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Implementing a wind measurement Doppler Lidar based on a molecular iodine filter to monitor the atmospheric wind field over Beijing

Li-fang Du*, Guo-tao Yang, Ji-hong Wang, Chuan Yue, Lin-xiang Chen

National Space Science Center, CAS, State Key Laboratory of Space Weather, Beijing 100190, China

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ABSTRACT

A wind measurement Doppler Lidar system was developed, in which injection seeded laser was used to generate narrow linewidth laser pulse. Frequency stabilization was achieved through absorption of iodine molecules. Commands that control the instrumental system were based on the PID algorithm and coded using VB language. The frequency of the seed laser was locked to iodine molecular absorption line 1109 which is close to the upper edge of the absorption range,with long-time (> 4 h) frequency-locking accuracy being $\leq$ 0.5 MHz and long-time frequency stability being 3.55×10^{-9}. Design the continuous light velocity measuring system, which concluded the cure about doppler frequency shift and actual speed of chopped wave plate, the velocity error is less than 0.4 m/s. The experiment showed that the stabilized frequency of the seed laser was different from the transmission frequency of the Lidar. And such frequency deviation is known as Chirp of the laser pulse. The real-time measured frequency difference of the continuous and pulsed lights was about 10 MHz, long-time stability deviation was around 5 MHz. When the temporal and spatial resolutions were respectively set to 100 s and 96 m, the wind velocity measurement error of the horizontal wind field at the attitude of 15–35 km was within $\pm$5 m/s, the results showed that the wind measurement Doppler Lidar implemented in Yanqing, Beijing was capable of continuously detecting in the middle and low atmospheric wind field at nighttime. With further development of this technique, system measurement error could be lowered, and long-run routine observations are promising.

1. Introduction

Atmospheric wind field detection is one of the hot topics in atmospheric researches, and it plays an important role in numerical weather prediction, as more and more extreme weather affects greatly many economic fields, such as agriculture, tourism and fisheries. The design, simulation and flight safety of aerospace vehicles also require atmospheric wind field data. In addition, atmospheric wind field has significant effects on the interaction and coupling of the troposphere and the stratosphere [1].

The testing balloon is common means to detect atmospheric wind field. However, this method is time-consuming. And it is also difficult to send the balloon into the sky, while it is easy to be lost under bad weather conditions, causing data lost [2]. Doppler Lidar is a powerful tool to detect spatial and temporal distribution of atmospheric wind field [3–6].

* Corresponding author.
E-mail address: lfdu@nssc.ac.cn (L.-f. Du).

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Given the special importance of the middle atmosphere to the human environment, safety of human space activities and research in solar-terrestrial physics, China is now paying more and more attention to the detection and study of middle atmosphere. In 2008, as one of the major national infrastructure projects, "Meridian Space Weather Monitoring Project" began to be constructed [7], aiming to establish a large-scale integrated ground surveillance chain to monitor the upper atmosphere, including laser radar, MST radar, incoherent scatter radar, sounding rockets and passive optical observation devices. In the future, an international meridian plan will be further proposed [8]. As part of the Meridian Project, construction of a Doppler Lidar was completed by the end of 2014. The Lidar system was used to carry out normal observations on wind field of the troposphere and stratosphere. The repetition frequency of the laser is 10 Hz, single pulse energy is 220 mJ, detector quantum efficiency is 20%, detection height is 35 km, and the horizontal wind speed error is about 6 m/s. Accurate real-time global three-dimensional distribution of atmospheric wind field is important to the study of atmospheric dynamics and the improvement of the numerical weather forecasting accuracy as well as early warning of biological pollution.

2. The basic principle of laser Lidar system

2.1. Introduction to wind detection using Doppler Laser

Doppler Lidar used in our system is based on the Doppler Effect between electromagnetic waves and moving objects, targeting atmospheric aerosols and atmospheric molecules. It describes atmospheric wind field by measuring the frequency difference between the backward echo signal and the emitting laser. It is currently one of the most advanced means of measuring atmospheric wind field and can provide high-precision, high spatial and temporal resolution data for an atmospheric wind field in real-time under clear sky conditions.

The principle of using Doppler Laser to measure wind field is shown in Fig. 1. where ν_0 is the laser emission frequency,θ is elevation angle, $\vec{V}$ is the horizontal velocity of the detected object, $V_r = V\cos\theta$ is the radial velocity component in the direction of the laser emission. The laser frequency observed at the detected point B is:

$$\nu_1 = \frac{\nu_0}{\sqrt{1-\frac{V_r^2}{c^2}}}\cdot\left(1+\frac{V_r}{c}\right) \approx \nu_0\cdot\left(\frac{c+V_r}{c}\right).$$

The frequency of the scattered light received at the ground is:

$$\nu_2 = \frac{\nu_1\cdot\sqrt{1-\frac{V_r^2}{c^2}}}{\left(1-\frac{V_r}{c}\right)} \approx \nu_1\cdot\frac{c}{c-V_r} \approx \nu_0\cdot\frac{c+V_r}{c-V_r}$$

The radial velocity of the object can be calculated by the frequency shift of the received light and the emitted light:

$$\Delta\nu = \nu_2 - \nu_0 \approx \nu_0\cdot\frac{2V_r}{c}$$

$$Vr = \frac{c}{2}\cdot\frac{\Delta\nu}{\nu_0}$$

The movement direction of objects can be determined by the Doppler shift $\Delta\nu$. If $\Delta\nu$ is positive, the objects moves towards the radar station; while if it is negative, the object moves away from the radar station.

2.2. The principle of frequency discrimination using molecular iodine filter

Doppler Lidar implemented in Yanqing used the non-coherent detection method using molecular iodine filter as Doppler shift detection devices. Molecular iodine filter has been applied to the Doppler Lidar system since the end of the last century, which has a super-narrow linewidth, high sensitivity and high noise suppression, satisfying the frequency discrimination requirement of the atmospheric scattering signal [9,10]. Considering the intensity of the absorption lines, shapes (edge slope), and the spacing between adjacent absorption line, the line near the maximum wavenumber of line 1109 was chose to detect frequency, and a larger wind field measurement range and a higher measurement sensitivity could be get.

While in operation, the frequency of laser was locked in the center of the edge of the high wavenumber of line 1109. Light transmittance could be obtained by the spectral response through the molecular iodine filter [11]. The transmittance difference of backscatter and emitting lasers was then used to calculate their frequency difference, known as Doppler shift which could then be used to compute the wind radial velocity at different heights. The atmospheric backscatter spectrum is composed of scattering of aerosol Mie and atmospheric molecular Rayleigh, as shown in Fig. 2. When the frequencies of the backscatter and emitted lights are the same, radial wind velocity is zero. If they are different, then there exits radial atmospheric wind field. To obtain the horizontal wind field vector information,at least two perpendicular velocity component are needed.

3. Configuration of wind measurement Doppler Lidar system

This Doppler Lidar system was consisted of a laser transmitter, binoculars receiving system and signal detection system. The system diagram is shown in Fig. 3. The basic parameters are shown in Table 1. And the structural modules comprise the system are as follows:

(1) Seed-locked laser module.
(2) Seed implantation Nd: YAG pulsed laser output module.
(3) 532 nm pulsed laser frequency monitoring module.
(4) 532 nm pulsed laser emitting module.
(5) The telescope receiver and signal detection module.

Transmission system simultaneously emit two laser beams containing similar volume of energy: one pointing to the east with an elevation angle of 60° to measure the