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A pure rotational Raman lidar using double-grating monochromator for temperature profile detection

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ABSTRACT

A pure rotational Raman lidar is constructed for measurements of vertical temperature profiles of atmosphere. A fiber-coupled, double-grating monochromator is used as the filter system so that a high spectral resolution of <0.23 nm and an out-of-band rejection rate of 10^7 are achieved. Comparison with in-situ measurements indicates that the accuracy of atmospheric temperature measurements using this lidar system is better than 1.1 K up to an altitude of 10 km. Different effects on signal accuracy resulting from various noise sources are analyzed and uncertainties in temperature due to detection noises are estimated.

1. Introduction

Temperature profile is an important factor to analyze the state of atmosphere. Temperature in the troposphere is influenced tremendously by surface radiation. A temperature inversion layer frequently appears in the troposphere and changes quite complicatedly. Lidar techniques are a useful remote sensing tool and can provide atmospheric temperature detections with high accuracy, fine temporal and spatial resolution and large detection range.

There are several types of lidar techniques to measure the atmospheric temperature profile. These include the Rayleigh scattering lidar, differential absorption lidar (DIAL), and vibrational Raman and rotational Raman scattering lidar. Among them, owing to the influence of Mie scattering, Rayleigh scattering lidar is usually applied to measure temperature profiles in the upper atmosphere above ~20 km [1]. The DIAL method is based on variation of gases absorption coefficient in a given wavelength band. It detects, for example, O_2 absorption to derive the O_2 number density and hence the atmospheric molecular concentration level, from which the atmospheric temperature profile can be deduced. However, laser emissions at two wavelengths ("online" and "offline") with high stability and spectral purity are required when using the DIAL method, and the measurement accuracy is limited [2]. A vibrational Raman lidar is based on inelastic scattering theory and detects atmosphere temperatures by analyzing the correlative properties of the backscattering signal intensity and temperature profile. Due to the low strength of Raman backscattering intensity, the signal-to-noise ratio (SNR) is very low [3]. In practice, because rotational Raman scattering is larger than vibrational Raman scattering, a rotational Raman lidar can provide a better SNR and has been used to obtain the temperature profile from the ground layer to the upper troposphere. Atmospheric temperature is measured by analyzing the relationship between the rotational Raman backscattering intensity and the temperature profile.

The use of pure rotational Raman lidar backscattering signals for atmospheric temperature profile was originally proposed in 1972 by Cooney [4]. Based on a theoretical calculation, Cooney pointed out that a nitrogen molecule Raman scattering lidar, equipped with a laser of output

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energy of 20 J per pulse at 694.3 nm, a receiving telescope area of 1 sq m^2 and a filter bandwidth of 1 nm, can acquire a temperature profile up to 2 km at a height resolution of 100 m and measurement error of ± 1 °C. With the technology improvement of laser, optical filter of high spectral selective transmittance and high out-of-band restraint, photoelectric detection, optical devices design and signal processing there have been many remarkable progresses in the Raman lidar technology. Nowadays, a representative work is the scanning Raman lidar system developed by NASA. With a telescope diameter of 76 cm and a laser pulse energy of 300 mJ at 355 nm, the detectable height has been extended up to 14 km with an accuracy of 2 K at a height resolution varying from 30 to 600 m.

A pure rotational Raman (PRR) lidar has been developed at the Beijing Institute of Technology. In this paper, this PRR system and the technical improvement made to this system are described. Error analysis is performed. Atmospheric temperature measurements are conducted and the results are compared with radiosonde temperature data.

2. PRR lidar theoretical basis and system specifications

The PRR lidar is based on the following exponential relationship between atmospheric temperature and ratio of two Raman signals of lower and higher rotational Raman quantum number [5]:

$$M(T(R)) = \frac{I(J_L)}{I(J_H)} = \exp\left[\frac{A}{T(R)} + B\right] = \frac{n_L(R)}{n_H(R)} \tag{1}$$

where A and B are constants related to the rotational energies and degeneracy factor, respectively; $n_L(R)$ and $n_H(R)$ are, respectively, the photon counts received in the lower and higher PRR quantum number channel at height R. After A and B are determined through calibration, atmospheric temperature can then be extracted:

$$T(R) = \frac{A}{\ln(n_L(R)/n_H(R)) - B} \tag{2}$$

Since the intensity of Raman scattering signal is several orders in magnitude lower than the Mie scattering and Rayleigh scattering signals, one of the technical challenges of PRR lidar to detect the temperature profile is to realize high rejection to the elastic backscattering signal.

A diagram of the PRR lidar we developed is shown in Fig. 1 and system specifications are summarized in Table 1. This system consists of a laser emission unit, a receiving optics unit, a follow-up optical unit, signal detection and data acquisition unit and a control unit, as shown in Fig. 1. The laser transmitting and receiving unit has a monostatic configuration, which contains a laser beam expander and a set of reflection mirrors. The expander can further reduce the laser beam divergence to 0.2 mrad.

One of the technical challenges in the development of the PRR systems is to achieve high rejection of the Raman channels to the elastic signals. To do this, our system uses a self-designed multi-channel double-grating monochromator to selectively separate the two PRR signals of S (Stokes) and O (anti-Stokes) spectral bands of N_2 and O_2 molecules.

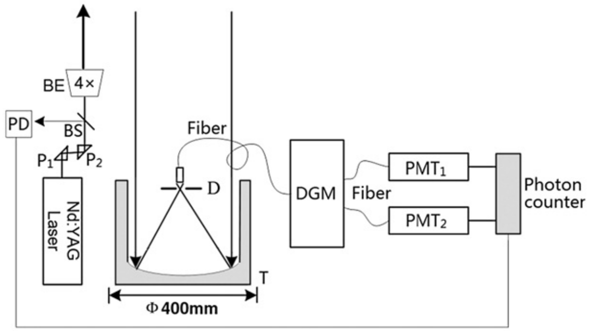

Fig. 1. Diagram of the PRR lidar. BE—beam expander; BS—beam splitter; D—diaphragm; T—receiving telescope; PD—PIN photodiode and synchronous trigger circuit; P1 and P2—guidance and alignment prisms; DGM—double-grating monochromator.

Table 1
PRR lidar specification.

Device	Specification	Value	Unit
Laser	Wavelength	532	nm
	Energy per pulse	280	mJ
	Repetition rate	20	Hz
	Pulse duration	5	ns
	Divergence	0.55	mrad
Expander	Magnification	4	
Telescope	Aperture	400	mm
	Field of view	0.1–1.5	mrad
PMT	Quantum efficiency	12%	
	Gain	7×10^6	
	Dark count at 20 °C	300	s^{-1}
	Rise time	3	ns
	TTS	4.5	ns
Photon counter	Sample rate	350	MHz

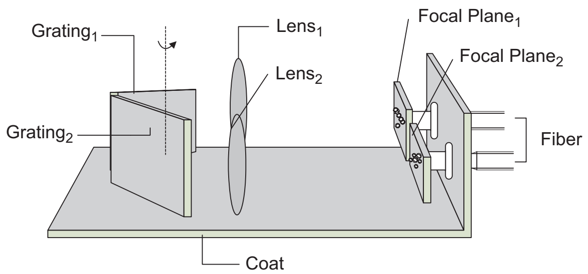

Fig. 2. Diagram of the double-grating monochromator.

As shown in Figs. 2 and 3, our designed double-grating monochromator is mainly formed by two blazed gratings using the incident Littrow mode for the 532 nm band. The system spectral resolution is better than 0.23 nm [6] and the out-of-band rejection rate is $\sim 10^7$. With this configuration, the PRR S and O spectral lines of N_2 and O_2 molecule can be distinguished from the elastic backscattering signal at 532 nm.

The two gratings used in the monochromator are coupled using optical fibers. The ends of these fibers are aligned on the focal plane of two convex lenses. These convex lenses are used to collimate the lights incident on