ATMOSPHERIC PARAMETER ESTIMATION USING THE REFLECTANCE AND POLARIZATION DATA

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ABSTRACT:

In this paper we have made the atmospheric optical parameter estimation using the reflectance and polarization data measured over Mediterrenean Sea (referred as the Medimar data) by the airborne POLDER sensor [1],[2]. Assuming an atmosphere-ocean system with a Cox-Munk type reflecting sea surface [3], the reflectance and polarization , including radiance contributions from multiple scatterings within the atmosphere and multiple reflections between the atmosphere and the sea surface, have been computed by using the adding and doubling method [4],[5] for several different atmospheric models. In this study the Junge type aerosol size distribution function was considered [6]. Our results based on this study are summarized as follows:

1) We found five Junge type aerosol models which can explain the observed reflectance data at 0.85μm in the principal plane.
2) However, none of these model explained the observed polarization patterns in the backward scattering direction.
3) Further study on other types of aerosol size distribution function are needed to find a aerosol model which can satisfy both the reflectance and polarization data.

1. BASIC FORMULATIONS

Assuming an atmosphere-ocean system with a rough anisotropic sea surface of Cox-Munk type reflection model , the theoretical upwelling Stokes vector I can be computed by the doubling and adding method [4]. Let us assume an incident solar flux πF_0 , per unit area normal to the direction of propagation, illuminates a plane parallel atmosphere with the optical thickness of τ from the direction of (μ_0, ϕ_0) , where symbols μ_0 and ϕ_0 are the cosine of the solar zenith angle and the solar azimuthal angle , respectively. The upwelling Stokes vector at the top of the atmosphere in the direction of (μ, ϕ) can be expressed by Eq.(1) in terms of the reflection matrix of the atmosphere-ocean system .

$$I(\tau : \mu, \mu_0, \phi - \phi_0) = \mu_0 R(\tau : \mu, \mu_0, \phi - \phi_0) F_0 \qquad (1)$$

By using adding method, R can be expressed in terms of the reflection and transmission matrices of the atmosphere, R_A and T_A , and the reflection matrix of the sea surface R_{sea}. For a given atmospheric model, it is possible to compute R_A and T_A by the doubling and adding method.

Since the reflectance data analysis in the perpendicular plane rejected an isotropic Cox-Munk model by us [5] , we consider only an anisotropic Cox-Munk model in this study. A general wave slope distribution (an anisotropic Gaussian) surface wind speed and direction can be expressed in terms of a Gram-Charlier series as described in [3].

$$\begin{aligned} G(Z_c, Z_u) = {} & (2\pi\sigma_c\sigma_u)^{-1} \exp\left[-(\xi^2 + \eta^2)/2\right] \\ & \times \left[1 - c_{21}(\xi^2 - 1)\eta/2 - c_{03}(\eta^3 - 3\eta)/6\right. \\ & + c_{40}(\xi^4 - 6\xi^2 + 3)/24 \\ & + c_{22}(\xi^2 - 1)(\eta^2 - 1)/4 \\ & \left. + c_{04}(\eta^4 - 6\eta^2 + 3)/24 + \cdots\right] \end{aligned} \qquad (2)$$

$$\xi = Z_c/\sigma_c \quad , \quad \eta = Z_u/\sigma_u \qquad (3)$$

where ξ, η are the standardized slope components and Z_c, Z_u are the slope components along the crosswind (X_c) and upwind (X_u) directions , respectively. Furthermore , σ_c , σ_u are the root mean squares of Z_c , Z_u , respectively. The explicit dependence of σ_c , σ_u and c_{ij} on the wind speed is given by Cox and Munk [3]. The relationship between the surface slope angle β and its X_c-, X_u-components is given by Eq.(4).

$$\beta = \tan^{-1}\left(\sqrt{Z_c^2 + Z_u^2}\right) \tag{4}$$

The sea surface reflection matrix is composed of a reflection matrix specifying the radiation reflected directly by the sea surface , and a water column reflectance which is the transmitted radiation from the sea. In other word, it is the radiation reflected diffusely by water molecules and hydrosols within the sea. It is very difficult to evaluate the under water radiation, because of many uncertainties in estimating the underwater radiative transfer model . In this paper we assume that the water column reflectance can be expressed by r_{wc} , for the simplicity. The angular dependence of r_{wc} may be neglected because of the observational difficulty in the measurements as discussed in Bréon and Deschamps [2]. In short wavelength (0.45μm) r_{wc} may be a few percent , whereas it is very close to zero in the near infrared (0.85μm)[7]. Then , according to the formulation by Takashima [8] with some modifications of his original form , the sea surface reflection matrix R_{sea} can be given approximately by Eq.(5).

$$R_{sea}(\mu, \mu_0, \phi - \phi_0) = \frac{\pi G}{4\mu\mu_0 \cos^4 \beta} Rot(\delta) R_s(2\omega) Rot(\gamma) + r_{wc} \tag{5}$$

where *Rot(α)* is the rotation matrix for a given rotation angle α and it is given in Eq.(6) . The angles , δ and γ are the rotation angles defining the reflection matrix with respect to the local meridian plane as a common reference for the Stokes vector.

$$Rot(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & -\sin 2\alpha & 0 \\ 0 & \sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

Furthermore, $R_S(2\omega)$ is the specular reflection function and ω is the incident or reflection angle to the facet .

2. AIRBORNE POLDER DATA ANALYSIS

We compute the theoretical reflectance and the degree of linear polarization curves against the viewing zenith angle in the principal plane at the wavelength of 0.85μm for a two layer atmospheric model of mixed atmosphere, consisting of aerosols and gaseous molecules, bounded by a rough sea surface layer. The principal plane is a plane containing both the solar and the viewing directions. For the analysis of the airborne POLDER data , the internal upwelling reflectance $\pi I_h/\mu_0\pi F$ and the degree of linear polarization $\sqrt{Q_h^2 + U_h^2}/I_h$ at the flight altitude of the aircraft (h=4700m) are computed in the principal plane by using the internal reflection function R_h , in stead of R at the top of the atmosphere. The quantities of I_h, Q_h and U_h are the 1st, 2nd, and 3rd components of the upwelling Stokes vector at the altitude of h, respectively.

In the computations of the theoretical reflectance and the degree of linear polarization the Junge type size distribution function was assumed. The size distribution of the Junge type aerosol model is given by Eq.(7) [6].

$$n(r) = \begin{cases} C \cdot 10^{\nu+1} & 0.02\mu m \le r \le 0.1\mu m \\ C \cdot r^{-(\nu+1)} & 0.1\mu m \le r \le 10\mu m \\ 0 & r < 0.02\mu m,\ r > 10\mu m \end{cases} \tag{7}$$

where C is a normalized constant satisfying , $\int_{r_{min}}^{r_{max}} n(r)dr = 1$ and r_{min} = 0.02μm , r_{max} = 10μm.

The theoretical calculations of reflectance at 0.85μm in the principal plane were made for the Junge type functions with ν = 3.5, 4.0 and 4.5. In this analysis we assumed that the radiation contribution from the underwater is negligible , i.e., r_w = 0.0 at 0.85μm [7]. Since we considered 9 different refractive indices (m = 1.33, 1.33-i0.01, 1.33-i0.05 : m= 1.5, 1.5-0.01, 1.5-i0.05: m= 1.75, 1.75-i0.01, and 1.75-0.05), and 15 wind speeds (from V = 8.0 m/sec to V=15.0 m/sec with an increment of 0.5 m/sec), there are 135 different combinations of the refractive index and wind speed. We should note that the measured wind speed and its direction were V=14.4 m/sec and W_d=220° at the time of the Medimar experiment. The refractive indices of m=1.33, 1.5, and 1.75 correspond to those of water, dust , and soot aerosols, respectively. For each of aerosol size distribution functions, 135 cases were examined whether the corresponding theoretical reflectance curves can satisfy the observed reflectance data or not. In this examination the surface wind direction of W_d=220° was fixed. We adopted a simple rule that the theoretically computed reflectance values should be at least within the range of observed error bars (±3 σ) at all viewing zenith angles. We found Junge type size distribution functions can satisfy the observed reflectance data when an appropriate wind speed is assumed. They are as follows: the Junge type function with ν = 3.5 and m=1.5-i0.01 (referred to the aerosol model A) for 10.5 m/sec ≦ V ≦ 13.5 m/sec , that with ν = 4.0 and m=1.33 (referred to the aerosol model B) for 10.5 m/sec ≦ V ≦ 11.5 m/sec, that with ν = 4.0 and m=1.75-i0.05 (referred to the aerosol model C) for 11.0 m/sec ≦ V ≦ 12.5 m/sec, that with ν = 4.5 and m=1.33-i0.01 (referred to the aerosol model D) for 10.0 m/sec ≦ V ≦ 12.5 m/sec, and that ν = 4.5 and m=1.75-i0.05 (referred to the aerosol model E) for 10.0 m/sec ≦ V ≦ 12.5 m/sec. In other words, the Junge type aerosol models, A-E could be candidate models, because they can satisfy the observed reflectance curve when an appropriate wind speed is assumed. We also found that the Junge type models with $\nu < 3.0$ and $\nu > 5.0$ can not satisfy the observed reflectance data.

The case of the aerosol model A ($\nu = 3.5$ and $m=1.5-i0.01$) is presented here in detail, because of two reasons: (1) an Ångström coefficient $\alpha=1.5$ obtained from the aerosol optical thickness measurements ($\tau=0.12$ at 0.85μm and $\tau=0.314$ at 0.45μm) suggests $\nu = 3.5$, according to Ångström's law, namely, $\nu = \alpha+2$, (2) The refractive index of typical aerosols, like dust and water soluble particles, is m=1.5. The surface wind speed does not change the shape of the reflectance curve in the back scattering direction, but it affects that in the sun glitter direction (at the viewing zenith angle between -30° to -50°) . We can estimate a range of wind speed from the sun glitter portion of reflectance curve in the case of aerosol model A. The range of the wind speed was thus estimated to be $10.5 \text{ m/sec} \leqq V \leqq 13.5 \text{ m/sec}$ from Fig.1-(a), whereas the observed one is V=14.4 m/sec. As shown in Fig.1-(b), the wind speed has little effect on the linear polarization. The theoretical reflectance and polarization curves of the aerosol model A for V=11.0 m/sec are shown in Figs.2-(a) and 2-(b), together with those of the aerosol models with m = 1.50, and m=1.50-i0.05. We obtain the best fit with the observed reflectance data in the case of m=1.5-i0.01. However, theoretical linear polarization values in the back scattering direction are much smaller than the observed ones in the aerosol model A case. As shown in Fig. 2-(b), the case of larger amount of aerosol absorption (m=1.5-i0.05) gives better results in linear polarization than other two cases. The reflectance data suggests a model with slight absorbing aerosols , whereas the linear polarization data suggests that with strong absorbing aerosols. This is a contradiction and we need more detailed analysis on this point near future, as well as the foam effects which were not taken into account in this study. In any cases, we found that the candidate aerosol models which are derived from the reflectance analysis have some difficulties to satisfy the observed linear polarization data in the backward scattering direction.

3. CONCLUSIONS

In this paper we have made an analysis of Medimar airborne POLDER data over the sea by the multiple scattering model. Our conclusions based on this study are summarized as follows:

(1) We found several Junge type aerosol models, A-E which can satisfy the observed reflectance data at 0.85μm in the principal plane by examining various combinations of aerosol optical parameters and wind speeds.

(2) It is possible to estimate the surface wind speed by examining the reflectance surge in the glitter direction at 0.85μm . The estimated ranges of the surface wind speed were presented for the aerosol models, A - E. It was found to be $10.5 \text{ m/sec} \leqq V \leqq 13.0 \text{ m/sec}$ in the aerosol model A (Junge type size distribution with $\nu = 3.5$, and refractive index $m = 1.5 - i0.01$) which is the most probable model among the candidate aerosol models suggested from the reflectance analysis at 0.85μm .

(2) However, we also found that none of these models can satisfy the observed linear polarization data in the back scattering direction.

(3) Further study on other types of aerosol size distribution function are needed to find a aerosol model which can satisfy both the reflectance and polarization data.

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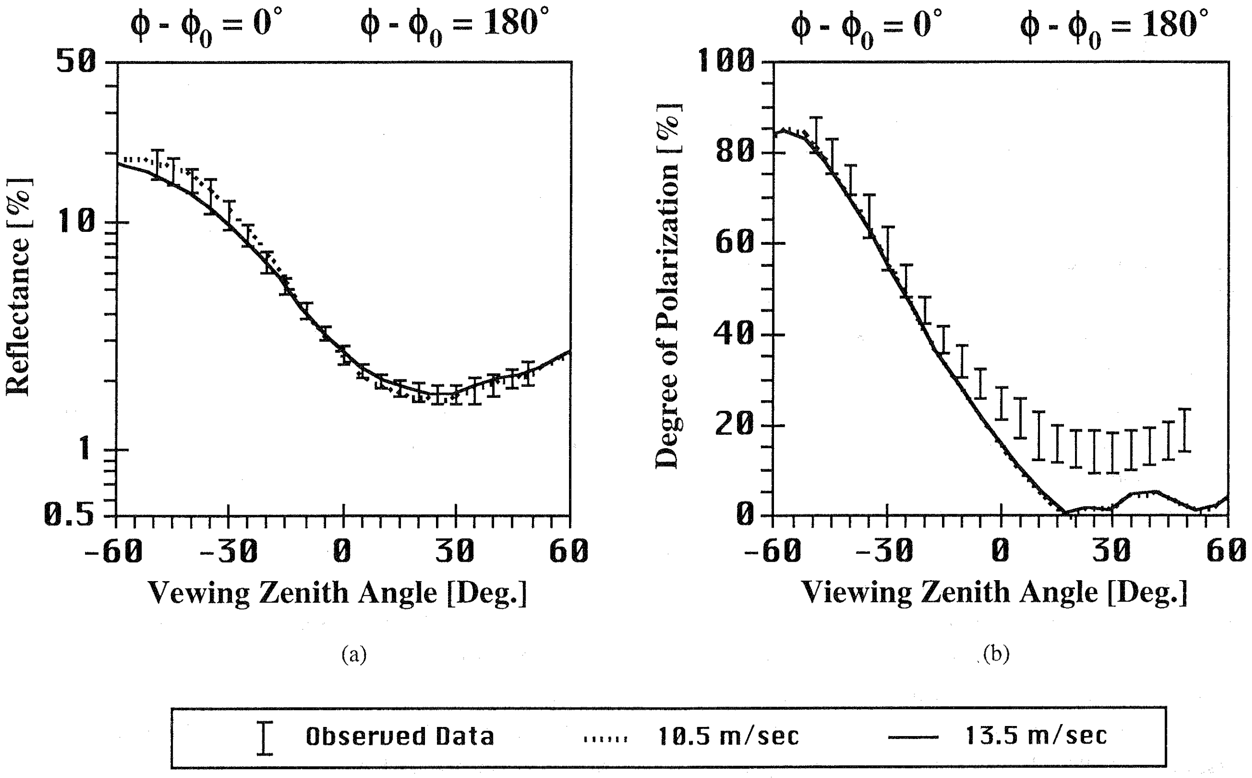
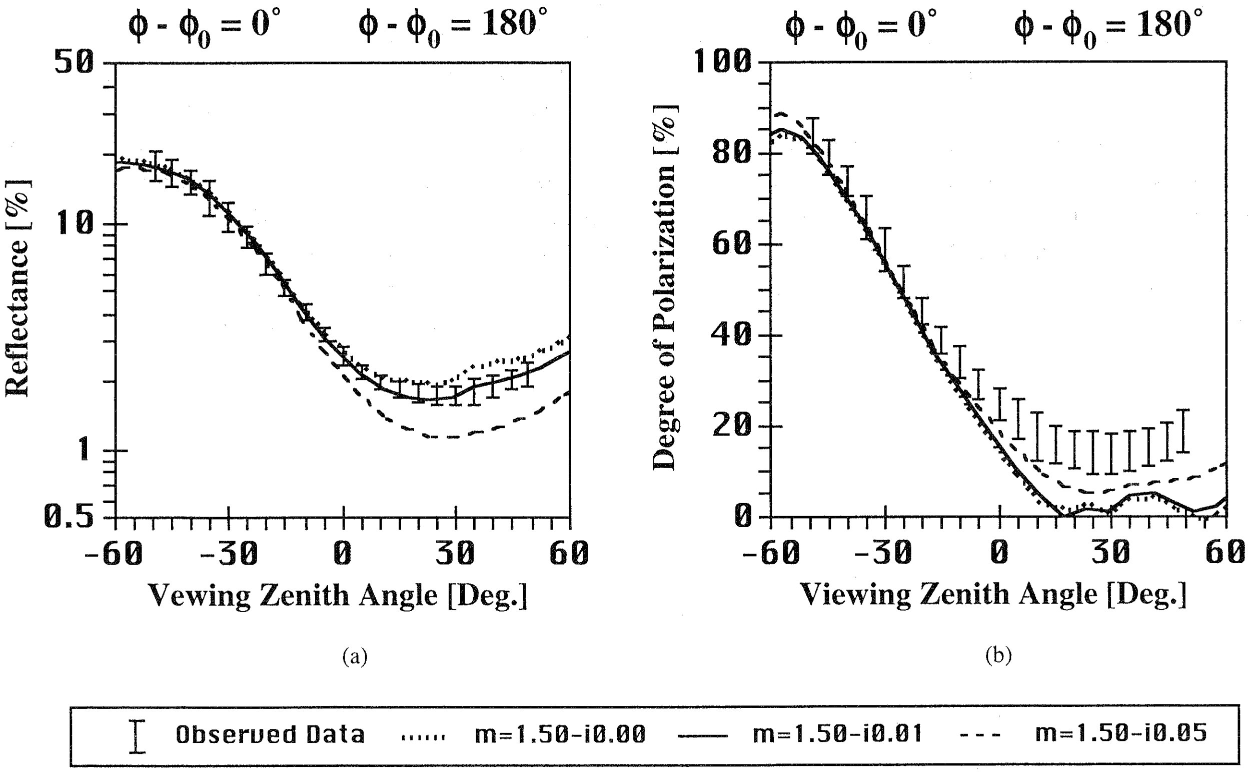


(a)

(b)

Fig. 1. The reflectance (a) and polarization (b) curves as a function of viewing zenith angle in the principal plane.
The wind speed is chosen as a parameter.



(a)

(b)

Fig.2. The same as in Fig. 1, except the imaginary part of refractive index is chosen as a parameter.