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Data inversion method for dual-frequency Doppler lidar based on Fabry-Perot etalon quad-edge technique

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ABSTRACT

In order to realize the accurate inversion of lidar data, the calibration method for the ratio of Fabry-Perot etalon (FPE) transmission to reflection curve is given, and the reliability of the method is verified by simulation test. The effective ratio of FPE transmission to reflection for the actual atmospheric detection is analyzed, and a nonlinear iterative algorithm for simultaneous inversion of wind field and backscatter ratio, as well as the specific iterative steps, initial value determination methods and corresponding error formula of parameters are proposed. The simulation results show that no matter whether the backscatter ratio R_β is small or large, the iterative process is always convergent and the correct inversion results can be obtained. The value of R_β has a great influence on the convergence rate of its own, but has little effect on the wind speed convergence rate. The smaller R_β is, the faster convergence rate of R_β is, vice versa. Error analysis inferred that under the shot-noise limit, the radial wind speed measurement error decreases rapidly with the increase of R_β for $1 < R_\beta < 2$, decreases slowly with the increase of R_β for $R_\beta > 2$; if the total number of backscattering photons of 50,000 received by telescope is assumed, the backscatter ratio measurement error increases with the increase of R_β; within the wind speed measurement dynamic range of ±25 m/s, the radial wind speed error is below 2m/s and the backscatter ratio relative error is less than 4.1% when $1.1 < R_\beta < 10$.

1. Introduction

High-precision, high spatial and temporal resolution real-time wind field data is of great importance for improving climate models, studying global climate change, promoting atmospheric thermodynamics and kinetics, improving the accuracy of weather forecasts, ensuring aircraft takeoff and landing safety, improving the utilization of wind energy and so on. Therefore, as one of the most effective tools for wind field detection, Doppler lidar has been deeply researched and developed rapidly, and has formed direct-detection system [1–6] and coherent system [7,8]. On the basis of the traditional double-edge detection technique, the author proposed a dual-frequency Doppler lidar based on FPE quad-edge technique. Compared with the traditional double-edge detection Doppler lidar, this lidar can effectively improve the wind detection performance [9,10].

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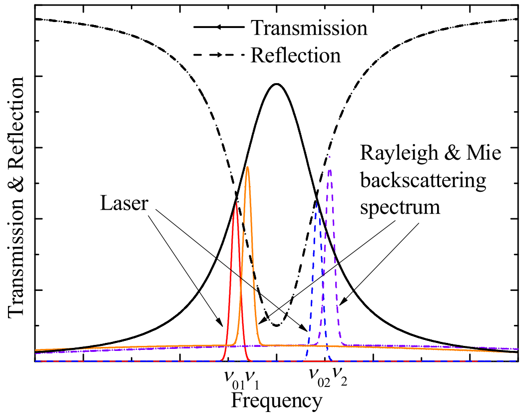

Fig. 1. Wind measurement principle based on F–P etalon quad-edge and dual-frequency technique.

However, the final performance of the lidar system not only depends on the hardware, but also the data inversion method. Whether the data inversion method is correct and effective is very important. Based on the analysis of the measurement principle and system structure of this dual frequency Doppler lidar, the data inversion problems of the system, including system calibration, parameter inversion and corresponding measurement errors, are studied in depth.

2. Measurement principle and system structure

As shown in Fig. 1, the transmission and reflection spectrum of FPE are intersected at the two waist. Two frequencies of the outgoing laser ν_{0i} ($i = 1, 2$) are locked in the vicinity of these two intersection points respectively to form the dual-frequency four-edge detection technique [9]. The outgoing laser is emitted into the atmosphere and is scattered by atmospheric molecules and aerosol particles with a macro velocity (wind speed). The backscattered light will have Doppler frequency shift and the amount of frequency shift is $\nu_d = \nu_i - \nu_{0i} = 2V_r/\lambda$, where ν_i ($i = 1, 2$) is the frequency of backscattered light, V_r is radial wind speed, λ is laser wavelength. Then, the transmittance and reflectance of the backscattered light passing through the FPE will change accordingly. The magnitude and direction of the radial wind speed can be derived from the pre-calibrated transmission and reflection curve of FPE and the measured change in transmittance and reflectance.

Fig. 2 shows the structure of dual-frequency Doppler lidar system based on FPE quad-edge technique [10]. The transmitting system adopts a narrow-linewidth and frequency stabilization tunable semiconductor laser with MOPA structure at 852 nm, and the transmitting laser frequency is changed alternately between ν_{01} and ν_{02} by using an acousto-optic frequency shifter. The transmitting laser is split into two beams by a beam splitter (T/R = 99/1). The reflected light is coupled by a branch of the 1 × 2 multimode fiber coupler A into a 100 m long fiber, whose backscattered light is used as reference and enters one branch of the 1 × 2 multimode fiber coupler B through the other branch of coupler A. The transmitted light passes through a beam expander, two reflectors and a two-dimensional scanner sequentially, and then enters into the atmospheric detection area with a preset angle. The atmospheric backscattered light is received by a telescope and then passes through a narrow-band interference filter to suppress the sky background light. After a 200 m long fiber delay, it enters the other branch of coupler B. The optical signal coming out from the combine of coupler B enters into a collimator through the 1 → 2 path of an optical circulator, and the collimated light beam is incident on the FPE. The optical signal passing through the FPE is converged through a convex lens, coupled to the photon counting detector APD1 by an optical fiber; the optical signal reflected by the FPE is converged in the reverse direction through the collimator, passes through the 2 → 3 path of the optical circulator and then is coupled to the photon counting detector APD2. The output signals of the two detectors are acquired by a dual-channel photon counting card, and then processed by an IPC for data processing, storage, inversion and result display. The system's laser, acousto-optic shifter, two-dimensional scanner, photon counting card and so on are all controlled by the IPC through the RS232 serial port.

3. Calibration of the ratio function of FPE's transmission to reflection

3.1. The ratio function of FPE's transmission to reflection

The transmission and reflection of the beam with Gaussian spectral distribution, uniform light intensity and full divergence angle of $2\theta_0$ incident on the FPE are [9]:

$$\Im(\nu) = T_{av}M(\nu) \tag{1}$$

$$\Re(\nu) = 1 - A - C_0\Im(\nu) \tag{2}$$