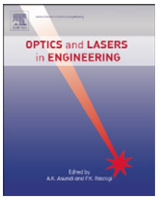
Optics and Lasers in Engineering 51 (2013) 961–966

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Improvement of the signal to noise ratio of Lidar echo signal based on wavelet de-noising technique

Zhirong Zhou, Dengxin Hua*, Yufeng Wang, Qing Yan, Shichun Li, Yan Li, Hongwei Wang

School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China

ARTICLE INFO

Article history:
Received 7 January 2013
Received in revised form
17 February 2013
Accepted 19 February 2013
Available online 28 March 2013

Keywords:
Lidar
Soft threshold
Wavelet
De-noising
Background light

ABSTRACT

According to the characteristics of a Lidar echo signal contaminated by noise, especially in strong background light, an effective de-noising method of wavelets based on a soft threshold is proposed to reduce the Lidar echo signal noise and improve the signal to noise ratio of system. The principles and methods of wavelet transforms and wavelet de-noising are utilized to de-noise the noisy signals. Some preliminary simulations are carried out to reduce the noise of the simulated signals in order to verify the feasibility of the de-noising method. In addition, using experimental data of the Lidar echo signals contaminated by noise in the strong background light, the de-noising range-square-corrected signals and the retrieved aerosol extinction coefficient are obtained. The results show evidence of the de-noising effects and demonstrate that this method can effectively de-noise the noisy Lidar signals in strong background light and achieve improvement in the signal to noise ratio of system.

1. Introduction

Lidar, as a powerful type of active remote sensing technology, with high temporal-spatial resolution and measurement accuracy, has been widely applied in real-time detection of atmospheric meteorological parameter fields, such as atmospheric environmental pollutants, aerosols and dust monitoring, etc [1–3]. According to the Lidar equation, since the power of a Lidar echo signal decays with the exponential attenuation of the atmospheric extinction coefficient and the square of the distance between the Lidar and the target, inevitably the smaller echo signals, which contain a lot of useful measurement information, are easily contaminated by the noise of the electric fluctuations and stray light, which will directly affect the effective detection range and accuracy of Lidar system. The development of all-weather Lidar is currently a hot topic and solar background light suppression technology is one of the key-techniques for it. Furthermore, Lidar echo signals during daytime are drowned out easily by the noise of strong background light, which must be reduced or filtered to ensure the detection accuracy and range.

Solar background light suppression technology mainly includes hardware and software algorithm methods to filter the noise. For the hardware filter methods, the special solar blind wavelength, large laser power or narrow-band filter are usually used in Lidar system design [4–10]. For the software algorithm methods, there are several de-noising or filtering methods: Empirical mode decomposition (EMD), Kalman filtering method, Wavelets transform and Fourier filtering window method, etc [11–13]. Due matching wavelength of echo signals and sun background light, as well as echo signals' characteristics of non-linearity and non-stationarity, background light may not be effectively excluded by hardware filtering, but by the subsequent digital filtering process. The Fourier filtering window method sacrifices spatial resolution because of lack of time-frequency localization; the Kalman filter will lead to large errors when the atmospheric extinction coefficient is changed sharply, i.e., its time-frequency localization is poor; the EMD filter is suitable for relatively high signal to noise, especially for nighttime detection [12,13]; Wavelet analysis has good characteristics of time–frequency localization and provides a powerful tools for signal processing in which signals can be decomposed into different frequency components by multi-scale analysis, especially in low signal to noise ratio (SNR) signal processing [14]. In this study, a Daubechies wavelet using Stein's unbiased risk estimation (SURE) soft threshold method is adopted. The Daubechies wavelet is biorthogonal, compactly supported, and suitable for filtering the signals of an exponential attenuation. The SURE soft threshold de-noising method is simple and effective for reconstructing the original signal by dealing with coefficients at all levels to extract Lidar signals and can retain a lot of detailed information in signal de-noising, especially in extracting weak signals [15–17].

In this paper, a wavelet de-noising algorithm is presented and used to reduce the signal interference of the background light and electric noises. The signals composed of low frequency and high

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* Corresponding author. Tel./fax: +86 029 82312441.
E-mail address: dengxinhua@xaut.edu.cn (D. Hua).

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http://dx.doi.org/10.1016/j.optlaseng.2013.02.011

frequency components are simulated and used to validate the feasibility of the wavelet by SURE soft threshold de-noising method. And the Mie Lidar scattering of daytime measurement is used to remove the noise and reconstruct the Lidar echo signals. By comparison of the aerosol's extinction coefficient of the original signal and the de-noised signal, it is shown that the wavelet de-noising method is effective in improving SNR in Lidar signal processing.

2. Characteristics of noises and de-noising algorithm

For the atmospheric Lidar system measurement, the Lidar remote sensing equation is given by

$$P(Z)=K\times P_0\times\frac{c\tau}{2}\times\frac{A_R}{R_H^2}\times\eta(Z)\times\beta(Z)\times\exp\left[-\int_0^Z 2\alpha(r)dr\right] \qquad (1)$$

where P_0 is the Lidar transmitter impulse peak power, Z the range or height from Lidar to target, K the system calibration constant, c the speed of light, τ the intervals between two transmitting laser pulses, A_R the effective receiving area of telescope, $\eta(Z)$ the geometric overlap factor of the transmitter of receiver beam paths, $\beta(Z)$ the backscattering coefficient, and $\alpha(r)$ the atmospheric extinction coefficient [18]. The configuration of the Lidar system is shown in Fig. 1, comprising of laser emission system, optical receiving system, signal detection and data acquisition system.

The received echo Lidar signal mainly includes useful atmospheric information, the solar background noise and electric noise coming from the signal detection and data acquisition system. Generally, the electric noise can be approximated as white noise because of its continuous time domain and random amplitude and phase, and the background noise can be approximated as mixed signal of white noise and a DC (direct current) signal. So the time equation of Lidar echo signal including noise $f(t)$ can be given as:

$$f(t)=x(t)+e(t)+s(t), \qquad (2)$$

where $x(t)$ represents the true value of the Lidar echo signal, $e(t)$ the white noise caused by electronic noise and stray light, $s(t)$ the DC signal of sky background and terrestrial radiation light.

The purpose of wavelet de-noising is to reduce the degree of contamination to $x(t)$ by $e(t)$ and $s(t)$. Discrete signals by the wavelet transform or decomposition at different resolutions show different characteristics, so the noise can be reduced using different thresholds and wavelet coefficients. Therefore, $f(t)$ is a finite power function, and then $f(t)\in L^2(R)$ (square-integral real number vector space). According to the definition of wavelets multi-resolution analysis, in the given vector space V_j, $f(t)$ can also be expressed as a series expansion in terms of scaling function and wavelets as follows:

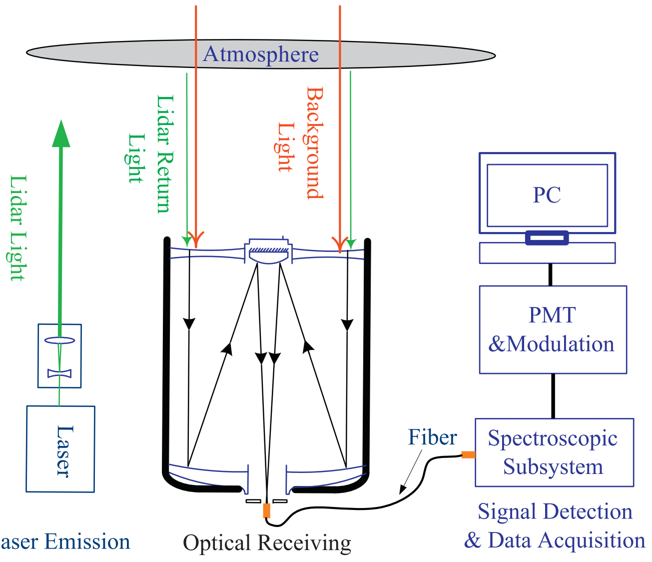

Fig. 1. Schematic diagram of the Lidar system.

$$f(t)=\sum a_k^{j-1}\varphi(2^{j-1}t-k)+\sum d_k^{j-1}\psi(2^{j-1}t-k) \qquad (3.1)$$

$$\varphi(2^{j-1}t-l)=\sum h_{k-2l}\varphi(2^{j-1}t-k) \qquad (3.2)$$

$$\psi(2^{j-1}t-l)=\sum(-1)^k\overline{h_{1-k+2l}}\varphi(2^{j-1}t-k) \qquad (3.3)$$

$$a_l^{j-1}=\frac{1}{2}\sum\overline{h_{k-2l}}a_k^j \qquad (3.4)$$

$$d_l^{j-1}=\frac{1}{2}\sum(-1)^k\overline{h_{1-k+2l}}a_k^j \qquad (3.5)$$

$$a_k^j=\sum\overline{h_{k-2l}}a_l^{j-1}+\sum(-1)^k\overline{h_{1-k+2l}}d_l^{j-1} \qquad (3.6)$$

where j, k, l belong to the set of integers, a_k^{j-1} and d_k^{j-1} represent the approximate coefficient and detail coefficient, respectively when the resolution is 2^{j-1}. The first summation $\Sigma a_k^{j-1}\varphi(2^{j-1}t-k)$ provides a function that is in a low resolution or coarse approximation of $f(t)$, and $\Sigma d_k^{j-1}\psi(2^{j-1}t-l)$ in the second summation, a higher or finer resolution function is added, which adds increasing detail. Eqs. (3.2) and (3.3), $\varphi(2^{j-1}t-l)$ and $\psi(2^{j-1}t-l)$ represent the scaling function and the wavelet function or mother wavelet, respectively. Eqs. (3.4) and (3.5) are recursive equations, and (3.6) represents the reconstruction equation.

The Lidar echo signals are decomposed into low-frequency signals and high-frequency signals. This is mainly caused by the particles scattering of aerosols of different density and size and by the electric noise of the photoelectric detector and stray lights. The basic wavelet de-noising principle is to employ wavelet transforms to decompose the echo signal according to the multi-scale functions. Because the average power of wavelet transform coefficients of white noise is inversely proportional to the scale j, the magnitudes of the wavelet transform coefficients of white noise will decay when the order of the wavelet transform increases [19].

The following steps must be taken to de-noise the noisy signals and extract useful signals:

1. First, it is necessary to determine the type of wavelet basis and wavelet decomposition level through the de-composition of original Lidar signals;
2. Second, it is important to choose the de-noising method to remove noise and subtract the part DC of background light extracted from the detection signals;
3. Finally, it is necessary to reconstruct the echo signal according to each level of the wavelet decomposition for low-frequency coefficients and high-frequency coefficients.

Figs. 2 and 3 show the respective profiles of the wavelet approximate coefficients a_l^{j-1} and wavelet detail coefficients d_l^{j-1}. Using the 5 levels decomposition of the Daubechies wavelet and the SURE soft threshold method, it is clear that the noise decreases as the decomposition level increases. This determines the levels or layers of the wavelet, so five levels are ideal in this case.