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A method to calculate Stokes parameters and angle of polarization of skylight from polarized CIMEL sun/sky radiometers

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ABSTRACT

The polarized CIMEL sun/sky radiometers have been routinely operated within the Sun/sky-radiometer Observation NETwork (SONET) in China and some sites of the AErosol RObotic NETwork (AERONET) around the world. However, the polarization measurements are not yet widely used due to in a certain degree the lack of Stokes parameters derived directly from these polarization measurements. Meanwhile, it have been shown that retrievals of several microphysical properties of aerosol particles can be significantly improved by using degree of linear polarization (*DoLP*) measurements of polarized CIMEL sun/sky radiometers (CE318-DP). The Stokes parameters *Q* and *U*, as well as angle of polarization (*AoP*) contain additional information about linear polarization and its orientation. A method to calculate Stokes parameters *Q*, *U*, and *AoP* from CE318-DP polarized skylight measurements is introduced in this study. A new polarized almucantar geometry based on CE318-DP is measured to illustrate abundant variation features of these parameters. The polarization parameters calculated in this study are consistent with previous results of *DoLP* and *I*, and also comparable to vector radiative transfer simulations.

1. Introduction

The polarization of skylight resulting from interactions of unpolarized solar electromagnetic radiation with particles in the atmosphere is more sensitive to some microphysical parameters of aerosol particles (e.g., particle size, shape, vertical profile of aerosols) than the total radiance [1–5]. The additional polarimetric measurements can significantly improve the retrievals of some aerosol parameters [5,6]. Several spaceborne and airborne instruments have been designed to detect the polarization status of light to derive aerosol properties, for example, POLDER (Polarization and Directionality of Earth's Reflectances), APS (Aerosol Polarimetry Sensor, failed to launch), RSP (Research Scanning Polarimeter), DPC (Directional Polarimetric Camera), 3MI (Multi-Viewing Multi-Channel Multi-Polarization Imaging Mission), and AMPR (Airborne Multi-angle Polarimetric Radiometer) [7–12]. Compared with spaceborne and airborne instruments, ground-based instruments, for example, RADS-IIP (Polarization Radiance Distribution Camera System) and some other experimental and commercial polarization cameras or radiometers, can attenuate significantly the effects of surface background on polarization measurements and provide more accurate information about aerosols [13–15]. A new ground-based polarized remote sensing instrument, the CIMEL Dual-Polar sun/sky radiometer CE318-DP, has been introduced into

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the AErosol RObotic NETwork (AERONET) and the Sun/sky-radiometer Observation NETwork (SONET) to study aerosol properties throughout the world and focus on China, respectively [16]. The SONET, set up in 2010, has about 15 long-term observation stations around China. In SONET, the typical urban industrial polluted stations Beijing (40.0°N, 116.3°E), Hefei (31.9°N, 117.2°E), and Guangzhou (23.1°N, 113.4°E), the rural station Zhangye (38.8°N, 100.3°E), the desert station Minqin (38.6°N, 103.0°E), the marine station Zhoushan (29.9°N, 122.1°E), and the semi-arid station Kashi (39.5°N, 75.9°E) are all equipped with CE318-DP. With high accurate, reliable, and continuous polarization measurements, these instruments can provide unique polarimetric measurements to study detailed properties of different types of aerosols in key areas of China. Furthermore, it is also useful for validating polarization measurements and aerosol products of new spaceborne and airborne polarization instruments (e.g., DPC and AMPR).

Skylight polarization measurements based on the CE318-DP can effectively improve retrievals of the fine mode size distribution, the real part of refractive index, and the sphericity parameter of aerosol particles compared with that relying solely on the radiance [6,17,18]. The existing algorithms based on CE318-DP observations use only degree of linear polarization (*DoLP*) and total radiance *I* which are independent of the reference plane. In addition to *DoLP* and *I*, the Stokes parameters *Q* and *U*, as well as angle of polarization (*AoP*) contain valuable additional information on intensity and orientation of linear polarization which are sensitive to some aerosol properties (e.g., particle shape, size and refractive index) [14,19,20]. Moreover, the parallel and perpendicular components of polarized radiance can be separated from the total radiance via the results of Stokes parameters *I* and *Q*. Unlike the polarized portion of the Rayleigh scattering component which is always polarized perpendicular to the scattering plane, the polarized components of the Mie scattering from aerosol particles can be polarized either parallel or perpendicular to the scattering plane [21]. The parallel and perpendicular components of the polarized radiance can provide unique measurements for atmospheric aerosol remote sensing. However, they are not available currently from CE318-DP measurements due to the unknown orientations of polarizers in the sky frame caused by operate mechanisms of this kind of instruments.

The aim of this paper is to extend the analysis of CE318-DP observations to obtain Stokes parameters *Q*, *U*, and angle of polarization. Both the solar principal plane and the almucantar geometries are considered. In Section 2, we introduce useful formulas to describe the polarization of skylight. In Section 3, we present a method to correct the initial orientation angle of polarizer axis, and then calculate the Stokes parameters *I*, *Q*, *U*, the degree of linear polarization, and the angle of polarization from CE318-DP polarized skylight measurements. In Section 4, we show the results of these polarization parameters of skylight under different scanning angles in the solar principal plane geometry and relative azimuthal angles in the almucantar geometry. In Section 5, the results are evaluated by comparing with those from the vector radiative transfer simulations and previous results of *DoLP* and *I*, following a discussion on uncertainty of the derived Stokes parameters.

2. Definition

Polarization is one of inherent properties of electromagnetic radiation [14,22]. The polarization of a light beam can be described by the 4-dimensional Stokes vector with parameters *I*, *Q*, *U*, and *V* [22,23]. Among them, *I* is the total radiance which is a measure of the intensity of light. *Q* is the intensity difference between polarized components of electromagnetic wave parallel and perpendicular to the reference plane. *U* indicates intensity difference between polarized components in planes 45° and −45° to the reference plane. The *Q* and *U* describe the linearly polarized radiation, by definition, which vary with the definition of reference frame. *V* describes the circularly polarized radiation. In nature, the direct (not scattered) sunlight is unpolarized. Any interactions of sunlight with particles in the earth's atmosphere may change both the intensity and the polarization of the propagating electromagnetic wave [1]. After scattered by particles in the atmosphere (i.e., air molecules, aerosol particles, water droplets and ice crystals of cloud), the skylight becomes partially polarized [1,2]. Previous studies show that partially polarized skylight can be roughly regarded as a superposition of linearly polarized and unpolarized light. The Stokes vector's first three elements *I*, *Q*, and *U* are the most important, while the circular polarization parameter *V* usually can be neglected for skylight in the atmosphere [24–26]. Therefore, the polarization of skylight in earth's atmosphere can be described by the first three Stokes parameters.

The degree of linear polarization is defined as

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

for the principal plane observation, the solar principal plane (defined as the plane containing both the directions of incident sunlight and the local zenith) is normally chosen as the reference plane. In this reference frame, *DoLP* can also be written as

$$DoLP = -\frac{Q}{I}. \tag{2}$$

The angle of polarization χ indicates the angle between the plane of polarization and the plane of reference. It can be calculated as

$$\chi = \frac{1}{2}\operatorname{atan}\frac{U}{Q}; \quad 0 \le \chi < \pi, \tag{3}$$

where the Stokes parameters *Q* and *U* are associated with the angle of polarization. From different values of χ differing by $\pi/2$ which satisfy Eq. (3), we must choose the value which also satisfies the following relation [27]:

$$\text{Sign of } (\cos 2\chi) = \text{Sign of } Q. \tag{4}$$

3. Measurements and methods

3.1. System description

The instrument used to measure polarized skylight in this study is the ground-based CIMEL Dual-Polar sun/sky radiometer, CE318-DP. It is equipped with two rotating wheels mounting filters and polarizers in the optical