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Uncertainties of atmospheric polarimetric measurements with sun-sky radiometers induced by errors of relative orientations of polarizers

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ABSTRACT

In this study errors of the relative orientations of polarizers in the Cimel polarized sun-sky radiometers are measured and introduced into the Mueller matrix of the instrument. The linearly polarized light with different polarization directions from 0° to 180° (or 360°) is generated by using a rotating linear polarizer in front of an integrating sphere. Through measuring the referential linearly polarized light, the errors of relative orientations of polarizers are determined. The efficiencies of the polarizers are obtained simultaneously. By taking the error of relative orientation into consideration in the Mueller matrix, the accuracies of the calculated Stokes parameters, the degree of linear polarization, and the angle of polarization are remarkably improved. The method may also apply to other polarization instruments of similar types.

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1. Introduction

Polarization is one of inherent properties of light. It is commonly described by the Stokes vector [1]. The linearly polarized components of the Stokes vector *I*, *Q*, and *U* are usually determined from total radiance measurements with three polarizers in different orientations [2,3]. The Dual-Polar sun-sky radiometer CE318-DP produced by the Cimel Electronique is an advanced, ground-based polarimetric radiometer that has been deployed in the AErosol RObotic NETwork (AERONET) and the Sun-sky radiometer Observation NETwork (SONET) to measure linear polarization of skylight [4,5].

The CE318-DP design consists of two rotating wheels (i.e., a polarizer wheel and a filter wheel) assembling nine polarizers and nine filters, respectively. As the key polarization elements, the nine polarizers are divided into three sets of triplets. Each triplet consists of three polarizers. The polarimetric measurements at each channel are performed by using the three rotating polarizers in front of a same spectral filter. The exact relative orientations of three polarizers are crucial in the calculations of the Stokes parameters *I*, *Q*, *U*, as well as the degree of linear polarization *DoLP* and the angle of polarization *AoP* [6,7]. The influence of relative orientations feeds into the Mueller matrix. Thus, measurement of the relative orientations of polarizers should already be considered in the polarization calibration. The spaceborne polarization instruments including POLDER-1 (POLarization and Directionality of the Earth's Reflectances)/ADEOS-1, POLDER-2/ADEOS-2, POLDER/PARASOL, DPC (Directional Polarimetric Camera)/GF-5, and CAPI (Cloud and Aerosol Polarimetric Imager)/TanSat had all taken the relative orientations of polarizers into consideration in their pre-flight calibrations [6,8,9]. However, the ground-based CE318-DP, which is usually used to validate the satellite measurements, has not considered the relative orientation angles so far. To the polarized sun-sky radiometer, calibration of the efficiencies of the polarizers and the difference between the responses for two of the three polarizers have been suggested in previous studies [10,11]. Nonetheless, the polarization parameters *I*, *Q*, *U*, *DoLP*, and *AoP* are all determined with the hypothesis that the relative orientation angle is exactly equal to 60° for any two of the three polarizers [3,5,11]. Errors in the relative orientation angles between the polarizers are inevitable due to imperfect installation and rotating position error. That might imply errors in the polarimetric mea-

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surements using the CE318-DP, which are systematically studied in this paper.

To cope with this problem, the orientations of polarizers for CE318-DP are measured by using rotating linearly polarized light as reference. However, the relative orientations are not determined through the difference between the minimum (or maximum) of the sinusoid fitting of the instrument signals, in consideration of the large uncertainties for the absolute positions of the minimum (or maximum) [6,8]. Instead, a new method, which simultaneously determines the relative orientations and efficiencies of the polarizers, is developed in this study. Furthermore, the impacts of errors of the relative orientations on the calculations of the Stokes parameters, the degree of linear polarization, and the angle of polarization are also discussed. This work can help to improve the accuracy of polarization parameter measurements for the sun-sky radiometer.

2. Methodology

2.1. Radiometric model

The radiometric model of the polarized sun-sky radiometer quantifies the response of the detector with respect to any input polarized light in each spectral channel [6,7,12]. The interaction of an incident polarized beam with a polarizing element (e.g., atmospheric particle, optical instrument) is described by the Mueller matrix. The CE318-DP is equipped with lens, linear polarizer, filter and detector. Interactions of the incoming light with these optical elements are described by the Mueller matrix of instrument by the relations [1]:

$$\vec{S'} = \mathbf{M} \cdot \vec{S}, \tag{1}$$

where $\vec{S}$ is the Stokes vector of the incident light and $\vec{S'}$ is the Stokes vector of the light beam after interactions with lens, polarizer, and filter then be received by detector. **M** is a 4×4 matrix known as the Mueller matrix of the instrument, which can be expressed as:

$$\mathbf{M} = T \begin{bmatrix} 1 & \eta\cos 2(\varphi-\alpha) & \eta\sin 2(\varphi-\alpha) & 0 \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix}, \tag{2}$$

with the efficiency of the polarizer $\eta = (k_1 - k_2)/(k_1 + k_2)$ [7]. k_1 and k_2 are transmittances of the linear polarizer along the preferred axis and along an axis of 90° with respect to the preferred axis. φ indicates the desired orientation angle of polarizer (e.g., 0°, 60°, or 120°). α represents the error angle of the relative orientation for two of the three polarizers. The Stokes vectors refer to the coordinate system, which is based on the instrument frame with the plane containing the direction of 0° polarizer-preferred transmission axis and the direction of propagation of light as reference [3]. The coefficient T refers to transmissions of the lens, filter, and linear polarizer. Polarization of the optics can be neglected, considering that the field of view is only 1.3° for the CE318-DP and the stress birefringence in the lens can also be ignored owing to application of the low stress assembly technology [7,13]. The elements of the Mueller matrix $m_{ij}(i=2,\ 3,\ 4;\ j=1,\ 2,\ 3,\ 4)$ are not specified because only the first row of the matrix is important for total radiance measurements.

The relative orientation for any two of the three polarizers is supposed to be 60°. For simplicity, we assume the desired orientations of the three polarizers P_1, P_2, and P_3 as 0°, 60°, and 120° with P_1 defining as the 0° polarizer. The error angles of relative orientations, which are imported through the imperfect installation of the polarizers and the rotating process, should be rigorously measured.

For each spectral band, three radiance measurements corresponding to the three orientations of linear polarizers are sufficient to characterize the Stokes parameters *I*, *Q*, and *U* of the incident light [7]:

$$\begin{pmatrix} I \\ Q \\ U \end{pmatrix} = \begin{pmatrix} 1 & \eta_1\cos 2(\varphi_1-\alpha_1) & \eta_1\sin 2(\varphi_1-\alpha_1) \\ 1 & \eta_2\cos 2(\varphi_2-\alpha_2) & \eta_2\sin 2(\varphi_2-\alpha_2) \\ 1 & \eta_3\cos 2(\varphi_3-\alpha_3) & \eta_3\sin 2(\varphi_3-\alpha_3) \end{pmatrix}^{-1} \begin{pmatrix} C_1 \cdot N_1 \\ C_2 \cdot N_2 \\ C_3 \cdot N_3 \end{pmatrix}, \tag{3}$$

where *I*, *Q*, and *U* denote the first three components of the Stokes vector $\vec{S}$. N_1, N_2, and N_3 are the digital numbers measured at three orientations. C_1, C_2, and C_3 indicate the absolute calibration coefficients for a polarized channel, which are applied to convert the instrumental output signal into radiance [7]. The coefficients α_1, α_2, α_3, η_1, η_2, η_3, C_1, C_2, and C_3 correspond to the three polarizers in each spectral channel. $\varphi_1 = 0°$, $\varphi_2 = 60°$, and $\varphi_3 = 120°$. $\alpha_1 = 0°$ because P_1 is defined as the 0° polarizer. Like the absolute radiance calibration for the non-polarized channel, the absolute calibration coefficients for the polarized channel C_1, C_2, and C_3 are easily obtained by measuring unpolarized reference light from an integrating sphere [3]. The measurements of α_2, α_3, η_1, η_2, and η_3 remain difficult. To deal with this problem, a rotating linearly polarized light beam is used as incident reference light. It can be expressed as:

$$\vec{S} = \begin{bmatrix} I \\ Q \\ U \end{bmatrix} = \begin{bmatrix} I \\ I \cdot \cos 2\chi \\ I \cdot \sin 2\chi \end{bmatrix}, \tag{4}$$

where χ incidents the angle of polarization of the incident light that is defined with respect to the reference plane in the instrument frame. χ varies from 0° to 180°. Substituting Eq. (4) into Eq. (3) to yields:

$$\begin{aligned} N &= \frac{I}{C}[1 + \eta \cdot \cos 2\chi \cdot \cos 2(\varphi-\alpha) + \eta \cdot \sin 2\chi \cdot \sin 2(\varphi-\alpha)] \\ &= \frac{I}{C} + \frac{I}{C} \cdot \eta \cdot \cos 2[\chi - (\varphi - \alpha)]. \end{aligned} \tag{5}$$

Then Eq. (5) can be transformed into:

$$N = y_0 + A \cdot \cos \pi \frac{\chi - \chi_c}{w}, \tag{6}$$

where $y_0 = I/C$, and $A = \eta \cdot I/C$. w is half cycle. The value of w is close to 90°. χ_c is the relative orientation of polarizer. The error angles of the relative orientations of P_2 and P_3 with respect to P_1 are obtained by:

$$\alpha_2 = 60° - (\chi_{c1} - \chi_{c2}), \tag{7}$$

$$\alpha_3 = 120° - (\chi_{c1} - \chi_{c3}) \text{ or } \alpha_3 = -60° - (\chi_{c1} - \chi_{c3}). \tag{8}$$

In this way the coefficients α_1, α_2, α_3, η_1, η_2, η_3, C_1, C_2, and C_3 are all attained. Substituting them into Eq. (3) gives the results of the Stokes parameters *I*, *Q*, and *U*. Then, the degree of linear polarization *DoLP* and the angle of polarization *AoP* can be calculated by:

$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I},\ 0 \le DoLP \le 1, \tag{9}$$

$$\chi = \frac{1}{2}\mathrm{atan}\frac{U}{Q},\ 0 \le \chi < \pi. \tag{10}$$

2.2. Measurement of relative orientations of polarizers

Laboratory experiments were conducted to measure the relative orientations and efficiencies of the polarizers for the CE318-DP #0966 and #0974. Then data were taken to test the consistency

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