Ground-based Polarization Remote Sensing of Atmospheric Aerosols and the Correlation between Polarization Degree and PM$_{2.5}$

CHEN Cheng $^{1,2}$, LI Zhengqiang $^1$, LI Donghui $^{1,2}$, LI Kaitao $^{1,2}$, ZHANG Ying $^{1,2}$, HOU Weizhen $^1$, XIE Yisong $^{1,2}$

1. State Environmental Protection Key Laboratory of Satellite Remote Sensing, Institute of Remote Sensing and Digital Earth Chinese Academy of Sciences, Beijing, 100101, China
2. University of Chinese Academy of Sciences, Beijing, 100049, China.

E-mail: chencheng@irsa.ac.cn

Abstract. The ground-based polarization remote sensing adds the polarization dimension information to traditional intensity detection, which provides a new method to detect atmospheric aerosols properties. In this paper, the polarization measurements achieved by a new multi-wavelength sun photometer, CE318-DP, are used for the ground-based remote sensing of atmospheric aerosols. In addition, a polarized vector radiative transfer model is introduced to simulate the DOLP (Degree Of Linear Polarization) under different sky conditions. At last, the correlative analysis between mass density of PM$_{2.5}$ and multi-wavelength and multi-angular DOLP is carried out. The result shows that DOLP has a high correlation with mass density of PM$_{2.5}$, $R^2 > 0.85$. As a consequence, this work provides a new method to estimate the mass density of PM$_{2.5}$ by using the comprehensive network of ground-based sun photometer.

1. Introduction

Polarization is one of the inherent characteristics in atmospheric detection. Because any target in atmosphere will have their unique characteristics nature of polarization, when non-polarized natural light interacts with air molecules and aerosol particles. The key advantage of using polarized observation is that polarization features strongly depend on the characteristics of scattering particles, which provides a new method to detect PM$_{2.5}$ (Particle with aerodynamic diameter $\leq$ 2.5 Micron), whereas the classic approach using natural light is difficult to do. Atmospheric aerosol polarization measurement from ground-based remote sensing has been well progressed in recent years. A new polar metric sun photometer, CE318-DP, has been used in AERosol RObotic NETwork (AERONET) sites [1]. CE318-DP, developed by the CIMEL Electronic (Paris, France), adopts a new mechanical design providing the polarization capability in solar principal plane at all measurement wavelengths centred at 340, 380, 440, 500, 675, 870, 936, 1020 and 1640nm, makes the angular and multi-wavelength polar metric measurements available.

PM$_{2.5}$, the particle with aerodynamic diameter less than 2.5 micro, is considered as a better exposure indicator than PM$_{10}$ (Particle with aerodynamic diameter $\leq$ 10.0 Micron) for health assessments [2].

Email: chencheng@irsa.ac.cn
However, the lack of a dense network to monitor PM$_{2.5}$ hinders health risk assessments at regional scale. Because the polarization features are strongly depending on the characteristics of scattering particles, we try to employ the ground-based polar metric sun photometer to detect PM$_{2.5}$.

In this paper, we present the ground-based remote sensing of atmospheric aerosols, achieving the multi-angular and multi-wavelength DOLP (Degree Of Linear Polarization) from CE318-DP. In addition, a polarized vector radiative transfer model is introduced to simulate the DOLP under different sky conditions. Then we provide a preliminary analysis on the DOLP and mass density of PM$_{2.5}$, and get a reasonable agreement. As a result, we provide a new method to estimate the mass density of PM$_{2.5}$ by using the comprehensive network of ground-based sun photometer.

2. Polarization measurements and simulations

2.1. Measurements

The polarization measurements are implemented at RADI (Institute of Remote Sensing and Digital Earth Chinese Academy of Sciences), Beijing, China, using multi-wavelength sun photometer, CE318-DP. The instrument at RADI can be found at Figure 1. By making multi-wavelength sky scanning, CE318-DP can obtain a spectral and angular distribution of DOLP of sky light [3].

Figure 1. The CE318-DP at RADI (40.0048°N, 116.3786°E, 59.0m), Beijing, China, in clear (Date: 2011-03-04) and haze (Date: 2011-02-22) air condition.

Light scattered in the atmosphere by air molecules and aerosol particles is partially polarized and can be described by Stocks vector [4]. In order to detect polarization signal, the CE318-DP polarized radiometers place three linear polarizes, which are keeping 60° between their axis orientation angles. $S_{p1}$, $S_{p2}$ and $S_{p3}$ are the measured raw signals from these three polarizes. CE318-DP measures the DOLP of the incoming light, as follows [5]:

$$DOLP = \frac{2\eta \sqrt{S_{p1}^2 + R_{12}^2 S_{p2}^2 + R_{13}^2 S_{p3}^2 - R_{12} S_{p1} S_{p2} - R_{13} S_{p1} S_{p3} - R_{12} R_{13} S_{p2} S_{p3}}}{S_{p1} + R_{12} S_{p2} + R_{13} S_{p3}}$$

(1)

where $R_{12}$, $R_{13}$ and $\eta$ are calibration coefficients. $R_{12}$ and $R_{13}$ are calibrated to correct the difference between the intensity responses of the three polarization units. $\eta$ is calibrated to correct the measured DOLP with the reference DOLP source. By using this methodology, DOLP was measured with an uncertainty of ~0.01 [5].

The field experiment of CE318-DP instrument (#350) has been performed in north China at Beijing site from 12/2010 to 03/2011. From these measurements, the DOLP of sky light is calculated at five wavelengths (440, 675, 870, 1020 and 1640nm) in SPP (Sun Principal Plane) geometry, using the
algorithm introduced above. Examples of measured multi-wavelength and multi-angular DOLP of sky light can be found at Figure 2.

![DOLP graphs](image1)

**Figure 2.** Examples of CE318-DP measured multi-wavelength and multi-angular DOLP in different air conditions. The left data is measured at clear air condition with PM$_{2.5}$ < 50 $\mu$g/m$^3$. The right data is measured at hazy air condition with PM$_{2.5}$ > 300 $\mu$g/m$^3$.

2.2. Simulations

The propagation and redistribution of radiation in surface-atmosphere can be fully described by vector radiative transfer equation, which is the basis of quantitative remote sensing. In this paper, we adopted the SOS model, which solves the vector equation of radiative transfer by using the successive orders of scattering approach, to simulate the Stocks parameters ($I, Q, U, V$) of skylight, then according the Stocks formalism the DOLP can be simulated. The formula to calculate DOLP is:

$$DOLP = \left( Q^2 + U^2 \right)^{1/2} / I$$  \hspace{1cm} (2)

We performed simulations for different air condition in order to make clear aerosols optical properties and its impact on the polarization radiance. The atmospheric aerosols optical properties, including aerosol optical depth (AOD), aerosol particle size distribution and complex refractive index which are all retrieved from CE318-DP observations at RADI. These aerosols properties are input to the SOS model to simulate the DOLP under different sky conditions. The detailed steps of simulation used in this study are given in Figure 3.

![Simulation flow chart](image2)

**Figure 3.** The flow chart of simulation scheme

The aerosols optical properties were retrieved at RADI site from 12/2010 to 03/2011. Then we perform the simulations to obtain the multi-wavelength and multi-angular DOLP of sky light. Examples of simulated multi-wavelength and multi-angular DOLP of sky light can be found at Figure 3.
4. One can see from the simulation results that the DOLP(440nm) is sensitive to the concentration of fine particles, on the contrary, the DOLP(1640nm) is not sensitive to the fine particles.

![Image](a) sunny day, date: 2011-03-04
(b) hazy day, date: 2011-02-22

**Figure 4.** The SOS model simulated DOLP multi-wavelength and multi-angular in different air conditions. The left data is simulated in sunny clear air condition, AOD(440nm)=0.34. The right data is simulated in hazy air condition, AOD(440nm)=3.15.

3. The Correlation between DOLP and PM$_{2.5}$

We present the DOLP measurements and simulations in different air conditions in the section 2. Our primary focus is on the analysis of the each band’s maximum DOLP in both sunny and hazy days. Preliminary result shows that DOLP(440nm) is sensitive to the concentration of fine particles, and DOLP(1640nm) is not sensitive to the fine particles. When the concentration of fine particles in high level, DOLP(440nm) $>$ DOLP(1640nm) $\sim$0.3, while the concentration of fine particles in low level, DOLP(440nm) $<$ DOLP(1640nm) $\sim$0.3. Further analysis shows that in hazy days the longer wavelength the larger of the DOLP value we measured, on the contrary in the sunny days the longer wavelength the smaller of the DOLP we get.

We scatter each band’s maximum DOLP at one group measurement, and fit the four wavelengths (440nm, 675nm, 870nm and 1640nm) DOLP using the linear equation. $K$ value is the slope of the linear equation. The Figure 5 describes the $K$ value variation with the mass density of PM$_{2.5}$. (i) Negative $K$ value indicates lower mass density of PM$_{2.5}$. (ii) Positive $K$ value indicates higher mass density of PM$_{2.5}$.

![Image](i)

**Figure 5.** Scatter plot four wavelengths’ maximum DOLP at one group measurement during different PM$_{2.5}$ mass concentrations, and fit them using linear equation. $K$ value is the slope of the linear
equation. (i) The blue line shows the DOLP decreases with wavelength increases, $K = -0.25$, when the PM$_{2.5}$ = 57. (ii) The brown line shows the DOLP increases with wavelength increases, $K = 0.26$, when the PM$_{2.5}$ = 343. (iii) The pink line with $K = -0.003$ is drew when the PM$_{2.5}$ = 136.

In addition, we have tested our measured and simulated data from 28th of December 2010 to 7th of March 2011. These are specifically in both sunny and hazy condition, mass density of PM$_{2.5}$ ranging from lower than 10 $\mu$g/m$^3$ to higher than 400 $\mu$g/m$^3$. We tend to establish an exponential regression of DOLP and K. Then an exponential regression was performed, the equation of exponential regression is $\text{PM}_{2.5} = 83.62 \times \exp(5.37 \times K)$, squares of correlation coefficient ($R^2$) = 0.86, regression points number ($n$) = 58. Results show that $K$ value of multi-angular and multi-wavelength DOLP has a high correlation with mass density of PM$_{2.5}$. This simple exponential model links daily ground-based polarization remote sensing and PM$_{2.5}$ mass concentration.

![Figure 6. Scatter plot between K and PM$_{2.5}$. PM$_{2.5}$ values are obtained from U.S. Embassy. K values are derived from daily polarization measurements. The equation of exponential regression is $\text{PM}_{2.5} = 83.62 \times \exp(5.37 \times K)$, squares of correlation coefficient ($R^2$) = 0.86, regression points number ($n$) = 58.](image)

4. Conclusion
This work developed a methodology to estimate the mass density of PM$_{2.5}$ using the comprehensive network of ground-based polarization sun photometer. To achieve this objective, first, we gathered the DOLP and daily PM$_{2.5}$ from 28th of December 2010 to 7th of March 2011. In a second time, we compared the measured and simulated DOLP in different air conditions. Our results show high correlations ($R^2 = 0.86$). It should be noted that this result only tests in a few cases, more extensive studies should be done to verify the result. Conclusions from this work contribute to the ground–based polarization remote sensing which is performed routinely today [1][7]. As a consequence, this work provides a new method to estimate the mass density of PM$_{2.5}$ by using the comprehensive network of ground-based sun photometer.

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