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Linear stokes imaging spectropolarimeter based on the static polarization interference imaging spectrometer

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ABSTRACT

The theoretical operation and experimental demonstration of a Fourier-transform linear imaging spectropolarimeter are presented. It is composed of a rotating Glan-Taylor prism and a Fourier-transform spectrometer based on Savart polariscope. The polarized light enters the spectrometer to create three sets of interferograms, where the spectral linear Stokes parameters can be calculated and acquired. Compared with previous instruments, the significant advantages of the described sensor are that there are no spatial aliasing in the polarized spectra and it can be used in wider spectral coverage with low cost, ultra-compact size and a simpler common-path configuration. Another static linearly Stokes imaging spectropolarimeter based on the field of view division technique and SPIIS is conceptually described. The spectral dependence of linear Stokes parameters can be recovered with Fourier transformation. Since there is no rotating or moving parts, the system is relatively robust.

1. Introduction

Imaging spectropolarimeter (ISP) is a novel instrument that integrates the functions of camera, spectrometer and polarimeter. It can acquire the image, spectrum and polarization data of a target simultaneously [1–3]. ISP provides richer information for target detection and identification. Stokes imaging spectropolarimetry is usually employed for ground, airborne and spaceborne remote sensing [4–6]. It collects the spectral variation of Stokes parameters coming from the reflection of sunlight by a scene or from its own radiation. The spectral dependence of Stokes parameters is defined by [7]

$$S(\lambda) = \begin{bmatrix} S_0(\lambda) \\ S_1(\lambda) \\ S_2(\lambda) \\ S_3(\lambda) \end{bmatrix} = \begin{bmatrix} I_{0^\circ}(\lambda) + I_{90^\circ}(\lambda) \\ I_{0^\circ}(\lambda) - I_{90^\circ}(\lambda) \\ I_{45^\circ}(\lambda) - I_{135^\circ}(\lambda) \\ I_R(\lambda) - I_L(\lambda) \end{bmatrix} \tag{1}$$

where $_\lambda$ is spectral variable, S_0 is the total intensity of the light, S_1 is the difference between linear polarizations of 0° and 90°, S_2 is the difference between linear polarizations of ± 45°, and S_3 is the difference between right and left circular polarization.

ISPs based on Fourier-transform spectrometer have been a hot research topic for several years. The Fourier-transform spectrometer has several advantages for spectral detection, such as high optical throughput and high spatial resolution [8,9]. Several productive Fourier-transform spectropolarimeters have been reported. One uses the channeled spectropolarimetric technique [10,11]. Such sensor can determine four Stokes parameters from a single interferogram. Since the recorded interferogram contains more than three channels, the spectral resolution of each spectral Stokes parameters is lower than that of the spectrometer. Another attractive method uses achromatic wave-plates as the polarization modulator by combination with time-division or aperture division technique [12–14]. These sensors can overcome the drawbacks of the channeled spectropolarimetric technique. However, the high-precision polarization modulator in such instrument still causes high cost and the limitation of spectral coverage. Recent progress in the Fourier transform imaging spectrometers based on birefringent interferometers has remarkably enhanced the performance of the ISPs, such as static polarization interference imaging spectrometer (SPIIS) based on Savart polariscope [15–18]. It has the advantages of ultra-compact size with common-path configuration and high optical throughput. However, such instrument can only acquire the linearly polarized component of S_1 or S_2. Since very little circular polarization can be expected in most passive imaging scenarios, obtaining spectral dependence of linear Stokes parameters would satisfy a number of applications [19].

In this paper, we propose a time-division Fourier-transform ISP based on the static polarization interference imaging spectrometer. A rotating Glan-Taylor prism is incorporated into the SPIIS. There is no any high-precision polarization modulator in the system. The proposed

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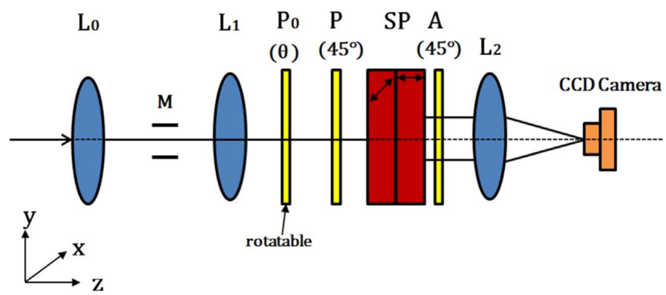

Fig. 1. Schematic layout of the Fourier-transform ISP.

method has several advantages, such as ultra-compact size with common-path configuration, high optical throughput and ultra-broad spectral coverage.

2. Theoretical analysis

2.1. Optical layout and principle

The schematic layout of the presented linear ISP based on SPIIS is depicted in Fig. 1. A rotatable polarizer is installed ahead of the SPIIS, which is composed of a fore-optics L_0 and L_1, a polarizer P, a Savart Polariscope (SP), an analyzer A, a reimaging lens L_2 and a digital CCD camera.

Light from a scene is imaged on intermediate image plane M by lens L_0 and then collimated by lens L_1. θ is orientation of the rotatable polarizer P_0. Light emerging from P becomes linearly polarized at 45° to the optic axes of SP. SP splits the incoming light into two equal amplitudes, orthogonally polarized components with a lateral displacement. After passing through the a analyzer A, the two component rays are resolved into linearly polarized light in the same orientation with equal amplitude and recombined onto the camera by L_2. Interference images in the spatial domain can be recorded. Due to the characteristics of the SPIIS, the interferogram for the same object pixel are collected by employing tempo-spatially mixed modulated mode (also called windowing mode) [14].

The mathematical expression of interferogram can be obtained by using the Mueller calculus. The Stokes vector of the emergent light from the analyzer A can be described as

$$S_{out} = M_A M_{SP} M_P M_{P_0} S_{in} \tag{1}$$

where the quantities $\mathbf{M_A}$, $\mathbf{M_{SP}}$, $\mathbf{M_P}$ and $\mathbf{M_{PO}}$ are the Mueller matrices of the the analyzer A, the SP, the polarizers P and P_0, respectively. $\mathbf{S_{in}}$ is the spectrally resolved Stokes vector of the incident light. Substituting expressions of the Mueller matrices into Eq. (1) yields the following results

$$S_{out} = \frac{1}{8}\begin{bmatrix}1&0&1&0\\0&0&0&0\\1&0&1&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&\cos\varphi&0\\0&0&-\sin\varphi&\cos\varphi\end{bmatrix}\begin{bmatrix}1&0&1&0\\0&0&0&0\\1&0&1&0\\0&0&0&0\end{bmatrix}$$
$$\begin{bmatrix}1&\cos 2\theta&\sin 2\theta&0\\\cos 2\theta&\cos^2 2\theta&\cos 2\theta\sin 2\theta&0\\\sin 2\theta&\cos 2\theta\sin 2\theta&\sin^2 2\theta&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}S_0(\lambda)\\S_1(\lambda)\\S_2(\lambda)\\S_3(\lambda)\end{bmatrix}$$
$$= \frac{1}{8}(1+\cos\varphi)\begin{bmatrix}(1+\sin 2\theta)S_0(\lambda)+(\cos 2\theta+\cos 2\theta\sin 2\theta)S_1(\lambda)\\+(\sin 2\theta+\sin^2 2\theta)S_2(\lambda)\\0\\(1+\sin 2\theta)S_0(\lambda)+(\cos 2\theta+\cos 2\theta\sin 2\theta)S_1(\lambda)\\+(\sin 2\theta+\sin^2 2\theta)S_2(\lambda)\\0\end{bmatrix} \tag{2}$$

where $\varphi = 2\pi\Delta/\lambda$, Δ is the OPD produced by SP.

Since the digital camera responds to radiation intensity instead of polarization state, only the first parameter of $\mathbf{S_{out}}$ can be measured

$$I_S(\Delta,\theta,\lambda) = \frac{(1+\cos\varphi)}{8}[(1+\sin 2\theta)S_0(\lambda) + (\cos 2\theta + \cos 2\theta\sin 2\theta)S_1(\lambda) + (\sin 2\theta + \sin^2 2\theta)S_2(\lambda)] \tag{3}$$

It is assumed that the light from the object has a broadband spectrum and gradually changes with wavelength λ from λ_1 to λ_2. So the interferogram I can be described as:

$$I(\Delta,\theta) = \int_{\lambda_2}^{\lambda_1} I_S(\Delta,\theta,\lambda)\,d\lambda \tag{4}$$

In order to determine the three linearly spectral dependence of Stokes parameters, the polarizer P_0 is rotated to three different angular orientations. The interfergrams detected by CCD can be expressed by

$$I(\Delta,\theta_1) = \int_{\lambda_2}^{\lambda_1}\frac{(1+\cos\varphi)}{8}[(1+\sin 2\theta_1)S_0(\lambda) + (\cos 2\theta_1 + \cos 2\theta_1\sin 2\theta_1)S_1(\lambda) + (\sin 2\theta_1 + \sin^2 2\theta_1)S_2(\lambda)]d\lambda \tag{5-1}$$

$$I(\Delta,\theta_2) = \int_{\lambda_2}^{\lambda_1}\frac{(1+\cos\varphi)}{8}[(1+\sin 2\theta_2)S_0(\lambda) + (\cos 2\theta_2 + \cos 2\theta_2\sin 2\theta_2)S_1(\lambda) + (\sin 2\theta_2 + \sin^2 2\theta_2)S_2(\lambda)]d\lambda \tag{5-2}$$

$$I(\Delta,\theta_3) = \int_{\lambda_2}^{\lambda_1}\frac{(1+\cos\varphi)}{8}[(1+\sin 2\theta_3)S_0(\lambda) + (\cos 2\theta_3 + \cos 2\theta_3\sin 2\theta_3)S_1(\lambda) + (\sin 2\theta_3 + \sin^2 2\theta_3)S_2(\lambda)]d\lambda \tag{5-3}$$

By removing the background intensities and taking inverse Fourier-transform of the patterns, the linear equation group of the linearly spectral Stokes parameters can be obtained

$$\begin{cases}(1+\sin 2\theta_1)S_0(\lambda) + (\cos 2\theta_1 + \cos 2\theta_1\sin 2\theta_1)S_1(\lambda)\\ \quad + (\sin 2\theta_1 + \sin^2 2\theta_1)S_2(\lambda) = 8\Im^{-1}\{I(\Delta,\theta_1)\}\\(1+\sin 2\theta_2)S_0(\lambda) + (\cos 2\theta_1 + \cos 2\theta_1\sin 2\theta_2)S_1(\lambda)\\ \quad + (\sin 2\theta_1 + \sin^2 2\theta_2)S_2(\lambda) = 8\Im^{-1}\{I(\Delta,\theta_2)\}\\(1+\sin 2\theta_3)S_0(\lambda) + (\cos 2\theta_1 + \cos 2\theta_1\sin 2\theta_3)S_1(\lambda)\\ \quad + (\sin 2\theta_1 + \sin^2 2\theta_3)S_2(\lambda) = 8\Im^{-1}\{I(\Delta,\theta_3)\}\end{cases} \tag{5-4}$$

The linear equation group of Eqs.(5–4) can be expressed as the matrix form:

$$M\bullet S_i = B \tag{6}$$

where

$$M = \begin{bmatrix}1+\sin 2\theta_1 & \cos 2\theta_1 + \cos 2\theta_1\sin 2\theta_1 & \sin 2\theta_1 + \sin^2 2\theta_1\\1+\sin 2\theta_2 & \cos 2\theta_2 + \cos 2\theta_2\sin 2\theta_2 & \sin 2\theta_2 + \sin^2 2\theta_2\\1+\sin 2\theta_3 & \cos 2\theta_3 + \cos 2\theta_3\sin 2\theta_3 & \sin 2\theta_3 + \sin^2 2\theta_3\end{bmatrix},$$
$$B = \begin{bmatrix}8\Im^{-1}\{I(\Delta,\theta_1)\}\\8\Im^{-1}\{I(\Delta,\theta_2)\}\\8\Im^{-1}\{I(\Delta,\theta_3)\}\end{bmatrix} \tag{7}$$

The spectral linear Stokes parameters can be acquired by calculating the inverse matrix of M:

$$\begin{bmatrix}S_0(\lambda)\\S_1(\lambda)\\S_2(\lambda)\end{bmatrix} = \begin{bmatrix}1+\sin 2\theta_1 & \cos 2\theta_1 + \cos 2\theta_1\sin 2\theta_1 & \sin 2\theta_1 + \sin^2 2\theta_1\\1+\sin 2\theta_2 & \cos 2\theta_2 + \cos 2\theta_2\sin 2\theta_2 & \sin 2\theta_2 + \sin^2 2\theta_2\\1+\sin 2\theta_3 & \cos 2\theta_3 + \cos 2\theta_3\sin 2\theta_3 & \sin 2\theta_3 + \sin^2 2\theta_3\end{bmatrix}^{-1}\bullet\begin{bmatrix}8\Im^{-1}\{I(\Delta,\theta_1)\}\\8\Im^{-1}\{I(\Delta,\theta_2)\}\\8\Im^{-1}\{I(\Delta,\theta_3)\}\end{bmatrix} \tag{8}$$