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Development of a mobile Doppler lidar system for wind and temperature measurements at 30–70 km

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ABSTRACT

A mobile Doppler lidar system has been developed to simultaneously measure zonal and meridional winds and temperature from 30 to 70 km. Each of the two zonal and meridional wind subsystems employs a ~15 W power, 532 nm laser and a 1 m diameter telescope. Iodine vapor filters are used to stabilize laser frequency and to detect the Doppler shift of backscattered signal. The integration method is used for temperature measurement. Experiments were carried out using the mobile Doppler lidar in August 2014 at Qinghai, China (91°E, 38°N). The zonal wind was measured from 20 to 70 km at a 3 km spatial resolution and 2 h temporal resolution. The measurement error is about 0.5 m/s at 30 km, and 10 m/s at 70 km. In addition, the temperature was measured from 30 to 70 km at 1 km spatial resolution and 1 h temporal resolution. The temperature measurement error is about 0.4 K at 30 km, and 8.0 K at 70 km. Comparison of the lidar results with the temperature of the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), the zonal wind of the Modern-Era Retrospective Analysis for Re-search and Applications (MERRA), and radiosonde zonal wind shows good agreement, indicating that the Doppler lidar results are reliable.

1. Introduction

Wind and temperature measurements from the ground to ~110 km altitude are essential to study the interactions between the lower, middle and upper atmosphere [1]. However, it is difficult to complete measurements with such a large altitude range using one single technique. Since 2006, National Space Science Center at Chinese Academy of Sciences (NSSC, CAS) has established an Atmospheric Environment Observatory at Langfang, China (116°E, 39°N). We have further established a number of mobile or re-locatable instruments [2], and made routine observations after 2010. The instruments include a Sodium Doppler Lidar [3], a Medium-Frequency Radar, a Meteor Radar, an Airglow Imager [4] and Radiosondes. The wind and temperature profiles from the ground to ~30 km and from 70 to 110 km were obtained. After 2011, a mobile Doppler lidar system was developed to measure wind and temperature between 30 and 70 km, to cover the height gap for the Langfang Atmospheric Environment Observatory.

Wind measurements between 30 and 70 km are very difficult and therefore rare. The altitude of this region is too high for radiosonde balloons, and has no strong backscattered signals from radio waves. Meteorological rockets were launched to probe in-situ winds and

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temperature at some locations [5,6], but could not provide continuous or long-term measurements or high temporal resolution. No spaceborne sensors can measure winds, although some instruments can measure temperature for this region, e.g. SABER (the Sounding of the Atmosphere using Broadband Emission Radiometry) [7–9], and MLS (the Microwave Limb Sounder) [10]. Therefore it is pressing and important to develop instruments to measure wind at 30 to 70 km. The Doppler lidar has the measurement capability to cover the 30 to 70 km region, because it employs UV–Visible laser light as the emission source. At short wavelengths, the laser light can be strongly scattered by atmospheric molecules. Usually, Doppler lidar instruments are classified into coherent lidar and incoherent lidar. Coherent lidar can measure winds in the troposphere by analyzing aerosol scattering signals using the heterodyne detection technique. Incoherent Doppler lidar can measure winds up to the mesosphere by detecting the scattered photons directly [11]. The lidar discussed in this paper is an incoherent system.

With the advances of laser technique, more incoherent Doppler lidars have been developed for middle and upper atmosphere studies. Usually, high power lasers and larger aperture telescopes are used in lidars to enhance the backscattered light signal, and to extend the measurable altitude. In general, the Fabry–Perot interferometer and iodine vapor filter are two main frequency discriminators in the Doppler lidar system to measure wind. She et al. compared these wind measurement techniques [12]. In general, the Fabry–Perot interferometer can be used in all different wavelength lidar systems (e.g. 355, 532, or 1064 nm), but the incident beam must be aligned very well. The iodine vapor filter was proposed to measure Doppler shift in lidary system by Liu et al. in 1996 [13,14] to reduce difficulties associated with the lidar receiver alignment. A Fabry–Perot Interferometer-based Doppler lidar with a 12 W, 532 nm laser and a 38 cm diameter telescope measured winds up to 60 km at Arecibo Observatory in Puerto Rico after 1990 [15]. Souprayen et al. presented a Rayleigh–Mie Doppler lidar measured wind from ~8 to 50 km using a Fabry–Perot interferometer at Haute Provence, France in 1999. The lidar used a 30 W, 532 nm laser and 16 telescopes of 0.5 m aperture [16]. Recently, a mobile Doppler lidar has been developed by the University of Science and Technology of China. It is composed of three subsystems for meridional, zonal and vertical wind measurements respectively, and they were installed on three container trucks. Each subsystem uses a 17.5 W, 355 nm laser and a 1 m-diameter telescope. Scanning Fabry–Perot interferometers were used in this lidar system to measure the Doppler shift [17]. A similar lidar with a Fabry–Perot interferometer is deployed for daytime atmospheric temperature measurements between 2 and 15 km by Witschas et al. [18]. In 1997, Friedman et al. developed a middle-atmospheric 532 nm Doppler lidar with 16 W laser using an iodine-vapor filter that was capable of measuring horizontal wind from 18 to 45 km [19]. A laboratory demonstration and a mobile 532 nm Doppler lidar system using iodine vapor filters was used to measure tropospheric wind by Liu et al. in 2002 [20–22]. In 2009, Shibata et al. described an incoherent wind Doppler lidar using an iodine filter measuring wind from 8 to 25 km. In this lidar system, double edges of iodine absorption spectrum were used to detect backscattered Doppler shift, improving the wind measurement sensitivity [23,24]. The Doppler lidar using iodine vapor filters at the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) was described by Baumgarten, 2010. It can measure the wind field up to 80 km with two lasers of 14 W power and two telescopes of 1.8 m aperture [25]. Those Doppler lidar systems and their experiments demonstrated that iodine vapor filters can be used to measure wind from the troposphere to the mesosphere.

Based on the successes of these lidar systems, the iodine vapor filter was selected for the mobile Doppler lidar developed by NSSC, CAS. The lidar is installed on two container trucks to obtain wind data in the westward and northward direction. This is the first mobile Doppler lidar system based on iodine vapor filter for wind and temperature measurement up to 70 km. It will be used to measure and study the wind and temperature structure of stratosphere and mesosphere in China. A preliminary observational campaign was conducted at Qinghai, China on August 2014 using one lidar on one truck. This paper describes the mobile Doppler lidar system and its preliminary measurement results.

2. Measurement principles

A large number of absorption lines of iodine molecular spectrum have been identified and an ‘iodine atlas’ made at the spectral range from ~420 to 1380 nm [26]. The absorption lines near 532 nm are usually used as the frequency reference to stabilize laser frequencies or to detect frequency shift as the Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) laser technology at 532 nm is very mature. The 1109 line of the iodine spectrum was chosen in this experiment. Its normalized transmission function is written as $F(\nu)$, where ν is the frequency. The laser frequency is stabilized at a point of the iodine spectrum edge, ν_0. The center frequency of scattered light is shifted $\Delta\nu$ due to Doppler shift. The frequency shift $\Delta\nu$ can be determined by comparing the transmissions $f(\nu,T,P)$ of scattered light passing through the iodine filter at frequency ν_0 and $\nu_0+\Delta\nu$. Considering the transmitted laser lineshape $G(\nu)$ and the atmosphere scattered Rayleigh spectrum lineshape $R(\nu,T,P)$, the scattered light transmission through the iodine filter $f(\nu,T,P)$ can be expressed as [17]:

$$f(\nu,T,P)=\int F'(\nu)\Re(\nu'-\nu,T,P)d\nu' \tag{1}$$

$$F'(\nu)=\int F(\nu'-\nu)G(\nu'-\nu)d\nu' \tag{2}$$

$$\int \Re(\nu'-\nu,T,P)d\nu=1 \tag{3}$$