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Spectrum reconstruction in interference spectrometer based on sparse Fourier transform

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ABSTRACT

The algorithm of SFT (sparse Fourier transform) is firstly used for monochromatic light spectrum reconstruction in this paper. Due to the increasing amount of interference data, the operation efficiency of traditional algorithms is not satisfied with the demand of technology. We take advantage of SFT to achieve the goal of lower algorithm complexity and fewer operation time, instead of FFT (Fast Fourier Transform). In addition, two methods of the modern spectrum estimation, AR (Auto-Regressive) model and MUSIC (Multiple Signal Classification), which are considered as high resolution spectrum estimation algorithms, are used for discussion and comparison. The experiment result shows that the SFT gets excellent performance in runtime.

1. Introduction

Driven by the development and application of imaging spectroscopy, imaging spectrometer has played an important role in space exploration and component analysis. Fourier transform imaging spectroscopy (FTS), or interference imaging spectrometer, which has been widely used in many aspects [1,2], can make information available both in space and spectral dimension of the same target. Compared with traditional spectrometers, it has the following advantages: high throughput (known as Jaquinot advantage), multi-channel (known as Fellgett advantage), high resolution, etc. Due to the relation of Fourier transform between interferogram and spectrogram, the Fourier transform spectrometer can extract features in spectrum by means of the integral of interferogram of the target, which is an indirect way of imaging spectroscopy.

The heart equipment of FTS is interferometer. In theory and practice, we usually take measures to divide the light from the target into two beams of coherent light which will interfere in the position of sensors, controlling the difference of optical path of two beams of light, to obtain a series of interference patterns. Fig. 1 illustrates the fundamental principle and simple date processing of Michelson interferometer. And then, some of pre-processing measures will be taken to eliminate noise and measurement errors as much as possible, which provide good quality of interferogram for spectral inversion in the last.

In the process of spectral recovery, it is FFT that plays a key role (see [3–5]) since the interference spectrometer is based on the theory of Fourier transform. However, the speed of FFT is not so high when it comes to larger amount of data from the sensors, on which depend the development of hardware. Meanwhile, the system on satellites proposes the requirement for real time and fast operation. It is necessary to simplify the method for good efficiency.

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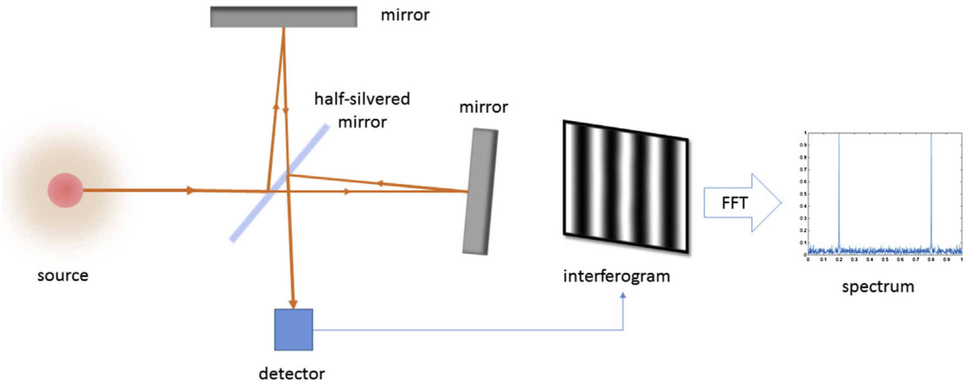

Fig. 1. Basic principle and simple data processing of Michelson interferometer.

In order to improve spectral resolution of spectral inversion, Jian et al. [6,7] brought one of methods of modern spectrum estimation into the field of spectral reconstruction. They introduced MUSIC algorithm based on eigen-decomposition for monochromatic light spectrum reconstruction for the first time and obtained higher resolving power. This algorithm is good at spectrum reconstruction of monochromatic light and very sensitive to model order.

But the complexity is so high that the methods cannot be suitable for fast operation in spectral recovery, especially with a large quantity of data. Haitham Hassanieh et al. [8] proposed sparse Fourier transform to solve the problem of fast Fourier transform in runtime for big data. The algorithm surely reduces the running time of FFT, making full use of the sparsity of signal in frequency domain to obtain an excellent result, which will be discussed in detail in Section 3.

This paper will focus on the application of SFT in monochromatic spectrum reconstruction and the rest of it is organized as follows: Section 2 discusses the traditional related theory and Section 3 depicts the algorithm of sparse Fourier transform in detail. The experiments are arranged in Section 4. In the end of this paper, we give analysis and draw conclusions.

2. Related theory

This section will discuss the traditional algorithms for interferogram processing.

2.1. Traditional Restoration Processing

According to the principle of Fourier transform spectroscopy [9], the recovery of spectrum can be acquired by means of Fourier transform for imterferogram, listed as the following equations:

$$I(\Delta) = \int_{-\infty}^{+\infty} B(\sigma) e^{j2\pi\sigma\Delta} d\sigma, \tag{1}$$

$$B(\sigma) = \int_{-\infty}^{+\infty} I(\Delta) e^{-j2\pi\sigma\Delta} d\Delta, \tag{2}$$

where I is the interferogram, B is the spectrum, Δ and σ mean the path difference and the wave number respectively. Generally speaking, the processing of interference curve mainly includes pre-processing, apodization technology, phase correction and FFT, where apodization is used to eliminate the effect of linear function of instrument for power spectrum and phase correction can correct phase error from migration of sampling position. It is the most direct and simple way for spectrum reconstruction concerning the relation between interferogram and spectrogram, using FFT in $O(N \log N)$ time where N is the size of data.

2.2. Modern spectrum estimation

The traditional algorithm is substantially equivalent to BT method (proposed by Blackman and Tukey) in classical spectrum estimation since both are the same to utilize Fourier transform for the autocorrelation function of signal to get power spectrum. However, the classical methods suffer from large estimated variance and bad resolution which could be overcomed by means of modern spectrum estimation [10].

2.2.1. AR model

AR model is a linear prediction model that it could be employed for predicting unobserved data when given a set of known data. In this theory, any random signal can be considered as a type of signal produced by white noise through the model, whose parameters could be calculated by collected data so that the unobserved data is not thought to be zero. Generally,