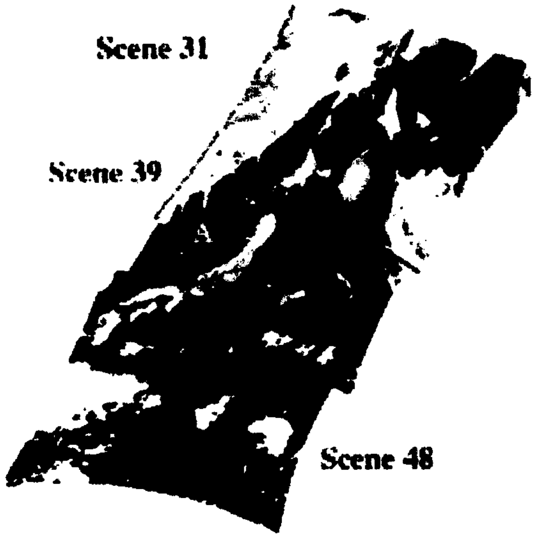


Fig. 1. POLDER's sequential images.

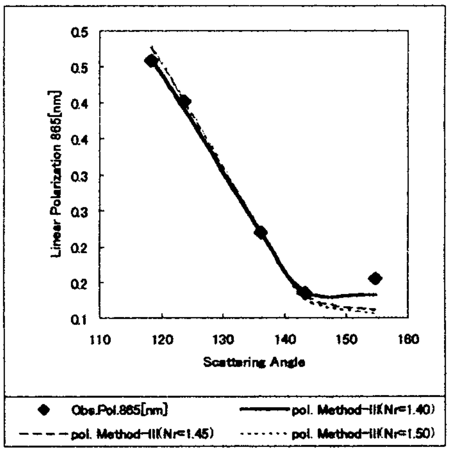


Fig. 3-(a). Comparison of theoreatical directional polarization values for retrieved models with mesured ones by POLDER at study site A

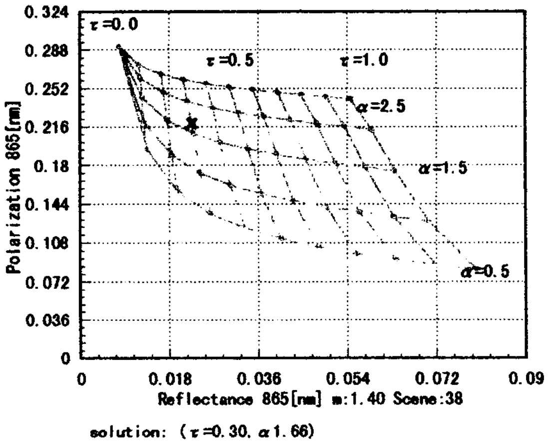
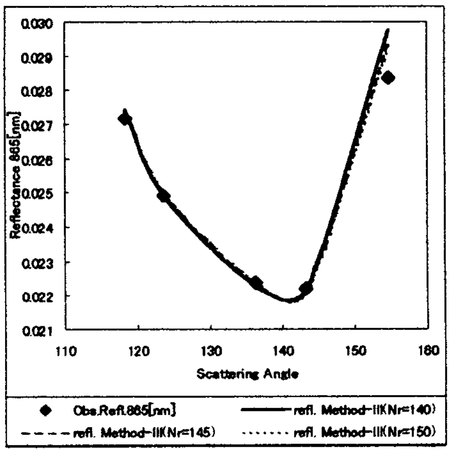


Fig.2. P-R diagram in a particular viewing condition at site A:

(θ_0=29.14, θ=55.87,ϕ-ϕ_0=88.25; scattering angle Θ=118.5) in scene 35 for N_r =1.40.

X mark indicates a point satisfying both observed reflectance and polarization values.



Comparison of theoreatical directional reflectance values for retrieved models with mesured ones by POLDER at study site A