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OPTIMUM COHERENT-LIDAR-DATA-BASED RETRIEVING OF HIGH-RESOLUTION DOPPLER VELOCITY PROFILES

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The effect is investigated of the speckle noise on some inverse techniques for retrieving high-resolution Doppler velocity profiles on the basis of coherent lidar data. The most effective digital filtering approach is found out and proved by simulations that ensures a maximum suppression of the speckle-noise influence at a minimum lowering of the range and temporal resolution. It consists in using nonrecursive smooth monotone filters with controllable passband and transition zone to smooth the coherent lidar signal autocovariance estimates and the retrieved Doppler velocity profiles.

1. INTRODUCTION Recently, we have developed some inverse mathematical techniques for retrieving with high range resolution of Doppler velocity profiles on the basis of coherent heterodyne lidar data [1,2]. These techniques allow one to achieve resolution cells much shorter than the sensing laser pulse length. Such a potential resolution is essentially better than one achievable by the well-known PP and PPP estimation techniques [3]. However, the speckle noise leads to the appearance of a random error disguising the retrieved Doppler velocity profiles. A way to suppress the speckle noise effect is to use a sufficiently large number N of laser shots, but this would lead to lowering the temporal resolution, i.e. the ability of observing fast changeable atmospheric processes. Consequently, to retain a satisfactory temporal resolution, one should search for additional ways to effectively damp down the speckle-noise effect. Thus, the main purpose of the present work is to choose and investigate the most effective digital filtering approach that ensures a maximum suppression of the speckle-noise effect at a minimum lowering of the range and temporal resolution.

2. INVERSE TECHNIQUES AND SPECKLE-NOISE PROBLEM The complex coherent lidar return signal $I(t = 2z/c) = J(t) + iQ(t)$ results from quadrature heterodyne detection of pulsed laser radiation backscattered by atmospheric aerosol particles; t is the time after the pulse emission, z is the corresponding coordinate of the pulse front along the lidar line of sight, c is the speed of light, $J(t)$ and $Q(t)$ are respectively the inphase and quadrature components of the signal, and i is imaginary unity. It is in general a non-stationary circular complex Gaussian random quantity with signal-to-noise ratio SNR=1. Correspondingly, the expression of the signal autocovariance is $Cov(t,\theta) = \langle I^*(t)I(t+\theta)\rangle$, where $\langle . \rangle$ and "*" denote respectively ensemble average and complex conjugation, and θ is a time shift. On the basis of this expression the following two relations are obtained for retrieving the radial (Doppler) velocity profile $v_D(z)$ in the case of laser pulses with "exponentially-shaped" envelope $f_o(\vartheta) = (e\vartheta/\tau)\exp(-\vartheta/\tau)$ (ϑ is a time variable and τ is a time constant determining the pulse duration, $f_o(\vartheta) \equiv 0$ for $\vartheta \leq 0$):

$$\omega_m(z = ct/2) = \theta^{-1} \arctan[\mathrm{Im}\Gamma(t,\theta)/\mathrm{Re}\Gamma(t,\theta)] \quad (1)$$

and
$$\omega_m(z = ct/2) = [\mathrm{Im}G(t)]/[\Phi(z = ct/2)(ce^2/\tau^2)] \quad , \quad (2)$$

where $\Phi(z)$ is the short-pulse signal power profile [1], $\omega_m(z) = \omega_o \chi(z) - \omega_h$, $\chi(z) = 1 - 2v_D(z)/c$, ω_o and ω_h are respectively the sensing and the heterodyne radiation frequencies, $\Gamma(t,\theta) = Cov_{ttt}^{\mathrm{III}}(t,\theta) + (6/\tau)Cov_{tt}^{\mathrm{II}}(t,\theta) + (12/\tau^2)Cov_t^{\mathrm{I}}(t,\theta) + (8/\tau^3)Cov(t,\theta)$, $G(t) = \Gamma_\theta^{\mathrm{I}}(t,\theta = 0)$, and the symbol "$^{\mathrm{I}}_{k}$" denotes differentiation with respect to the variable k [2]. The derivatives in the expressions of Γ and G lead to decreasing the SNR of the final results for $\omega_m(z)$ $[v_D(z)]$ [4]. Therefore, an effective noise-suppression data-processing approach is necessary to obtain accurate profiles of $v_D(z)$ without lowering the range and the temporal resolution. Such an approach is to use digital filters for smoothing the autocovariance estimates $C\hat{o}v(t,\theta)$ and the restored Doppler-velocity profiles.

We have mainly investigated the speckle noise suppression effect of nonrecursive filters because of their simple and clearly interpretable design [4]. The direct design of such filters and compositions of them allows one to achieve a prescribed passband width. However, the transition zone extent is not directly controllable and is too large. This leads to penetration through the filter of undesirable noise frequencies, and to suppression of useful signal frequency components. Besides, the oscillating character of the transfer functions leads to the appearance of parasitic oscillations in the restored Doppler velocity profiles. Smooth monotone nonrecursive filters are designed by using a general approach [4] allowing one to achieve smooth transfer functions with controllable clear-cut passband and sharp (narrow) transition zone. Thus one can sharply separate the frequencies to be retained from those to be removed.

Below we compare by simulations the efficiency of directly designed and smooth monotone nonrecursive filters.

3. SIMULATIONS Simulations are performed for the models of $v_D(z)$, $\Phi(z)$, and $f_o(\vartheta = 2z/c)$, shown in Fig.1 and Fig.2. The profiles of $v_D(z)$ and $\Phi(z)$ are strongly varying within the pulse length. The coherent heterodyne lidar return signal $I(t=2z/c)$ is simulated as a circular Gaussian random variable profile with short-pulse power profile $\Phi(z)$ [1]. The estimate $\hat{Cov}(t,\theta)$ is obtained as $\hat{Cov}(t,\theta) = N^{-1}\sum_{n=1}^{N} I_n^*(t) I_n(t+\theta)$. In the simulations performed here, N=300. Retrieving the Doppler-velocity profile $v_{D_r}(z)$ is conducted according to the relations (1) and (2). A result of row-data-based restoration of $v_D(z)$ [by using Eq.(1) without any filtering] is represented in Fig.2, where the disguising effect of the speckle noise is well seen. The transfer functions of some nonrecursive digital filters we have designed and used in the simulations are given in Fig.3. It is seen that the smooth monotone filters can have clear-cut flat passband and sharp transition zone determined by the input design parameters. At the same time, the passband of directly designed filters (e.g. many times applied, sharpened or not [4], moving averages) is practically a part of their transition zone.

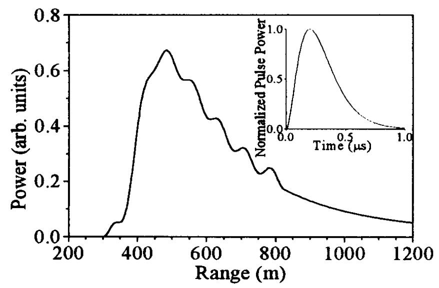

Fig.1. Models of the short-pulse signal power profile $\Phi(z)$ and (inset) the laser pulse shape (τ=0.2 μs) used in the simulations.

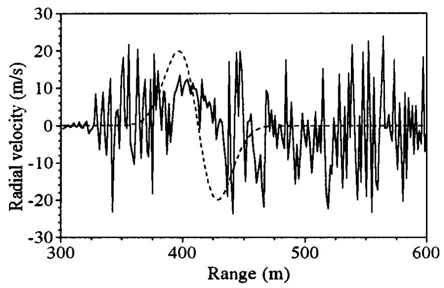

Fig.2. The original prifile $v_D(z)$ (dashed curve) and the profile $v_{Dr}(z)$ restored by using algorithm (1) without any filtration.

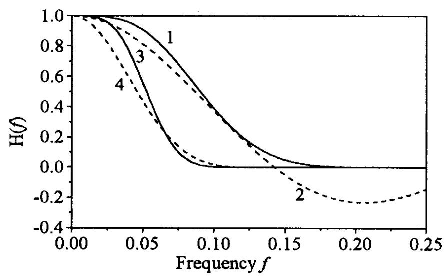

Fig.3. Digital filter transfer functions H(f):

(1) Smooth monotone filter with $\pi/7\Delta t$ wide passband, 3d order of tangency at f=0 and 39th order of tangency at $f=f_N=\pi/\Delta t$;

(2) $7\Delta t$ wide window moving average;

(3) five time applied smooth filter (1);

(4) four time applied filter (2).

In Fig.4a we have shown the restored Doppler-velocity profile $v_{D_r}(z)$ [compared with the true one $v_D(z)$] obtained on the basis of Eq.(1) by four-time consecutively employing a seven-point moving average for smoothing $\hat{Cov}(t,\theta)$ and the initial result for $v_{D_r}(z)$. One can see that there are noticeable distortions and parasitic oscillations in $v_{Dr}(z)$ with respect to $v_D(z)$. In Fig.4b we have compared the original profile $v_D(z)$ with that restored on the basis of Eq.(1) by employing the smooth monotone filter (3) in Fig.3, for smoothing $\hat{Cov}(t,\theta)$ and $v_{Dr}(z)$. Obviously, the final result for $v_{Dr}(z)$ is nearly coincident with the model to be recovered $v_D(z)$.

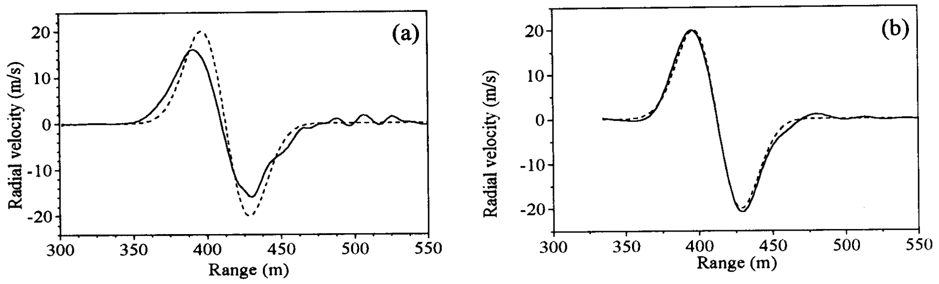

Fig.4. Profile $v_{Dr}(z)$ restored by algorithm (1) with filtration of $\hat{Cov}(t,\theta)$ and $v_{Dr}(z)$ using (a) the filter (4) and (b) the filter (3) in Fig.3.

4. CONCLUSION Because of the possibility to achieve clear-cut and controllable passband and transition zone, the smooth monotone low-pass filter processing of the autocovariance estimates and the restored velocity profiles leads to accurate and controllable restoration of the high-resolution Doppler-velocity profiles. The use of directly designed low-pass filters and compositions of them (in which the passband practically coincides with the transition zone) is accompanied by more essential distortions in the restored profiles including parasitic oscillations. Therefore, non-recursive smooth monotone low-pass filters should be used for processing coherent lidar data in order to obtain accurate Doppler-velocity profiles.

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