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Effect of keystone on coded aperture spectral imaging

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ABSTRACT

Compared to conventional imaging spectrometry, coded aperture snapshot spectral imaging (CASSI) has the advantages of high throughput snapshot imaging etc. But because of the presence of the dispersive element, CASSI system suffers the effect of the same optical aberrations as traditional single slit spectrometer. To study the effect of keystone on signal acquisition, the model of spatial–spectral aliasing and the reconstructed result in CASSI system, combined with the principle of coded aperture spectral imaging and the reconstruction algorithm, the relative peak signal-to-noise ratio (PSNR) of the reconstructed image and the maximal error of the reconstructed spectral curve at different spectral band bending were calculated and analyzed. The experimental result showed that spectral band offset of the signal acquired by the detector will change the degree of spatial–spectral aliasing. Compared to the reconstructed results with no spectral band bending, distinct errors are exhibited when spectral band bending emerges. And the reconstructed spectral curve tends to be smooth on both sides of the spectral channel. In order to reconstruct the spectral cube with high accuracy, spectral band offset should be no more than half a pixel.

1. Introduction

Imaging spectrometry is a technique that can simultaneously obtain the spatial information and spectral information of the object. Because of its three-dimensional nature, the resulting data is called as the spectral data cube. The addition of spectral information has been applied to many fields including agriculture [1], geology [2], biomedicine [3] and military [4]. The Imaging spectrometry community has developed different types such as slit-aperture dispersive spectrometers [5] and Fourier-transform spectrometers [6]. With the development of technology, coded aperture snapshot spectral imaging (CASSI) [7] is proposed and then has been studied extensively in [8,9]. A detailed summarization was presented in [10]. It provides a mechanism for taking a 3D spatial–spectral data-cube with a single shot 2D measurement. Based on the conventional slit-aperture dispersive spectrometry, a coded mask which modulates and compresses the 3D spatial–spectral data-cube about the scene is imported appropriately in the light path. The 3D spatial–spectral information about a scene of interest is first encoded and captured with one snapshot at the two-dimensional (2D) detector array. Compressed sensing (CS) theory [11] is then used to reconstruct the 3D data-cube from the 2D image. Compared to the conventional imaging spectrometry, CASSI eliminates the disadvantages of low light throughput and temporal scanning, greatly reduces the amount of original data, and alleviates the pressure of the data storage and transmission.

Imaging spectrometer suffers from optical aberrations and misalignments, which make spectral information distortional. These spectrographic distortions educe spectral and spatial misregistrations, which are known as “smile” and “keystone” properties (Fig. 1). Smile property, usually shown as a function of position in the field of view, is represented as a change of the central wavelength of a specific spectral channel. And keystone property represented as a change in the position of the same spatial pixel on the scene is a band-to-band misregistration. So it is also called as spectral band bending and can commonly be written as a function of wavelength. [12,13] These distortions may be caused by geometric distortion, as can be seen in camera lenses, or by chromatic aberration, or a combination of both [14]. In CASSI system, these distortions will change the original form of the aliasing information and degrade the accuracy of reconstructed spatial–spectral information. Therefore, it is very necessary to analyze and measure the

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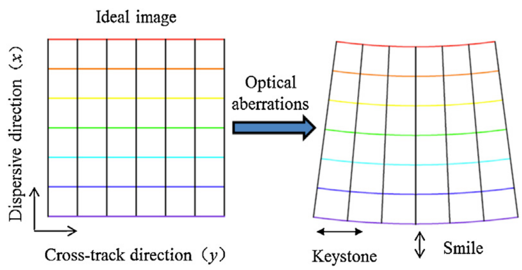

Fig. 1. Smile and keystone properties.

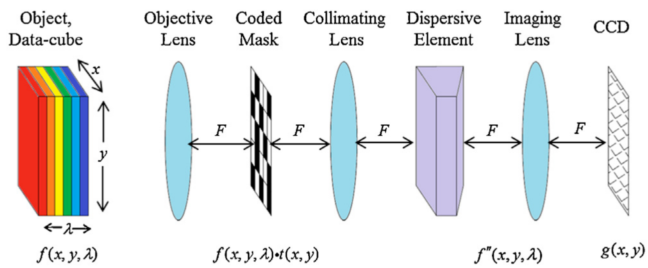

Fig. 2. Schematic of CASSI imaging.

effect of optical aberrations on CASSI. We have reported how spectral line bending affects CASSI. And in this paper, we will present the effect of keystone on imaging and reconstruction of the system.

The remainder of this paper is organized as follows. Section 2 explains principle of coded aperture spectral imaging. Section 3 is a description of the effect of keystone on the signal sampling of CASSI. Section 4 presents simulated implementation of our approach. This work is summarized in Section 5.

2. Principle of CASSI

CASSI colligates many disciplines including spectral imaging, numerical computation method and compressed sensing. Through a combination of optics and computational methods, the field of view (FOV) is expanded from a line in the conventional imaging spectrometry to a plane which greatly increases the light throughput. And through a combination of optics and compressed sensing, spatial–spectral imaging information of a 3D data-cube is acquired with just a single 2D measurement of the coded and spectrally dispersed source field. The amount of original data acquired by the instrument is greatly reduced and the stability of the instrument is remarkably improved. The basic principle of CASSI is shown in Fig. 2.

Assume the spectral density entering the objective lens is $f(x,y,\lambda)$. Then it is relayed to the coded mask. Let $t(x,y)$ be the transmission function of the coded mask. After modulated by the coded mask, the spectral density is represented as

$$f'(x,y,\lambda) = f(x,y,\lambda)\,t(x,y). \tag{1}$$

If the dispersive element is prism with the center wavelength λ_c and dispersion coefficient $\alpha(\lambda)$ and the dispersion is along the x-direction only, after propagation through the dispersive element, the spectral density at the detector plane is

$$\begin{aligned} f''(x,y) &= \iint f'(x',y',\lambda)\times\delta(x'-(x-\alpha(\lambda)\times(\lambda-\lambda_c)),y'-y)\\ &\quad \mathrm{d}x'\mathrm{d}y' \\ &= f(x-\alpha(\lambda)\times(\lambda-\lambda_c),y,\lambda)\times t(x-\alpha(\lambda)\times(\lambda-\lambda_c),y). \end{aligned} \tag{2}$$

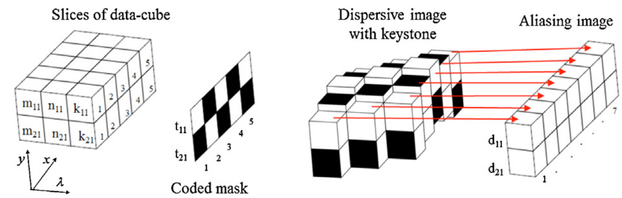

Fig. 3. Discrete model of spatial–spectral aliasing with keystone.

The Dirac delta function describes the light propagating through unity-magnification imaging optics. Commonly, the image at the detector array is the intensity of incident light rather than the spectral density. The measured signal of point (x,y) on the detector is an integration process in the range of the wavelengths at the corresponding point. Thus, the continuous image obtained by the detector array can be denoted as

$$\begin{aligned} g(x,y) &= \int_{\lambda_1}^{\lambda_2} f''(x,y,\lambda)\,\mathrm{d}\lambda \\ &= \int_{\lambda_1}^{\lambda_2} f(x+\alpha(\lambda)\times(\lambda-\lambda_c),y,\lambda) \\ &\quad \times t(x+\alpha(\lambda)\times(\lambda-\lambda_c),y)\,\mathrm{d}\lambda. \end{aligned} \tag{3}$$

In Eq. (3), we can say that the image on the detector array is aliasing information. The information of reconstructed data cube is much more than the measurement on the detector. This undetermined problem can be solved by using CS theory [11]. There has been variety of reconstructed algorithms. In this paper, because of its faster computational speed, Two-step Iterative Shrinkage/Threshold (TwIST) [15] will be used.

3. The effect of keystone on the singal sampling of CASSI

While the magnification of the optical system is different from wavelengths, keystone property is a band-to-band misregistration. Supposing the point (x,y) with band offset $\sigma(x,\lambda)$, Eq. (3) will be rewritten as

$$\begin{aligned} g(x,y) = \int_{\lambda_1}^{\lambda_2} & f(x+\alpha(\lambda)\times(\lambda-\lambda_c),y+\sigma(x,\lambda),\lambda)\times \\ & t(x+\alpha(\lambda)\times(\lambda-\lambda_c),y+\sigma(x,\lambda))\,\mathrm{d}\lambda. \end{aligned} \tag{4}$$

For the purpose of illustrating Eq. (3) more convincingly, it is necessary to fabricate the discrete model of spatial–spectral aliasing with keystone. Two adjacent slices of data cube are selected along y-direction to describe keystone and spatial–spectral aliasing. As shown in Fig. 3, for a $5\times2\times3$ data cube, we assume the maximum band offset is half a pixel and the followed offset is a quarter of a pixel. Considering the measurements of the second row of the detector, a system of linear equations can be established, as shown in Eq. (5). Ideally, when there is