Iterative Deconvolution Algorithm for Improving Range Resolution of a CO₂-Laser Based Lidar System

Young Je PARK and Hong Jin KONG

Department of Physics, Korea Advanced Institute of Science and Technology, 373-1, Kusong-Dong, Yusong-Ku, Taejon, 305-701 Korea

(Received January 27, 1997; Accepted May 30, 1997)

An iterative deconvolution algorithm for improving range resolution of long-pulse lidars is proposed, and can be applied to the lidar data obtained with the typical pulse of a CO₂-laser which consists of a gain-switching peak and a long tail. The lidar signal itself with certain temporal shift is set to be the start profile for the unknown maximally resolved profile in the proposed technique, and then is corrected in proportion to the difference between the lidar return calculated with the assumption and the real one. The same process is repeated until the correction is smaller than tolerance. Simulations are made to test the performance of the proposed algorithm. We investigate the errors in the vicinity of data boundary in the retrieved profile when a part of lidar data is absent. The sensitivity of the iteration algorithm to noise in the lidar signals and the laser pulse profile is also numerically determined.

Key words: long-pulse lidar, carbon-dioxide lidar, deconvolution, range resolution

1. Introduction

Range resolution of a lidar system is determined by the laser pulse length and the electronic bandwidth of detectors and the relevant circuitry. Long-pulse lidars such as CO₂-DIAL and Doppler lidars based on CO₂ laser have range resolution of from hundreds of meters up to a few kilometers. To resolve small-scale inhomogeneity or to analyze the near-range signal with long-pulse lidars, the effects of laser pulse length should be eliminated. No direct inversion method applicable to the long-pulse lidar signal has been reported with range resolution smaller than the laser pulse length. Some hardware techniques for improving range resolution have been reported, including the pulse clipping technique which is to extinguish the tail of the laser pulse before sending it to the atmosphere, and the pulse compression technique in which a modulated laser pulse and a matched filter are used. However, the former technique causes shortening of the maximum sounding range due to loss of more than half of the pulse energy, and the latter makes the lidar system complicated because it requires a high speed modulator and electronics. These facts have led to the development of software approaches to remove the convolution effect of the long laser pulse on the lidar return signals. After deconvolution, the retrieved signal can be processed further by well-established methods such as the Klett inversion method applicable to the lidar signals when laser pulse duration is negligible.

The deconvolution technique is based on the fact that the lidar return is the convolution of the maximally resolved lidar signal with the temporal shape of the transmitted laser pulse. Deconvolution techniques using the Fourier transform and the matrix formulation were previously reported and their performance was demonstrated for improving the range resolution of lidars. In applying these deconvolution techniques, some points should be considered on deconvolution errors. Firstly, the deconvolution results are very sensitive to small variation in the lidar profile so that this property can limit the improvement of range resolution as the sampling interval becomes short. Secondly, both techniques may fail to be appropriate to some specific temporal shape of laser pulses. The Fourier deconvolution technique fails when any relevant Fourier component of the temporal shape of the laser pulse is too small. The matrix technique will be successful only if the numerical values of inverse matrix elements are well-bounded. Another point to be considered is the deconvolution error in the vicinity of the data boundary due to the absence of part of the lidar signal. Because the lidar return from the near range atmosphere is often blocked in sensing the wide range atmosphere to avoid the dynamic range limitation problem of detector, the behavior of the retrieved data near the boundary should be examined.

In this work, we propose an iterative algorithm for deconvolution of long-pulse lidar signals, and we evaluate its performance and limitation by applying it to the aerosol-scattered signals calculated by computer simulation for a CO₂-lidar system with a typical pulse of a transversely excited atmospheric TEA CO₂-laser. It is shown numerically that small-scale inhomogeneity can be recovered by the proposed technique with greater accuracy than the previously reported techniques especially for the temporal pulse shape consisting of one sharp peak and a long tail. The error behavior in the vicinity of the data boundary is analyzed when the proposed technique is applied to lidar return in which the initial lidar data are absent. The response of the deconvolution results to white noise in the lidar signals and in the laser pulse profiles is also analyzed numerically. This method can give a highly resolved profile with good accuracy if the laser pulse has...
one sharp peak and a long tail, typical in TEA CO$_2$-laser pulse output.

2. Formulation of Iterative Deconvolution Algorithm

The lidar signal $P(t)$ for an arbitrary laser pulse is expressed by

$$P(t) = \int T_i(t)P_i(t-t')dt' , \quad \int T_i(t)dt = 1 ,$$  

where $T_i(t)$ is the normalized temporal shape of a laser pulse, $P_i(t)$ is the lidar return in the case of $\delta$-function-like laser pulse:

$$P(t) = P_0(R = \frac{ct}{2}) = E_0 \xi \frac{A(R)}{R^2} \beta(R) \frac{c}{2} \exp(-2\alpha(r)dr) ,$$

where $\xi$ is the optical system efficiency, $A(R)$ is the range-dependent effective telescope area, $\beta(R)$ is the backscatter coefficient, and $\alpha(R)$ is the extinction coefficient of the atmosphere. Equation (2) is the conventional single scatter lidar equation. To obtain the maximally resolved profile $P_\text{m}(t)$ from the lidar return signal $P(t)$, we consider an iterative procedure. The lidar return signal itself with certain temporal shift is assumed to be the start function of the maximally resolved profile for the first iteration. In other words, we set $P_\text{m}(t)$ equal to the real lidar signal $P(t+\tau_0)$, where $\tau_0$ is the moment when the temporal profile of the laser pulse has peak value. Temporal shift by $\tau_0$ is introduced considering the peak position of laser pulse profile from the starting moment. With that shift the convergence of the iterated signals can be improved, especially for small-scale inhomogeneity. In the first iteration, we calculate the lidar return by Eq. (1) on the assumption $P_\text{m}(t)=P_\text{m}(0)(t)=P(t+\tau_0)$. There will be a difference between the real $P(t)$ and the calculated lidar return with this assumption, and it is denoted by $\Delta^0P(t)$, i.e.,

$$\Delta^0P(t) = P(t) - \int T_i(t')P_\text{m}(0)(t-t')dt' .$$

This error originates in the difference $\Delta^0P(t)$ between the true $P(t)$ and the assumed one. It can be written as follows:

$$\Delta^0P(t) = \int T_i(t')\Delta^0P_\text{m}(t-t')dt' .$$

Since this formula is again a convolution equation for the difference signal, we can make an approximation that $\Delta^0P(t) \approx \Delta^0P(t+\tau_0)$. Then, the first iterative solution will be

$$P_i^1(t) = P(t+\tau_0) + \Delta^0P(t+\tau_0) .$$

Note the same temporal shift is also introduced in the difference with the same reasoning as above. Next, we do the second iteration process assuming that $P_i^1(t)=P_i^{1\text{th}}(t)$, calculate the lidar signal using Eq. (1) and define that

$$\Delta^1P(t) = P(t) - \int T_i(t')P_i^{1\text{th}}(t-t')dt' .$$

Then, the solution after the second iteration will be

$$P_i^{2\text{th}}(t) = P_i^{1\text{th}}(t) + \Delta^1P(t+\tau_0) .$$

If the same process is repeated $n$ times, the $n$-th iterative solution can be expressed as follows:

$$P_i^n(t) = P_i^{(n-1)\text{th}}(t) + \Delta^nP(t+\tau_0) , \quad n=1,2,3,\ldots ,$$

where

$$\Delta^nP(t) = \Delta^{(n-1)\text{th}}P(t) - \int T_i(t')\Delta^{(n-1)\text{th}}P(t-t')dt' .$$

In this way, the iteration process continues until the calculated lidar return approaches the real $P(t)$ within some tolerance. Using Eq. (8) and Eq. (9) the maximally resolved profile can be derived from the long-pulse lidar data with the temporal profile of the laser pulse. General discussion on the convergence of the iterated signal seems difficult. Instead, we practically apply the algorithm to the simulated data for a CO$_2$-lidar and discuss the convergence numerically with a specific example.

3. Application of the Iterative Technique

3.1 Calculation of Lidar Signal with a Model Lidar System

A long-pulse lidar signal is generated by simulation for a CO$_2$-lidelar system of incoherent detection to test the proposed iterative technique. The model lidar system consists of these basic elements: a laser, a transmitting optics and a receiving telescope, and a cryogenic HgCdTe detector. The laser pulse output has pulse energy of 1 J/pulse, temporal profile of 100 ns gain-switching peak with $\sim$1 $\mu$s tail, spatial profile of gaussian, beam diameter and divergence after collimation of 240 mm 1.2 mrad, respectively. The receiving telescope has diameter of 500 mm, focal length of 1490 mm, and field of view of 1.3 mrad. We consider biaxial configuration with the separation of 380 mm between the parallel axes of transmitting and receiving optics.

We assume a homogeneous atmosphere with the extinction coefficient of 0.1 km$^{-1}$ and the backscatter coefficient of 0.0004 km$^{-1}$ sr$^{-1}$, which correspond to a hazy type of weather. In addition we make sinusoidal variations in backscatter intensity in the localized region ranging from 450 m to 600 m to simulate small-scale inhomogeneity of the atmosphere.

With the above lidar parameters and atmospheric parameters, the maximally resolved signal $P_\text{m}(t)$ in the case of infinitely short pulse duration is calculated using the conventional lidar equation, Eq. (2), and the lidar signal $P(t)$ for long-pulse lidar is calculated using Eq. (1) as well as the conventional lidar equation. Since the lidar signal means the optical power irradiated onto the detector surface in this paper, the properties of detector and its electronics are not considered in these calculations. The results are plotted in Fig. 1. It is obvious that a long laser pulse results in distortion of near-range profile as well as obscuration of the small-scale inhomogeneity of the atmosphere as described in previous work. The lidar signal profile in Fig. 1 is used for various numerical tests through this paper.

3.2 Application of the Iterative Algorithm

The proposed iterative technique is applied to the calcu-