Abstract
A new system has been developed and calibrated to measure the characteristics and distribution of skylight polarization. With a series of measurements obtained, we verified that the distribution of degree and angle of skylight polarization accords well with the predictions of Rayleigh scattering. The differences of the characteristics and distribution of skylight polarization across the principal plane owning to measurements’ errors have been analyzed and discussed.

Keywords: Skylight polarization; Stokes vector; Rayleigh scattering

1. Introduction
Polarization is one of the important characteristics of skylight, which has long been studied for many reasons. Early interests of skylight polarization involved explaining natural phenomena, and then indicated the atmospheric turbidity and surface properties (Coulson 1974) [1, 2]. Recently, it has become apparent that many insects (e.g. bees and desert ants *Cataglyphis*) exploit celestial polarization pattern of the blue sky for spatial navigation (Wehner, 1984, 1992) [3, 4].

Coulson [5] listed the various types of polarimeters developed for skylight polarization measurement. The different configurations are used in various fields. Bence Suhai and Gabor Horvath [6] presented the first high-resolution maps of Rayleigh behavior in clear and cloudy sky conditions measured by full-sky imaging polarimetry. But most of imaging polarimeters can only record the polarization patterns from some limited spectral bands by using photographic film or CCD image sensor as detectors.

In this paper, a new point-source spectral irradiance polarimeter (SIP) system has been developed for measuring the distribution and spectral characteristics of skylight polarization. The distribution of skylight polarization in the principal plane in local place displayed, the differences of the characteristics and distribution of skylight polarization across the principal plane owning to measurements’ errors have been analyzed and discussed.

2. Methodology
The experimental setup was based on the Mueller calculus, the Stokes vector \( S \) is used to describe the polarization state of a light beam, and the Mueller matrix \( M \) to describe the characteristics of an optical system in the measurement. The Stokes vector \( S \) is defined as \( S = [I, Q, U, V]^T \), where \( I, Q, U \) and \( V \) are stokes vector elements. In general, the linearly polarized light is the most common type of polarization in nature [5], so the quantity of the parameter \( V (V = 0) \).
From the Stokes vector $S$, the total irradiance intensity is $I$ (μW/cm$^2$). The degree of polarization $P$ ($0 \sim 100\%$) and the angle of polarization $\chi$ ($-90^\circ \sim +90^\circ$) can be defined as [7]:

$$P = \frac{(Q^2 + U^2)^{1/2}}{I}, \; \tan 2\chi = \frac{U}{Q} \quad (1)$$

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 with the Mueller matrix. Then, the intensity of light passing through an ideal linear polarizer is given by:

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

where $\alpha$ is the angle between the polarizer-preferred transmittance plane and the reference plane.

According to the equation (2), if the linear polarizer rotated at $\alpha=0^\circ$, $60^\circ$, and $120^\circ$, respectively, we will get a matrix of ternary linear equations. Conversely, the Stokes vector $[I, Q, U, V]^T$ ($V=0$) can be calculated as:

$$\begin{align*}
I &= \frac{1}{4}(I'(0^\circ) + I'(60^\circ) + I'(120^\circ)) \\
Q &= \frac{1}{3}(2I'(0^\circ) - I'(60^\circ) - I'(120^\circ)) \\
U &= \frac{1}{3}(I'(60^\circ) - I'(120^\circ))
\end{align*} \quad (3)$$

3. Experimental investigation

The setup of SIP system is shown in Fig. 1. The SIP system is mainly composed of an improved astronomical telescope and a fiber optic spectrometer. With our modifying, the telescope has become the polarized optical system, which can carry out the real time measurement and scan the entire firmament. A linear polarizer which can be rotated at different angle is mounted in front of the optical system. The aperture of the polarimeter is about 4.5°. The fiber optic spectrometer has 2048 pixel CCD detector array, the resolution of the spectrometer can reach 1.4nm, and the spectral range of the spectrometer is from 400 to 1100nm.

The measurements were taken on the top of the School of Mechanical Engineering Building in Dalian University of Technology (at approximately 38°55’N, 121°36’E), at 2:30 p.m. on 21 September 2007, and it was the clear sky. Fig. 2 depicts the geometry of the measurement system. The measurement points were taken at every 5°of $\theta_o$ along the principal plane, while the principal plane cross though the sun(S), zenith (Z) and observed point (P). The point (O) is the detector’s position. $\theta_s$ is the elevation angle of sun, $\theta_o$ is the elevation angle of detector, respectively.

At every measurement point, the system recorded the irradiance spectrum, and then yielded the modulation of three parameters ($I$, $P$, and $\chi$), when linear polarizer was rotated in $0^\circ$, $60^\circ$, and $120^\circ$. Here, $\chi$ is defined as angle between the local horizon and the E-vector. For example, $\chi=0^\circ$ represents horizontal E-vectors.

Figure 3 shows the polarized irradiance curves of skylight obtained at the points far from the sun for calibration. The maximum of irradiance happened while spectral band is 450±15nm, which has been proved by the “ultraviolet paradox of the perception of skylight polarization” [3].
4. Results and discussion

Figure 4 shows a series of intensity $I$, degree $P$, and angle $\chi$ of polarization patterns of the solar vertical plane at the wavelength 450 nm.

Figure 4(a) demonstrates that irradiance occurs at the position close to the sun strongly and irradiance decreases gradually from the point of sun to both sides as $\theta_0$ increases.

Figure 4(b) shows that the degree of polarization $P$ reach its maximum when $\theta_0 = 125^\circ$ ($\theta_S = 35^\circ$), and decreases steadily out of this position. In addition, the features that decrease in the degree of polarization of skylight at the longer wavelength are typical of local conditions, and the relatively high reflectance of ground surface in the longer wavelength range is an additional contributing factor.

Figure 4(c) illustrates that the angle of polarization $\chi$ was mostly within the range $0^\circ < \chi < 10^\circ$. The unusual fluctuation shows that the angle of polarization fluctuated and traversed the horizontal axis within the range $5^\circ < \theta_0 < 65^\circ$, when $\theta_S = 35^\circ$. From our data of $\chi$
in Fig. 4(c), we can conclude that the angle of polarization is independent of wavelength and perpendicular to the principal plane, only except for the small regions of sun. On the other hand, the expectable value of $\chi$ should be zero by theory, but some other factors influence the measurements, such as system deviation and non-calibrated reference axis.

![Fig. 4](image)

Fig. 4. Irradiance intensity $I$, degree of polarization $P$, and angle of polarization $\chi$ versus the elevation angle of detector $\theta_D$, in the spectral region of 450nm. (a): the irradiance intensity curve; (b): the degree of polarization curve; (c): the angle of polarization curve.

![Fig. 5](image)

Fig. 5 (a) and (b): Degree ($P$) and angle ($\chi$) of polarization of the principal plane measured from 400nm to 750 nm of the spectral ranges when $\theta_S=35^\circ$, respectively.

The degree of polarization $P$ was always greater in the spectral ranges from 400nm to 610nm and smaller between 610nm and 750nm of the spectrum in Fig. 5(a). The $P$ reached the maximum value in all wavelength when $\theta_D = 125^\circ$ approximately. This reflects the wavelength dependence of Rayleigh scattering and explains the blue sky.

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The degree of polarization and angle of the plane of polarization were calculated and displayed. Measurement errors arise from errors in the recorded light intensity and the calibrated Mueller matrix elements. Except, unavoidable stray light and noise in the optical and electronic system influence the calculated data, the measurements’ being taken in a series that extends ~1.5 min (ideally measurements should be taken at the same time), normally skylight does not change significantly in 1.5 min, especially when the Sun elevation is high [2].

As shown in Fig. 5(b), few differences were measured in the angle of polarization as a function of wavelength. It shows that the angle of polarization is independent of the wavelength in the principal plane. We already know some important biological factors that many polarization-based insects cannot navigate when the degree of polarization is below the known perceptual thresholds so far studied [5, 8]. With the related degree pattern of polarization in Fig. 4(b), the unusual pattern of \( \chi \) occurs close to the sun about \( \pm 30^\circ \) region [Fig. 4(c)], where the degree of polarization is below 9%.

5. Conclusion

By using our point-source SIP system, we measured the parameters of skylight polarization in the principal plane. Since the angle of polarization depends only on the plane of scattering angle, the fluctuation of the angle of polarization can be caused by multiple scattering and diffuse reflection, which can change the orientations of scattering angles. Therefore, the E-vector deviations near the sun can produce large errors for orientating and locating the sun. Further experiments will be necessary to determine the details of these affections and weather conditions.

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References