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天空偏振光测量系统的设计

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摘要: 根据一束光的偏振特性可以由斯托克斯矢量来表征的原理, 设计搭建了一种天空偏振光测量系统。该系统由计算机、赤道仪、光纤光谱仪和配备了可旋转偏振片的改进式天文望远镜组成, 在 400~900 nm 的光谱分辨率为 1.4 nm。赤道仪经过标定后可以实现 0~180°方位角以及 0~90°高度角的调整, 角度分辨率为 2.5°。系统的光学全视场为 4.5°, 使用该系统可以测量全天空的光强辐射度、偏振度以及偏振方位角。由标定结果可知, 系统光强测量的重复率在 450~500 nm 为 99%, 在 500~900 nm 为 (95±3)%; 在 400~750 nm 偏振度测量误差 < 2%, 在 475 nm 处达到 1.2%。偏振方位角的测量误差 < 2°。

关键词: 天空偏振光; 偏振光测量; 斯托克斯矢量; 偏振度; 瑞利散射

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Design of skylight polarization measurement system

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Abstract: According to the principle that light polarization can be expressed with a Stokes vector, a new system to measure the polarized skylight distribution is developed. The system is composed of a computer, a modified equatorial mount, an optical fiber spectrometer and an improved astronomical telescope mounted with a rotatable linear polarizer. The spectral resolution of this system is 1.4 nm for the measurement when wavelength ranges from 400 nm to 900 nm. Using modified equatorial mount, the system can scan the points of celestial hemisphere at azimuth ranges from 0° to 180° and elevation 0° to 90° at an angular resolution of 2.5°. For a full-angle viewing field of 4.5°, this system can measure the radiance intensity, the Degree of Linear Polarization (DOLP), and the Angle of Linear Polarization (AOLP) of the celestial. The calibration results show that the repeatability of intensity measurements is 99% in spectral ranges from 450 nm to 500 nm, and (95±3)% from 500 nm to 900 nm. The uncertainty of DOLP is less than 2% in spectral ranges from 400 nm to 750 nm, especially 1.2%

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at 475 nm. The angle error of AOLP is smaller than 2° .

Key words: skylight polarization; polarization measurement; Stokes vector; degree of polarization; Rayleigh scattering

1 Introduction

Polarization is one of the important characteristics of skylight to explain natural phenomena, and to indicate the atmospheric turbidity and surface properties^[1]. Furthermore, it has become apparent that many animals are sensitive to the polarization of skylight, such as birds, honeybees and ants^[2-3]. The desert ant *Cataglyphis* can orient itself by means of the sun and the polarized light patterns in the sky (Wehner 1982). As various parameters known to influence the degree of polarization in the earth's atmosphere, such as the reflection of ground, the content of water vapor, dust and haze, it is important to provide data to evaluate how skylight polarization might be advantageous for orientation. So we designed and built a measurement system of skylight polarization.

Measurements of skylight polarization were made by various means^[3-6]. Brines & Gould (1982) undertook measurements at several points of the firmament by means of a point-source scanning polarimeter^[2]. They could measure points at every 5° in azimuth and elevation of a half hemisphere of the sky. Such a polarimeter has an advantage of scanning a given area of the optical environment and then measuring the polarization sequentially in many directions. However, scanning a larger area with this point-source polarimeter is troublesome and time-consuming. By contrast with this, using full-sky imaging polarimetry, the spatial distribution of polarization can be determined^[3-4] easi-

ly and quickly.

In the present work, we measured the skylight polarization by using the system. Radiance intensity, the Degree of Linear Polarization (DOLP), and the Angle of Linear Polarization (AOLP) of celestial hemisphere had been measured.

2 Measurement principle

As several calculi have been developed for analyzing polarization, generally the Mueller calculus is the most suitable for describing radiance measurement. In the Mueller calculus, the Stokes vector \mathbf{S} is used to describe the polarization state of a light beam, and the Mueller matrix \mathbf{M} is used to describe the characteristics of an optical system in the measurement. The Stokes vector \mathbf{S} is defined as $\mathbf{S} = [I, Q, U, V]^T$, where I , Q , U and V are stokes vector elements. In general, the linearly polarized light is a common type of polarization in nature^[7], so we don't measure the quantity of the parameter V ($V \approx 0$).

Transformation of a Stokes vector $[I, Q, U, V]^T$ into a new Stokes vector $[I', Q', U', V']^T$ by an optical process can be represented as a linear process $\mathbf{S}' = \mathbf{MS}$. Then, the intensity of light passing through an ideal linear polarizer is given by:

$$I'(\alpha) = \frac{1}{2}(I + Q\cos 2\alpha + U\sin 2\alpha), \quad (1)$$

where α is the angle between the polarizer-preferred transmittance plane and the reference plane.

According to the equation (1), if the linear polarizer rotates at $\alpha = 0^\circ$, 60° , or 120° , respec-

tively, we will get a matrix of three linear equations. Conversely, the Stokes vector $[I, Q, U, V]^T (V \approx 0)$ can be calculated as:

$$\begin{cases} I = \frac{2}{3}(I'(0^\circ) + I'(60^\circ) + I'(120^\circ)) \\ Q = \frac{2}{3}(2I'(0^\circ) - I'(60^\circ) - I'(120^\circ)) \\ U = \frac{2}{\sqrt{3}}(I'(60^\circ) - I'(120^\circ)) \end{cases} \quad (2)$$

When these incoming Stokes vector parameters are determined, the DOLP and the AOLP can be calculated by equation (3):

$$\text{DOLP} = \frac{(Q^2 + U^2)^{1/2}}{I}, \quad \text{AOLP} = \frac{1}{2} \arctan\left(\frac{U}{Q}\right). \quad (3)$$

3 Instrument description and calibration

The principal components and actual setup of the skylight polarization measurement system are shown in Fig. 1. The system is a computer, a modified equatorial mount, an optical fiber spectrometer and an improved astronomical telescope with rotatable linear polarizer in front. The equatorial mount is modified to be an angle adjuster. With this mount, the elevation and azimuth of the measurement can be adjusted rapidly in order to scan the entire hemisphere.

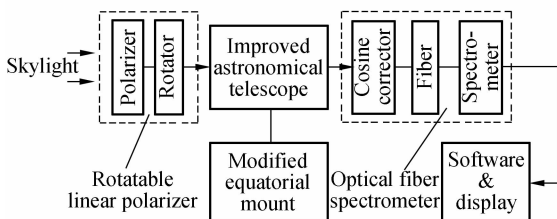


Fig. 1 Principal components and actual setup of skylight polarization measurement system

Using this system, kinds of measurement methods can be carried out, not only the repetitive 1-D plane scan, but also 2-D scan of the complete celestial hemisphere. The results are displayed on the computer software. The alphanumeric readout consists of date/time, DOLP, AOLP, the components of the Stokes vector, and the distribution pattern of skylight polarization. All the specifications of the system are listed in Tab. 1.

Tab. 1 Specifications of measurement system

Detector	spectrometer with 2 048 pixel CCD
Spectral range	400 to 900 nm at 1.4 nm resolution
viewing field	4.5° of full-angle viewing field
Transmission of polarizer	2% to 42% for visible light
extinction ratio	less than 1% for visible light
Scan angle range	0° to 180° of azimuth, 0° to 90° of elevation at 2.5° resolution
Measurement speed	12 s per scanning point

By using the linearly polarized light source with a known polarization state as system input, the system is calibrated. The calibration results show that the repeatability of intensity measurements is 99% in the spectral range from 450 nm to 500 nm, and $95\% \pm 3\%$ from 500 to 900 nm respectively. The uncertainty of DOLP is less than 2% of the spectral range from 400 nm to 750 nm, especially 1.2% at 475 nm. The angle error of AOLP is less than 2°.

4 Measurement results

Our measurements are taken from the roof of a four-storey building in Dalian University of Technology (38°55'N, 121°36'E) and carried out in several days with different weather conditions. In these measurements, we took some characteristic curves and results for explanation. We first showed the measurement at every 5° a-

long the whole solar vertical plane of the spectral range from 400 nm to 750 nm at 35° elevation of the sun (in Fig. 2). And then, the points were measured at every 15° azimuth and elevation angles of an entire celestial hemisphere and the sun at 45° elevation (shown in Fig. 3).

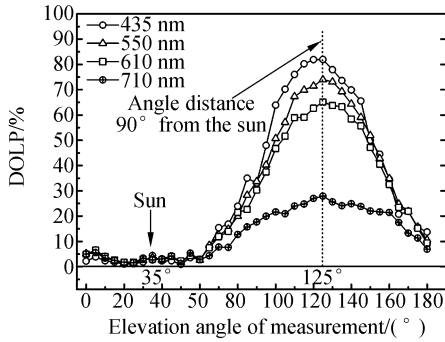


Fig. 2 DOLP curves of solar vertical plane measured from 400 nm to 750 nm at 35° elevation of the sun.

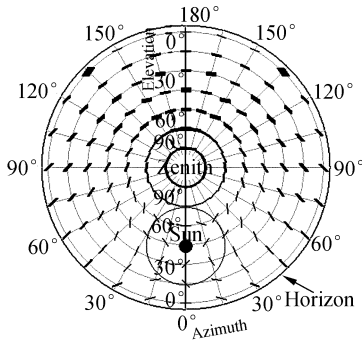


Fig. 3 Distribution of DOLP and AOLP relative to the horizon at a wavelength of 475 nm and a elevation of the sun of 45°. The solar vertical is toward the bottom of the figure and azimuth increases uniformly counter clockwise 0° to 180°.

Fig. 2 demonstrates that the DOLP reaches its minimum value near 0 observed near the sun, and then increases steadily until the maximum presented when the angle distance is about 90°

from the sun (represented by the dot line). These characteristics exhibit the general geometrical form, simply predicted by Rayleigh theory. In addition, DOLP is highly dependent on wavelength. The value DOLP is always higher at the shorter spectrum wavelength than those longer spectrum wavelengths. For example, the DOLP at 435 nm is greater than the value at 610 nm spectrum.

Fig. 3 shows the hemispheric distribution pattern of DOLP and AOLP. The thickness of lines indicates qualitatively DOLP, and the orientation represents AOLP. The black point in the figure represents the sun. The pattern here also shows that the maximum polarization across the sky from all the points at an angle distance about 90° from the sun. Besides, the result effectively illustrates the symmetry and dependence of the sky patterns on the position of the sun, only except the scanning points near the sun (the circle around the sun).

5 Conclusions

In the present paper, a new system to measure the skylight polarization distribution has been developed. All the measurements of this system base on the radiance intensity. The system can effectively acquire the radiance distribution information of skylight polarization. We use this system to measure simultaneously the radiance intensity, DOLP, and AOLP of polarized light at 5° intervals across solar vertical plane, and at 15° intervals to scan the points of entire hemisphere. We expect that the measuring time and the angle error of AOLP of this system can be reduced in further study.

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