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Prototype development and field measurements of high etendue spatial heterodyne imaging spectrometer

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ABSTRACT

High etendue spatial heterodyne imaging spectrometer (HESHIS) is a new pushbroom Fourier transform hyperspectral imager with no moving parts. It is based on a Sagnac interferometer combined with a pair of parallel gratings. In this paper, the basic principle of HESHIS is reviewed and the first prototype of HESHIS is designed and developed. The spectral band of this prototype is designed at O_2-A band (757 nm to 777 nm) and the average spectral resolution is 0.04 nm. Using the prototype, the pushbroom imaging experiments are carried out and the original interference images are obtained. The spectral data cube is generated using spectrum reconstruction method and high-resolution spectra are achieved.

1. Introduction

High Etendue Spatial Heterodyne Imaging Spectrometer (HESHIS) is a pushbroom Fourier transform hyperspectral imager that records a 2D image of a scene superimposed with interference curves [1,2]. It is based on a Sagnac common-path interferometer with a pair of matched parallel gratings introduced in it to generate a heterodyne interferogram. Similar to other temporally and spatially combined modulated Fourier transform spectrometers [3–9], the spectral data cube of HESHIS is recovered by Fourier transform of the extracted interferogram from a sequence of images acquired by scanning the scene [10]. As a point to point imaging spectrometer, different points from the scene are imaged onto different pixels of the detector. The intensity of one pixel is only determined by one corresponding point of the scene, and it is not affected by the rays from other points. Hence the entrance aperture in HESHIS is not restricted to resolving power and there is no entrance slit in it. This characteristic makes HESHIS retain the high throughput advantage of FTS [1,11]. Moreover, it has high spectral resolution advantage, this is because the frequency of interferogram is reduced to a heterodyne wavenumber. Thus, we can retrieve the input spectrum with less sampling points or achieve a high spectral resolution spectrum using the same sampling points. This is similar to SHS (Spatial Heterodyne Spectroscopy) [12,13], where the mirrors in each arm of the Michelson interferometer are replaced with diffraction gratings to generate the heterodyne interferogram.

As a new Fourier transform spectrometer, a prototype of HESHIS is designed and developed. The original pushbroom interference images and the recovered spectral data cube are presented in this paper. In the following parts, the basic principle of HESHIS is reviewed in Section 2. Section 3 presents the optical and mechanical design of HESHIS. The first pushbroom imaging experiment and the recovered spectral data cube are shown in Section 4. The conclusions are drawn in Section 5.

2. Basic principle of HESHIS

A sketch of the optical layout of HESHIS is shown in Fig. 1. It consists of a collimating lens, a lateral shearing interferometer, a collecting lens and a detector. The lateral shearing interferometer is modified by introducing a pair of matched parallel gratings in a Sagnac interferometer. The groove direction of the grating is perpendicular to the plane of Fig. 1. The collimated light from one point of the scene is split into two portions by the beamsplitter, a transmitted portion and a reflected portion. After passing through the lateral shearing interferometer, the coherent two beams exit the interferometer with a lateral displacement. As the diffraction effect of the parallel gratings, rays with different wavenumbers will have different lateral displacements (such as the red lines and the blue lines shown in Fig. 1). The collecting lens collects the two beams onto the corresponding point of the detector. The intensity of the interferogram generated by the coherent two beams depends on the optical path difference (OPD). Different points from the scene are collimated into the interferometer with different angles, and then they are imaged onto different pixels of the detector with different OPDs. For

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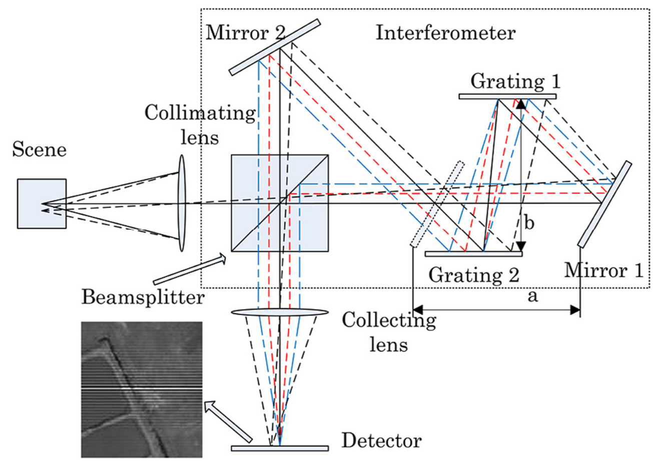

Fig. 1. Optical layout of HESHIS. Rays with different wavenumbers are separated with different displacements by the interferometer. Different points from the scene are collimated into the interferometer with different angles, and then they are imaged onto different pixels of the detector with different OPDs. Rays with different lateral displacements (red lines and blue lines) from the chief ray and an off-axis ray (black dashed lines) are shown in this figure. For the entire field of the scene, it is imaged on the detector superimposed with interference fringes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

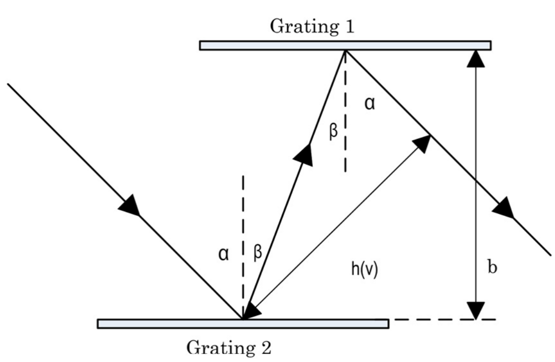

Fig. 2. The lateral displacement of the incident and outgoing rays passing through the parallel grating pair.

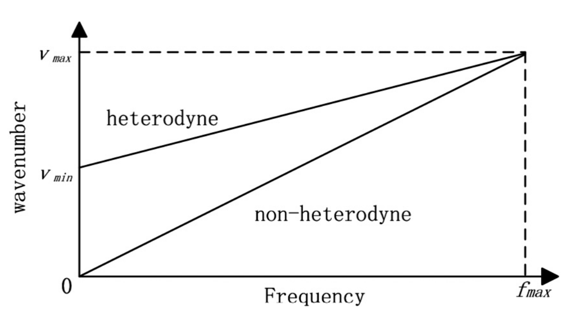

Fig. 3. Relationship between wavenumber and the frequency of the interferogram.

the entire field of view, the scene is imaged onto detector superimposed with interference fringes.

The lateral displacement of the two beams varies with wavenumber and it consists of two parts. One is generated by the Sagnac interferometer and the other is introduced by the parallel gratings. In the Sagnac interferometer, the distance between Mirror 1 and the symmetric position of Mirror 2 is a, this will introduce a lateral displacement d:

$$d = 2a\sin(2\theta), \tag{1}$$

Table 1
HESHIS system parameters.

	Item	Design
Spectral parameter	Spectral range	757 to 777 nm
	Average spectral resolution	0.04 nm
Gratings	Groove density	1200 lines/mm
	Diffraction order	1
	Grating size	90 mm × 90 mm
Optical system	Focal length of telescope	25 mm
	Focal length of collimating lens	160 mm
	Focal length of collecting lens	320 mm
	System field angle	±6.4°
Interferometer	Distance between the gratings	290 mm
	Shift of Mirror 1	222.9409 mm
	Incident angle on the gratings	$\alpha = 45°$
Detector	Detector array	1024 × 884
	Detector pitch	11 μm × 11 μm

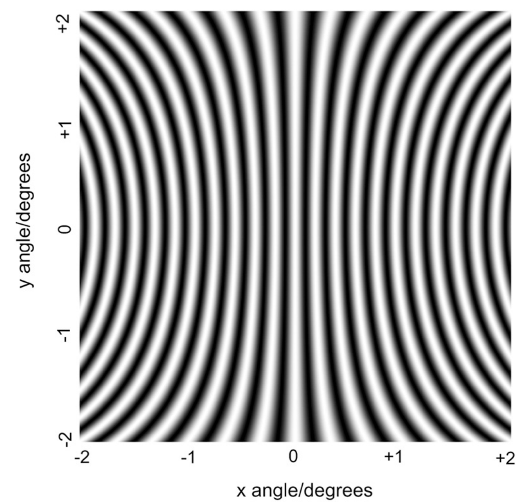

Fig. 4. Interference image of a monochromatic uniform surface light source. It can be seen that the interference fringes are curved because of the off-axis rays.

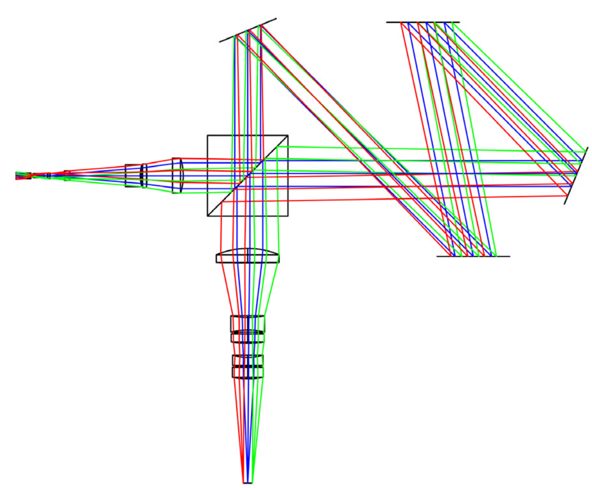

Fig. 5. Total system optical design result of the HESHIS prototype.

where θ is the incident angle of the chief rays on Mirror 1. In Fig. 1, where θ is 22.5°, we can calculate that the lateral displacement introduced by the Sagnac interferometer is $d = \sqrt{2}a$. The displacement generated by the grating pair is illustrated in Fig. 2. As the two gratings are parallel with each other, the outgoing rays and the incident rays