Improvement of signal-to-noise ratio in chaotic laser radar based on algorithm implementation

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Chaotic laser radar based on correlation detection is a high-resolution measurement tool for remotely monitoring targets or objects. However, its effective range is often limited by the side-lobe noise of correlation trace, which is always increased by the randomness of the chaotic signal itself and other transmission channel noises or interferences. The experimental result indicates that the wavelet denoising method can recover the real chaotic lidar signal in strong period noise disturbance, and a signal-to-noise ratio of about 8 dB is increased. Moreover, the correlation average discrete-component elimination algorithm significantly suppresses the side-lobe noise of the correlation trace when 20 dB of chaotic noise is embedded into the chaotic probe signal. Both methods have advantages and disadvantages.

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Optical chaotic signals generated from lasers have attracted extensive attention in recent years and have a wide range of applications[1−5]. The chaotic laser radar (chaotic lidar) was proposed[6,7] based on the wideband and δ-function-like correlation properties of a chaotic laser. In a chaotic lidar, the target is identified by correlating the reference chaotic signal with the delayed probe signal reflected or backscattered from the target. Although the correlation technique has been used in the random-modulation continuous wave (RM-CW) lidar[8,9], the range resolution is still limited on the order of meters by the modulation speed and pseudorandom code rate. Compared with pseudorandom-code-modulated CWs, noise-like optical chaotic waveforms generated by nonlinear dynamical semiconductor lasers have bandwidths larger than 10 GHz[10], which ensure high-range resolution and unambiguity. Furthermore, the chaotic laser with multi-gigahertz bandwidth can be easily obtained without an electro-optical modulator.

However, unlike the RM-CW lidar, in which an ideal pseudorandom code with perfect autocorrelation characteristics is used[9], the side-lobe noise of the correlation trace induced by the randomness of the chaotic signal is unavoidable. The high side-lobe noise of the correlation trace may bury the weak object correlation peak and degrade the signal-to-noise ratio (SNR). In real applications, the chaotic probe signal in the transmission channel may be disturbed by other signals and various noises, such as the random noise produced by the lidar system itself, the interferences or noises from the sun, the active jamming from other pulsed or CW lidars, etc. The noisy chaotic signal has more waveform distortions than a clean chaotic signal. These distortions further increase the side-lobe noise of the correlation trace and degrade the SNR. Thus, the suppression of the side-lobe noise of the correlation trace is a fundamental and important problem in chaotic lidar applications.

The side-lobe noise of the correlation trace is effectively suppressed by recovering the chaotic probe signal polluted by channel noises. The chaotic laser signal is a wideband and nonstationary signal. Conventional noise reduction methods such as linear low-pass filtering do not work well since the signal and noise often have overlapping bandwidths. Moreover, many noise reduction methods are proposed for nonlinear time series[11,12], which are complex and impractical in specific situations. The wavelet theory and its method provide a new tool that reduces the noise from a chaotic sequence[13]. This method is considered nonparametric and is applicable to nonlinear noisy data even without prior information of their dynamics.

In this letter, a chaotic ranging system is established and the effects of different types of channel noises on the SNRs are investigated. Wavelet denoising is employed to detect the chaotic signal in noisy environments. After the effect of noise reduction is limited using the wavelet method, a correlation average discrete-component elimination algorithm is developed to suppress the side-lobe noise of the correlation trace. The experimental results of the two algorithms for SNR improvement are also presented.

The diagram of the laboratory experimental arrangement of the chaotic ranging lidar system is shown in Fig. 1. The chaotic source is an 808-nm, 500-mW, single-mode laser diode with optical feedback from a mirror. The laser diode is biased at 200 mA ($1.4I_{\rm th}$) with 70-mW output power, and a chaotic state with 10.24% optical feedback is obtained. The chaotic laser generated by the chaotic source is split into the reference and the probe light using a beam splitter. The reference light is focused using a converging lens and detected by a photodetector (PD). Meanwhile, the probe light is transmitted to the target through the transmitter, and the reflected or backscattered light is collected by the receiver and detected by another identical PD. The transmitter consists of a collimating lens and a beam expander, and the receiver is a Maksutov-Cassegrain telescope with a 9-cm receive aperture and 1.2-m focal length. The waveforms of the reference signal and the echo probe signal detected by the two PDs are displayed and recorded on a digital

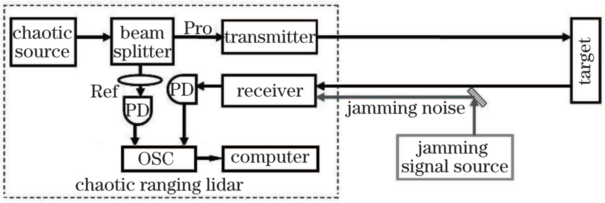

Fig. 1. Experimental setup of the chaotic ranging lidar system with an external jamming source.

oscilloscope with 500-MHz bandwidth and 5-Gs/s sampling rate. The data processing of the cross-correlation is calculated using a computer, and the target position is achieved from the main peak of the cross-correlation trace. This proposed chaotic lidar system can realize medium-range (<200 m) operations with a spatial resolution of 9 cm, which is limited by the bandwidth of oscilloscope used.

The influence of the channel noise level on the SNR of the chaotic laser ranging is investigated by using a jamming signal source to simulate the active jamming noise embedded in the receiver along with the echo chaotic probe signal (as shown in Fig. 1). Different signal sources are selected to simulate different types of noise jamming. In the process, the other weak noises, such as the quantization and the receiver noise, are neglected. The measurement range of the chaotic ranging lidar is actually affected by the side-lobe noise of the correlation trace. Moreover, the SNR is defined as the ratio of the correlation peak value to 3σ, where σ is the standard deviation of the side-lobe noise of the correlation trace and 3σ implies that 99.7% noise is included.

Due to the limited experimental conditions, the influences of different types of noises on the SNRs are first numerically estimated by correlating the noisy signals with the reference signals. The noise level is scaled using the relative noise intensity (RNI), which is defined as the ratio of noise power to chaotic probe signal power. The examined chaotic probe and reference signals are experimentally obtained, and the additional perturbations are separated as white Gaussian noise, chaotic signal from other states, continuous 60-MHz sine wave signal, and pulse signal, which has a pulse recurrence frequency of 1 MHz and pulsewidth of 10 ns. The pulse signal and continuous sine wave are intentionally chosen as interference noises to simulate the active jamming from other conventional pulse and CW lidar.

Four additional noise signals affect the SNRs in a similar approximately linear way. For Gaussian noise, which is plotted as diamonds in Fig. 2, the SNR of the correlation curve can also reach approximately 12 dB with 0 dB RNI and decrease to 3 dB as the noise level is increased to 20 dB. This result clearly shows the antijamming ability of the chaotic laser signal. For the 60-MHz sine signal, the chaotic lidar has a lower noise tolerance. However, this tolerance is related to the frequency of the sine signal. Thus, noise tolerance increases with the increase in the frequency of the sine signal. Furthermore, the pulse recurrence frequency of the pulse signal influences noise tolerance.

In practice, some efficient procedures should be adopted to recover the chaotic signal from noise disturbance and to improve the quality of chaotic probe data. In the current study, the wavelet method was used to reduce the noise in a chaotic signal. The wavelet-based algorithm proposed by Donoho *et al.*[14] attempts to recover a signal from noisy data. This algorithm can be completed in three steps: (1) wavelet transform of the noisy signal; (2) thresholding the resulting wavelet coefficients; (3) inversion of the wavelet transform to obtain the denoised signal. The nonlinear shrinking of coefficients in the wavelet transform domain distinguishes this procedure from linear denoising methods. In the following, the experimental results of the wavelet threshold denoising method for reducing noise in a chaotic laser signal are presented. In a wavelet denoising process, a soft threshold approach is used to select the threshold value, and the sym8 wavelet (symlet) is chosen to perform the wavelet transform decomposition with the level of 4. The symlets do not have explicit mathematical expressions. Therefore, they can be calculated only numerically. A more detailed description of symlets can be found in the work of Daubechies[15].

In the experiment, a continuous sine-wave laser signal is chosen as the noise disturbing signal obtained via current modulation in a laser diode with a 100-MHz sinusoidal electrical signal. Then, the reflected chaotic signal along with the sine jamming signal was received. A clean echo chaotic signal is obtained by adopting the wavelet denoising algorithm and is then correlated with the reference signal to improve the SNR. A cooperative target is placed at a relatively short range of about 5 m to neglect the influence of the other impairment factors, such as the quantization and receiver noise.

Figure 3(a) first shows the echo chaotic probe signal without the noise disturbance, whereas Fig. 3(b) shows the ranging result. The peak of the correlation trace is located at a distance of 4.95 m, and the SNR is 12.8 dB. Figure 3(c) shows the contaminated chaotic echo signal of a strong 100-MHz continuous sine-wave noise with a RNI of 17 dB. Then, the contaminated chaotic echo signal is correlated with the reference chaotic signal, and the measurement result is shown in Fig. 3(d). The figure shows that the side-lobe noise of the correlation trace is significantly increased and the corresponding SNR is reduced to only 3.2 dB. Figure 3(e) shows the denoised chaotic probe signal waveform. Then, the reconstructed chaotic echo signal is further correlated with the reference chaotic signal, as shown in Fig. 3(f), and the corresponding SNR

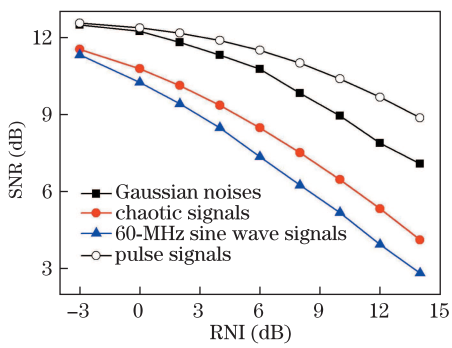

Fig. 2. Four additional signals used as noises that interfere with the chaotic lidar's correlation detection by decreasing the SNR.

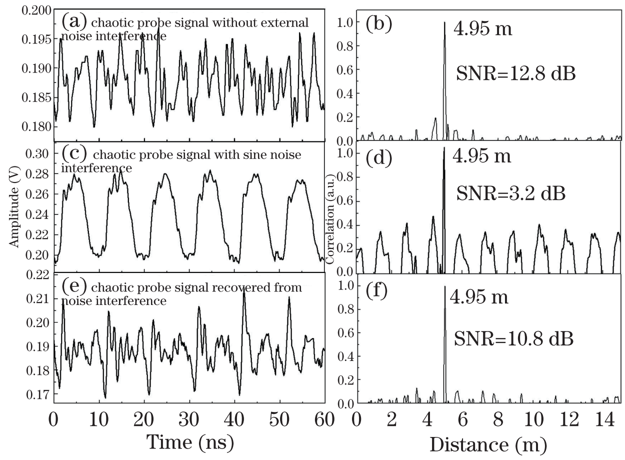

Fig. 3. Experimental results. Chaotic probe signals (a) without channel noise interference, (c) polluted by sinusoidal jamming signal, and (e) reconstructed using the wavelet denoising method. Ranging results (b) without noise interference, (d) with noised chaotic probe signal shown in (c), and (f) with the denoised chaotic probe signal shown in (e).

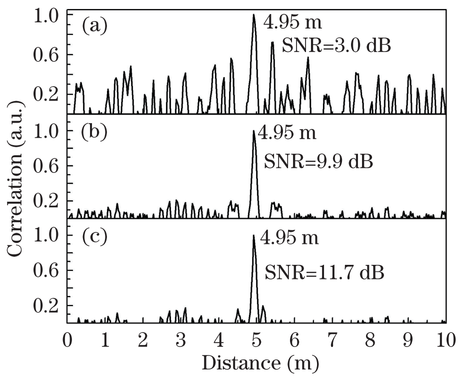

Fig. 4. Ranging results (a) without the use of the correlation average discrete-component elimination algorithm, after averaging for 30 times (b) without and (c) with employing the discrete-component elimination method.

is improved to 10.8 dB. The SNR has almost recovered to its level before noise disturbance.

In the experiments, attempts are also made to eliminate different types of noise in the chaotic laser signal using the wavelet denoising method based on discrete wavelet transform. The results indicate that the aforementioned method is very efficient in eliminating low-frequency noise and signals in a chaotic laser signal. However, it does not eliminate white noise. Thus, the future work aims to look for a simple and effective method for separating high-frequency white noise from the chaotic laser signal.

As aforementioned, the wavelet threshold denoising method is not a real powerful tool for eliminating Gaussian and chaotic noise in chaotic laser signals. Furthermore, even without the external jamming noise, the side-lobe noise induced by the randomness of the chaotic laser signal itself still limits the enhancement of the SNR of the correlation trace. Thus, a correlation average discrete-component elimination algorithm is proposed to overcome this limitation.

This algorithm can cancel out the side-lobe noise of the correlation trace as follows. First, reference signal sequence X and the corresponding echo signal sequence Y are recorded synchronously. Second, the cross-correlation between reference signal X and probe signal Y is calculated and normalized as $\mathrm{Crosscorr}_i = X \otimes Y/\max(X \otimes Y)$. Moreover, the autocorrelation of reference signal X is calculated and normalized as $\mathrm{Autocorr}_i = X \otimes X/\max(X \otimes X)$. Third, the first and second steps are repeated as many times as necessary, and the averaged correlation sequences are obtained using $\mathrm{Crosscorr}_{\mathrm{AVG}} = (1/N)\sum_{i=1}^{N}\mathrm{Crosscorr}_i$ and $\mathrm{Autocorr}_{\mathrm{AVG}} = (1/N)\sum_{i=1}^{N}\mathrm{Autocorr}_i$, where N is the number of averaging iterations. Fourth, the highest discrete reflection point in the cross-correlation trace is determined, and the correlation sequence $\mathrm{Autocorr}_{\mathrm{AVG}}$ is subtracted from the cross-correlation sequence $\mathrm{Crosscorr}_{\mathrm{AVG}}$ to eliminate the inherent noise of the correlation of the chaotic signal and to improve the SNR further.

The aforementioned steps clearly indicate that the averaging algorithm, that is, the method of averaging the values of several measurements, has the same results as that of increasing the probe signal energy to improve the SNR. The discrete-component elimination algorithm[16] is performed by subtracting the autocorrelation data from the cross-correlation data, that is, by precisely calculating the side-lobe noises generated from the discrete reflection points and by eliminating the inherent correlation noise of the chaotic signal. The recursive use of this algorithm can substantially improve the SNR. Moreover, even many weak reflection points can be distinctly detected, and this algorithm is effective in reducing the side-lobe noise of the correlation trace induced by all types of noise disturbance.

The effectiveness of the correlation average discrete-component elimination algorithm in SNR improvement is demonstrated in Fig. 4. In the experiment, another chaotic laser is used as jamming noise source that embeds the 20-dB strong chaotic noise into the probe chaotic signal. In Fig. 4(a), the discrete reflection at 4.95 m can be observed without averaging. However, the SNR is only 3.0 dB. The result obtained by averaging only 30 times without discrete-component elimination is shown in Fig. 4(b). The side-lobe noise level is substantially suppressed, and the SNR is increased to 9.9 dB. Moreover, Fig. 4(c) shows the result after the discrete-component elimination algorithm is applied to the same trace in Fig. 4(b). The figure shows that the side-lobe noise is further suppressed, and the SNR is now approximately 2 dB higher. Evidently, this method can effectively suppress side-lobe noise induced by various factors. However, SNR is improved at the cost of measurement time.

In conclusion, two methods for optimizing the correlation performance of chaotic lidar detection and improving the SNR are demonstrated. The side-lobe noise of the correlation trace induced by the randomness of the chaotic signal itself and other channel noise interferences limits the SNR and measurement range of chaotic lidar. Thus, the influences of different types of noises on the SNRs are numerically investigated. Then, a wavelet analysis is employed to denoise the polluted chaotic laser signal. The experimental results demonstrate the effectiveness and efficiency of the proposed approach in eliminating low-frequency noise disturbance. However, side-lobe noise cannot be suppressed by only a simple wavelet method. Thus, the correlation average discrete-component elimination algorithm is proposed to improve the SNR, and the feasibility of this algorithm is verified using experimental data. This algorithm further improves the SNR at the cost of measurement time.

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