Algorithm for high-frequency data filtering for laser spectrometer with a linear CCD array photodetector on the basis of wavelet transformation with automatic fitting of coefficients

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The paper describes the results of testing of the adaptive algorithm for fitting the coefficients of wavelet-filtering of data from a linear CCD array photodetector of a pulsed laser spectrometer. It is shown that application of the filtering allows a reliable separation and detection of a signal fully masked by the receiving system noise.

Introduction

To study the re-emission of molecular media, excited by a two-frequency optical field, and to check the hypothesis about generation of a field with high moment of momentum in the molecular medium,[1,2] a biharmonic laser spectrometer (Fig. 1),[3] is used. A peculiarity of any projected experiment for checking this hypothesis[2] is a necessity to record a narrow re-emission line, whose intensity is not yet estimated reliably. The re-emission spectrum should be recorded by a multi-element photodetector, namely, ILX-511 CCD Linear Image Sensor, because application of a photomultiplier tube is hampered by the parasitic illumination from the pumping radiation and the need to observe a wide spectral range during a pulse. Thus, in such an experiment it is important to obtain the maximally possible useful signal from the linear CCD array.

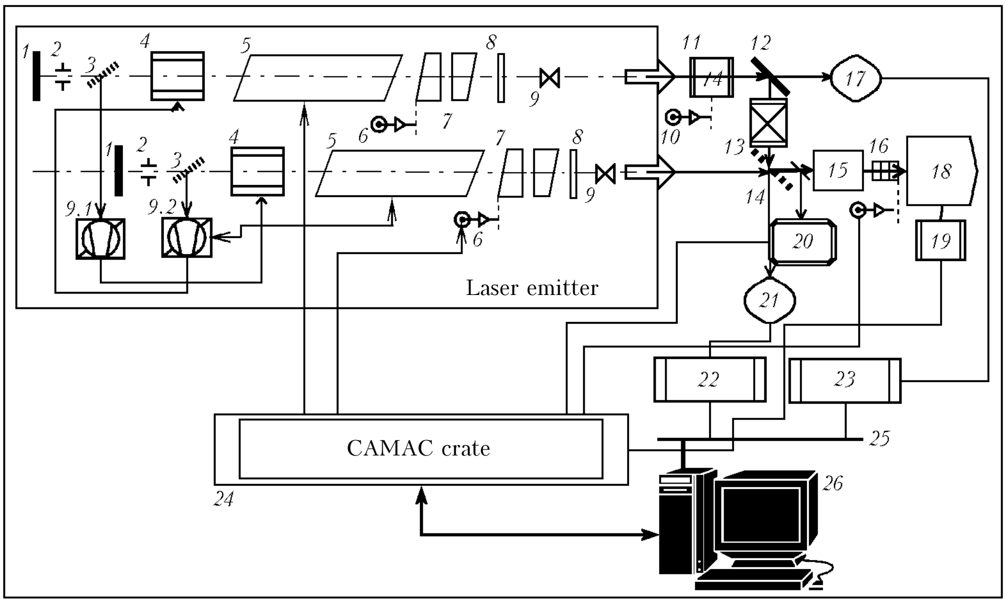

Fig. 1. Schematic layout of the spectrometer: 100% mirror *1*; diaphragm *2*; polarizer *3*; electrooptic shutter *4*; quantron *5*; stepper motor and Fabry–Perot etalon *6*, *7*; exit mirror *8*; rapid photodetectors and control unit *9.1*, *9.2*; doubler *9*; stepper motor *10*; controllable quarter-wave plate *11*; 100% mirror *12*; Glan prism *13*; beam splitter *14* ; optics and studied medium *15*; rejection filter *16*; rapid photodetectors *17*, *21*; DFS-452 spectrograph and CCD linear image sensor *18*; control unit *19*; IMO radiation power meter *20*; high-speed ADCs *22*, *23*; CAMAC crate and data acquisition and control units *24*; local network *25*; controlling computer and software *26*.

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The threshold sensitivity of CCD devices is limited not only by the quantum yield of the photodetector cell and the thermal noise, but also by the commutative and the measurement system noises.[4] The signal, received from a fully blacked out photodetector, is a superposition of the Gaussian noise and the commutation noise, caused by the periodic structure of cells in the linear CCD array. That is, the signal at the output of the linear CCD array photodetector can be described by the equation

$$s(t) = f(t) + \sigma(e(t) + \omega(t)),$$

where $f(t)$ is the useful signal; σ is the noise level; $e(t)$ is the Gaussian component of the noise signal; $\omega(t)$ is the periodic component of the noise signal, and the information about noise lies in the high-frequency range of the signal spectrum, while the useful component lies in the low-frequency range.

To reduce measurement noise of this type, smoothing algorithms based on the Fourier transform are traditionally used.[5,6] However, the limited data set (limited number of pixels in the linear CCD array) and the absence of some formal algorithm for selection of the optimal transformation window[6] complicate the use of such algorithms.

Wavelet analysis is one of the most advanced noise smoothing technologies, free of disadvantages inherent in the traditional approach based on the Fourier transform.[10]

Non-periodic, spatially localized functions, for example, functions with one or two close global extremes and rapidly decaying at the infinity, are taken as a wavelet. Usually, a minimal requirement to such functions is the presence of one zero moment, that is, the zero integral of the function over the whole range of definition. A widely known example of the wavelet is the second derivative of the Gaussian (the density function of the normal distribution), which is referred to as the "Mexican hat."

The vector space basis is a set of linearly independent vectors, in which any vector of the space can be represented in the form of their linear combination. The scalar product of the signal with the basis vector (functions) is considered as a *continuous wavelet transformation*. Wavelet coefficients of the transformation reflect the closeness of the signal to the wavelet of the given scale.

In the discrete case, filters with different cutoff frequencies are used to analyze the signal at different scales. The signal is transmitted through tree-connected low-pass (LP) and high-pass (HP) filters.

The scale is changed due to signal filtering, and the signal resolution, which is a measure of the amount of the detailed information, changes due to decimation (elimination of some readouts, that is, a decrease of the discretization frequency) and interpolation.

The signal is transmitted through the LP and HP filters and decimated twofold. As a result, the time resolution at the first step decreases twofold, because the signal is characterized by only a half of readouts. However, the frequency resolution doubles, because the signal occupies now only a halved frequency band, and the uncertainty decreases. Then, the output of the LP filter is applied to the same circuit, and the output of the HP filter is the wavelet coefficient.

The synthesis of the signal is carried out in the reverse order as compared to analysis. The signal at every level is interpolated and transmitted through the LP and HP synthesis filters (analysis and synthesis filters are identical, except for the reverse order of coefficients).

The technology of the wavelet transformation, in contrast to the Fourier transformation, is free of the Gibbs effects and gives good results at short sequences. However, the selection of the optimal filtering coefficients for wavelet smoothing is a complicated procedure, which cannot be fully formalized.[8,9]

The aim of this work was to apply the adaptive algorithm to selection of the filtering coefficients and to study experimentally the efficiency of separation of a weak useful signal from the spectrograph, equipped with the ILX-511 linear CCD array, using the application of noise smoothing tools based on the wavelet transformation.

Within the framework of the wavelet technology, the noise smoothing involves four stages:

- expansion of a signal in the wavelet basis;
- selection of the threshold value for each expansion level;
- rejection of detailing coefficients, lying below the selected threshold (thresholding);
- inverse wavelet transformation (reconstruction of the signal).

The quality of noise smoothing directly depends on the selected depth of expansion, which affects the degree of signal change rejections, and on the threshold value in the thresholding procedure.[7–9] There are several criteria for the threshold selection. Nevertheless, the exact value of the threshold is to be refined experimentally.[9] This paper proposes an adaptive algorithm for the threshold automatic fitting by comparing the result of noise suppression with some known, reference signal.

When preparing to spectroscopic measurements with the diffraction spectrograph, some well-known spectrum must be in hand and some knowingly noise-free data must be taken as a reference signal. In this paper, the threshold of ε was fitted through iterative increase of ε value and following comparison of the noise-free signal with line positions in the neon spectrum (530 nm region, Atlas data). The following algorithm is proposed:

1) to black out the linear CCD array and to record the blackout signal;

2) to record a fragment of the emission spectrum of the TN-0.5 neon lamp;

3) to compensate for the irregularity of sensitivity among CCD pixels by subtracting the blackout signal;

4) to average the blackout signal and to use it as a threshold value for the procedure of peak search;

5) to find line peaks (Item 2) and to assign them to the ideal Atlas data;

6) to decrease the light signal at the spectrometer input in such a way as to make the peak search procedure to return "fail," but the peaks in the spectrogram can be distinguishable;

7) to carry out the direct and inverse discrete wavelet transformations of the blackout signal with the selection of the initial threshold value by a soft criterion[8,9] in order the mean value of the smoothed signal be zero. To save the threshold values as initial for Item 8;

8) cycle-by-cycle, to carry out the direct and inverse discrete wavelet transformations of the weakened signal of the selected fragment of the neon emission spectrum. At each iteration, to apply the peak search procedure to the obtained signal and to compare the result with the Atlas data. To increase the threshold value until the best agreement with the Atlas data. To exit from the cycle with the found optimal value of ε (Fig. 2).

The direct and inverse discrete wavelet transformations were carried out by the lifting procedure based on the standard LIFTPACK code.[11] A feature of the lifting scheme is not only a high speed, but also the use of the so-called second-generation wavelets, well representing non-periodic and pulsed signals. The noise smoothing efficiency can be estimated by the following scheme: the light flux at the spectrometer input is attenuated by NS-3 neutral filters until neon lines at the wavelet filter input become undistinguishable. The noise suppression efficiency can be judged from the fact that to remove line peaks from the noise-free signal, more than fourfold attenuation of the light flux is needed, whereas without filtering the distinguishable peaks disappear already with only one neutral filter. Figure 3 shows the recorded attenuated fragment of the emission spectrum of the TN-0.5 neon lamp with and without filtering; the exposure time in both cases was the same and equal to 30 ms.

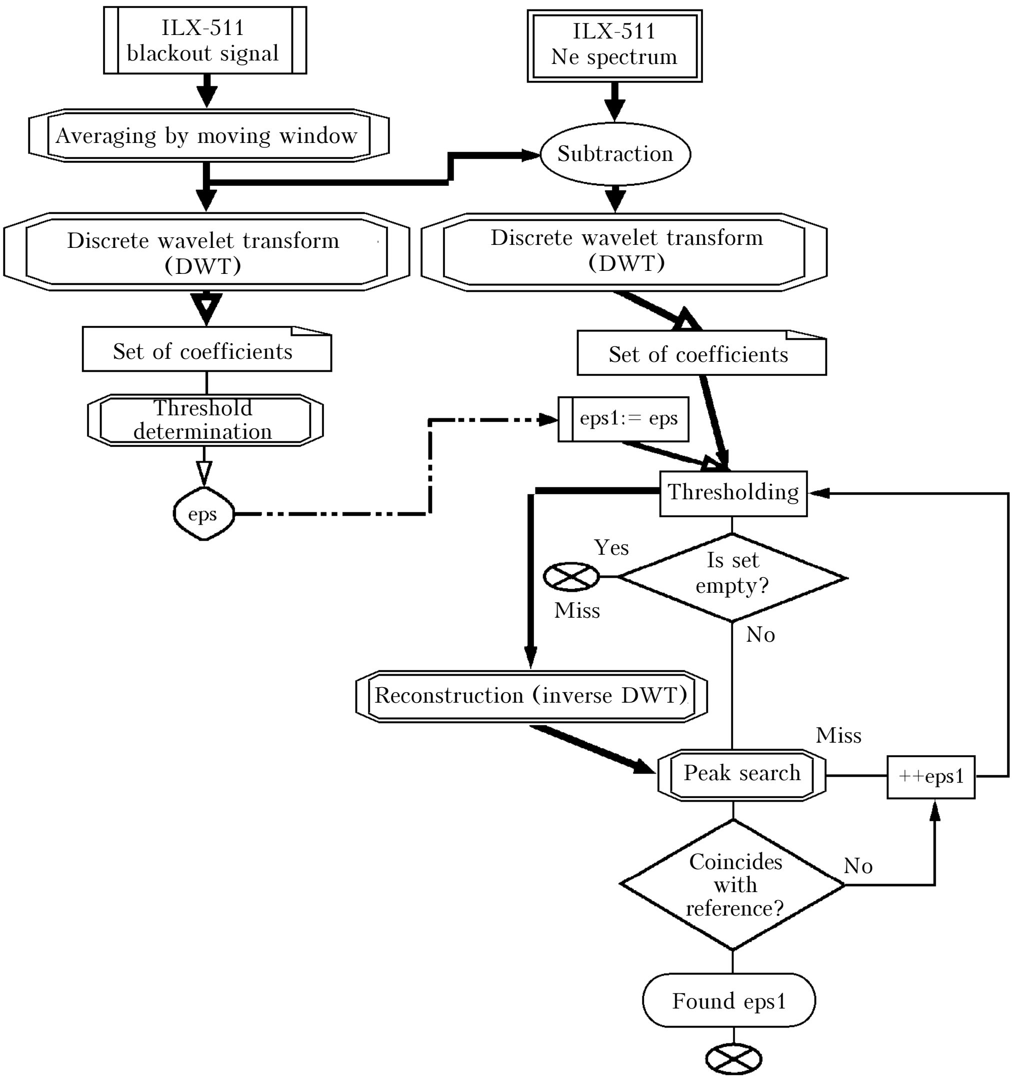

Fig. 2. Algorithm for selection of filtering coefficients.

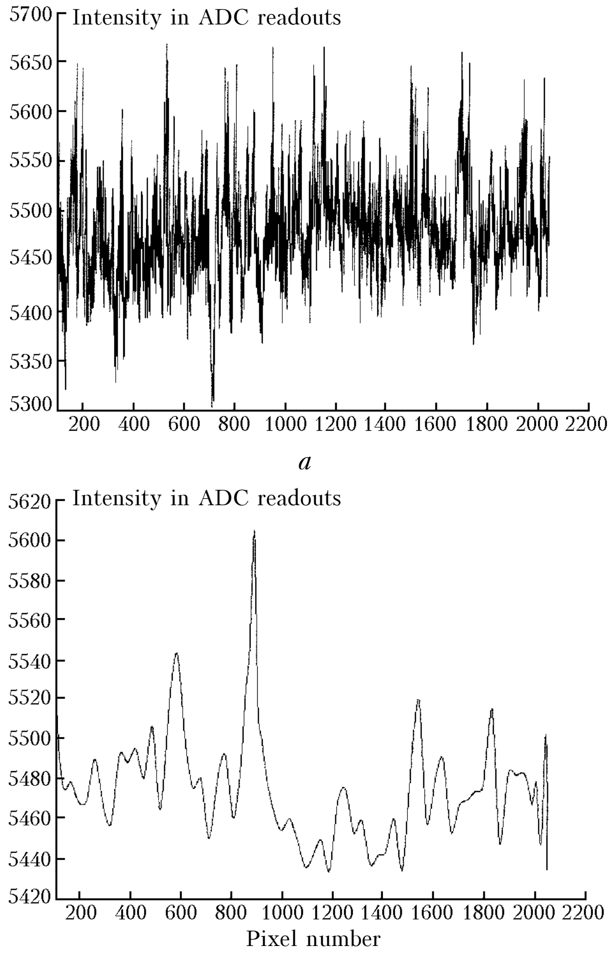

Fig. 3. Initial (*a*) and filtered (*b*) weak signals.

For comparison, Fig. 4 shows the result of filtering by the moving window of a weakened signal of the neon spectrum fragment with the following smoothing by a cubic spline.

The peak search procedure fails to assign even one line from these data, whereas the application of this procedure to the data subjected to the wavelet filtering yields two of four lines. It can be seen that the use of the wavelet filtering is quite founded in this spectrometer.

The filtering procedure was organized as a data-filtering module in the automated data acquisition system.[13]

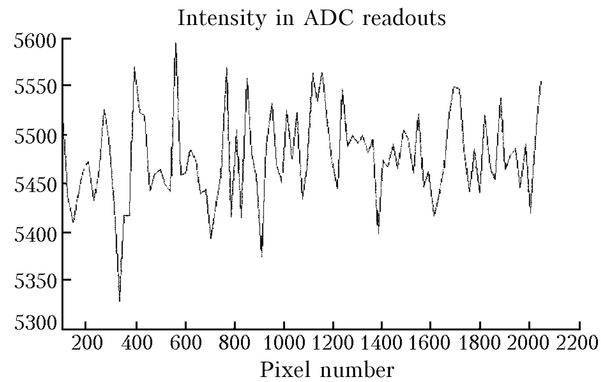

Fig. 4. Result of filtering by the moving window of an extra-weakened signal.

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