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Deriving the geocentric vector and the solar vector from the atmospheric polarization pattern on LEO satellites

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ABSTRACT

Using the polarimetric imaging sensor on LEO (Low-Earth Orbit) satellites to photograph the atmospheric polarization pattern derived from the polarized light backscattered by the atmospheric particles is proposed in this paper. First, the formation of polarization pattern and its measurement principle are introduced based on Rayleigh scattering, and the extraatmospheric polarization pattern is analyzed. Afterwards, it is presented that how to attain the geocentric vector and the solar vector simultaneously from the polarization pattern through the least squares method, which is verified by simulation subsequently. The simulation results show that it is feasible to derive the two vectors from the captured image.

1. Introduction

The atmospheric polarization pattern formed after the sunlight is scattered by atmospheric molecules and aerosols, is exploited by many wild animals and insects to derive compass information. Bees can sense the polarization pattern through their compound eyes. After finding the honey source, they need an azimuth reference determined by E-vector of the polarization pattern to give its direction by means of dancing [1–5]. Many migratory songbirds, such as Savannah sparrows, also have the capability to use polarized light cues, especially the region of sky near the horizon, to recalibrate the compass in the course of migration every year [6]. Monarch butterflies in North America sense the polarization pattern of ultraviolet band and regard E-vector as the reference direction to aid navigation when they migrate to Mexico [7,8]. Desert ants could utilize the polarization pattern as a compass to return to their nest on the shortest path possible after performing a large-scale foraging excursion [9–11]. Certainly, other animals such as spider and shrimp, can also use the polarization pattern for orientation [12,13].

Imitating polarization navigation of insects, kinds of bio-polarization sensors are designed to measure the polarization pattern, and various methods are proposed to obtain compass information from the polarization pattern. Kane Usher puts forward that the scanning method with a digital camera is used to measure polarization pattern. Meanwhile, the image information attained is analyzed preliminarily to obtain the degree of polarization and polarization angle [14]. CMOS image sensor is designed, which outputs light intensity information of different polarized directions to achieve the degree of polarization and polarization angle [15–19]. Daobin Wang designs a real-time bionic camera-based polarization navigation sensor to measure polarization pattern through three images of different polarized directions (0°, 45° and 90°), the accuracy of which can obtain 0.3° [20]. Jinkui Chu has implemented a metal grid polarization sensor, whose accuracy is superior to 0.1° [21–23].

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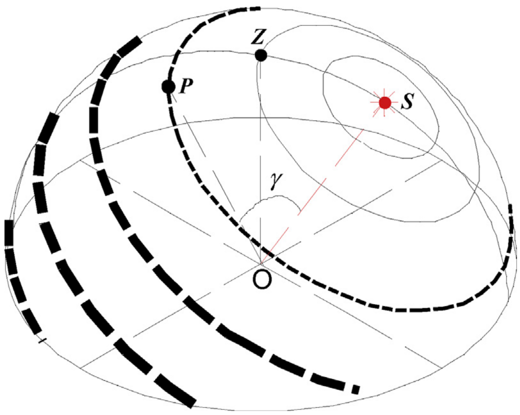

Fig. 1. 3-dimensional polarization pattern.

Zhiwen Xian designs a bio-inspired polarization navigation sensor and gives a new method of calculating polarization angle [24,25]. Based on these sensors, different calibration methods of polarization sensors are proposed including the variable substation and curve fitting, the multi-objective optimization and Non-Dominated Sorting Genetic Algorithm, and the least squares [26–28]. In addition, some researchers are also trying to apply the new information derived from the polarization pattern to positioning and attitude determination [29–31].

Although more and more people are studying bio-polarization navigation, they primarily focus attention on polarimetric studies in the atmosphere while the extraatmospheric polarimetric characteristics research is still situated in the exploratory phase. In contrast to the endo-atmosphere polarization pattern formed due to the polarized light forescattered by the atmospheric particles and aerosols, the polarization pattern outside the atmosphere is derived from the polarized light backscattered by these particles. The backscatter polarization pattern photographed outside the atmosphere contains the azimuth information of the earth and the sun. Thus, it is put forward in this paper that the geocentric vector and the sun vector could be extracted from polarization pattern, which can provide relevant measurement information for the LEO satellite's orbit determination and attitude determination. Jun Zhou has studied the extraatmospheric polarimetric characteristics initially, and presented the idea of applying the new navigation information derived from the polarization pattern to satellite navigation [32,33].

To demonstrate the feasibility of obtaining the geocentric vector and solar vector based on the polarization pattern, this paper is organized as follows. In Section 2, we give a brief overview of the polarization pattern and principles of the polarimetric imaging sensor. In Section 3, the least square method of obtaining the geocentric vector and the solar vector is put forward. In Section 4, the simulation is carried out to demonstrate the feasibility of obtaining the geocentric vector and the solar vector simultaneously by means of least squares and the results are analyzed. Some conclusions are drawn in Section 5.

2. Polarization pattern description and its measurement

2.1. Measurement of polarization pattern

Rayleigh scattering occurs when the atmospheric molecule is much smaller than the wavelength of the incident light, which results in the polarization pattern. Fig. 1 shows the 3D polarization pattern formed based on the single scattering Rayleigh model. O is the observation position. $\overrightarrow{OS}$, $\overrightarrow{OZ}$ and $\overrightarrow{OP}$ represent the solar direction, the zenithal direction and the observing direction respectively. The width of the dashed line indicates the degree of polarization (DOP) while its tangent direction indicates the E-vector orientation observed from the center of hemisphere. Then, the DOP of $\overrightarrow{OP}$ is

$$DOP(\gamma) = \frac{1-\cos^2\gamma}{1+\cos^2\gamma} \times DOP_{\max} \tag{1}$$

where γ is the angle between the solar direction and the observing direction. $DOP_{\max}$ is the maximum value of DOP, which is smaller than 1.0 generally due to the interference of many kinds of factors like the weather.

The polarization characteristic of light is generally expressed by the Stokes vector $\boldsymbol{S} = (I,\quad Q,\quad U,\quad V)$, in which I represents the total light intensity, Q represents the linearly polarized light intensity of 0° direction, U represents the linearly polarized light intensity of 45° direction, and V represents the circularly polarized light intensity. V is negligible, generally speaking. Then, the DOP can be calculated according to I, Q and U.

$$DOP = \frac{\sqrt{Q^2+U^2}}{I} \tag{2}$$