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Denoising analysis of compact CCD-based spectrometer

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ABSTRACT

CCD spectrometers are widely used in many fields for quick and accurate measurement of spectra. This paper firstly analyzes various noise phenomena by using Ocean Optics USB4000 spectrometer, including readout noise, photoelectron noise, dark noise and fixed pattern noise. Secondly, noise models of CCD-based spectrometers are built based on the theoretical analysis of noise phenomena. A number of noise-limiting techniques are applied to broadband spectra and line spectra with different noise levels. Lastly by comparing the denoising results, the optimal denoising algorithms are proposed for different spectral characteristics and noise levels.

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1. Introduction

Spectrometers are widely used in scientific researches and technical applications. Physical properties of an object can be determined by analyzing its spectrum, such as wavelength and intensity. With the development of micro-electronic technology and micro-machining technology, miniaturization has become a major trend to spectrometers. Compared with the traditional spectrometers, Charge-coupled device (CCD) spectrometers have a series of advantages, such as compact structure, small size, and steady performance. However, the actual measured signals always contain noise, thus reducing the accuracy of measurement. It is crucial to denoise the signals in order to improve the accuracy.

There are many reports on noise analysis and the denoising methods of spectrometers. Galban et al. [1] have characterized the types of noise in a Ocean Optics USB4000 spectrometer. Zonios et al. [2] have illustrated the features of each kind of noise and stray light in a research on Ocean Optics USB2000 spectrometer. Davenport et al. [3] have analyzed the effects of temperature and of the light source. Fu et al. [4] have simulated noisy signals and have denoised the signals with four methods, namely Savitzky-Golay smoothing method, empirical mode decomposition (EMD) method [5,6], wavelet threshold denoising method [7,8], and optimal cubic spline method. Boudraa et al. [9] have used EMD method to reduce the noise of several kinds of signal. Kopsinis et al. [10] have proposed a new noise reduction method called clear iterative EMD interval thresholding (EMD-CIIT), which has a good denoising effect on signals with low signal-to-noise ratio (SNR).

Firstly in this paper, a detailed analysis of characterization of CCD spectrometer's noise is performed. The noise is divided into four main categories: readout noise, dark noise, fixed pattern noise and photoelectron noise. Secondly, noise models are built with Ocean Optics USB4000 spectrometer based on the theoretical analysis of noise phenomena. Thirdly, the CCD-based spectrometer is used not only to test absorptivity, reflectivity, and transmittance by using the broadband spectra of light

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Table 1
Specification of the USB4000, as provided by the manufacturer.

Parameter	Ocean Optics USB4000-UV-VIS
Spectral range	200-850 nm
Spectral resolution	1.5-2.3nm FWHM
Pixels	3648
Bit resolution	16 bit
Total signal: noise	300: 1
Dark noise	50 RMS counts
Grating	600 lines/mm, set to 200-850 nm (blazed at 300 nm)
Slit	25 μm
Stray light	<0.05% at 600 nm; <0.10% at 435 nm; <10% at 250 nm

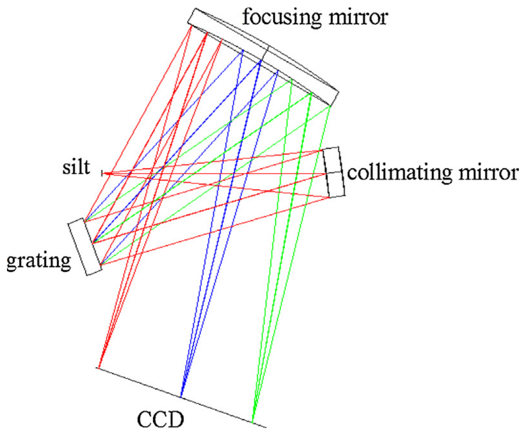

Fig. 1. Diagram of crossed-beam Czerny-Turner optical system.

sources (e.g. tungsten halogen lamp), but also to conduct wavelength calibration by using line spectra of light sources (e.g. Mercury-Argon, Th-Ar, Fe arc lamp etc.) or to determine material components by using line spectra (e.g. Raman spectra). With Gaussian curve as the original spectrum, we simulate the noisy spectral models by combing broadband spectra or line spectra with the noise model. Lastly, we denoise the noisy spectra using wavelet denoising method and clear iterative EMD interval-thresholding (EMD-CIIT) to determine the optimal denoising method for each kind of noisy spectra. By comparing the denoising result, the optimal denoising algorithms are proposed for different spectral characteristics and noise levels.

2. CCD-spectrometer description

This paper uses an Ocean Optics USB4000 (USB4000-UV-VIS-ES) spectrometer. The specification of the spectrometer is given in Table 1 [11,12]. An optical fiber (0.5 m length, 600 μm core radius) is used to connect the light source with the spectrometer.

The Ocean Optics USB4000 adopts a crossed-beam Czerny-Turner optical structure [13] and the diagram of the optical structure of spectrometer is shown in Fig.1. A divergent wavefront enters the entrance slit and is collimated by the first spherical mirror (collimator mirror). Then the light is diffracted in the tangential plane by the grating. Next, diffracted light reaches the second spherical mirror (focusing mirror), which focuses the light onto the detector (CCD). Each pixel of the detector is responding to different wavelength of the light. The intensity of optical signal corresponding to different wavelength is obtained.

To acquire broadband spectra, the tungsten halogen lamp (Ocean Optics, LS-1) is used as the light source. The spectral range varies from 360 nm to 2500 nm.

3. Noise analysis and modeling

3.1. Noise analysis

The error source of the measurement system based on compact CCD spectrometer is defined as noise phenomena. The noise from CCD spectrometers can be divided into four main categories, namely readout noise, photoelectron noise, dark

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