Measurements of Density, Pressure and Temperature in the Middle Atmosphere with Rayleigh Lidar

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ABSTRACT

Ground-based observations of the middle atmospheric density, pressure and temperature profiles can be obtained by Lidar. A single-wavelength Rayleigh Lidar system based at Hefei (31°N,117°E) has been used to measure the atmospheric density, pressure and temperature in the middle atmosphere in night in the altitude range from about 25 to 40 km. The structure of Rayleigh lidar system, principles of middle atmospheric density, pressure and temperature measurement which is based on the Rayleigh scattering theory and method to retrieve atmospheric density, pressure and temperature profiles were described respectively. This instrument combined a 500mW Nd:YAG laser transmitter with a 0.4 m receiver mirror to observe returns from altitudes between 25km and 40km.The lidar observed atmosphere density, pressure and temperature profiles are validated through comparison with the measure data provided by sounding balloon. According to the data from actual measurement, the inversion of the vertical distribution of middle atmosphere density, pressure and temperature are in good agreement with the result of sounding balloon. Generally, in the altitude range 25 to 40 km, the density ratio profile of Rayleigh lidar to the sounding balloon density fluctuates between 0.98 and 1.10, the pressure ratio profile of Rayleigh lidar to the sounding balloon is between 0.99 and 1.06 and the deviation of the temperature is less than 6 k.

Keywords: Lidar; Atmospheric Density; Temperature; Rayleigh scattering; Middle atmosphere

1 Introduction

In recent years, the middle atmosphere has received increasing attention. The altitude range of the middle atmosphere is from 10km to 100km, which includes upper troposphere, stratosphere, mesosphere and lower thermosphere. And stratosphere and mesosphere play the dominant roles in the middle atmosphere. The middle atmosphere which occupied the very large volume is very sparse. There are complex photochemical and dynamical phenomena in middle atmosphere that are closely related to mankind's existence and development and space activities.

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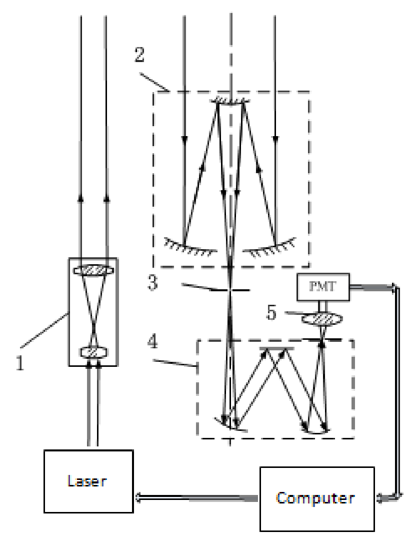
Due to rare atmosphere and great height, it is quite difficult to research the middle atmosphere dynamics. Therefore, studying the dynamics of middle atmosphere has been demonstrated by several of middle atmospheric program (MAP) campaigns.

Currently , the middle atmosphere have been studied using sounding balloon, micro-rocket, space-borne instruments and ground-based Rayleigh lidars.[1][2][3]The cost of balloon and micro-rocket instruments are relatively expensive and the number of measurements are limited. Though space-borne instruments are nearly global in coverage , they have limitations, as they do not provide continuous measurements, in addition to being low in height resolution and accuracy. However, because of its short wavelength and strong directional beam, Lidar inherently has high detection sensitivity and spatial resolution. Ground based Rayleigh lidar, employing Rayleigh backscatter from molecules for measurement of middle atmosphere, enables the measurement of the density , pressure and temperature profiles in the middle atmosphere region with accuracy better than that can be achieved by other satellite or rocket techniques. The capability of the Rayleigh lidar for high time and height resolution measurements has offered a new approach for studying various aspects of the middle atmosphere. Just with these characteristics, the lidar technique has come to be an effective means for studies on middle atmosphere over the past thirty years.[4]

In this paper, a Lidar used to remote sensing in the altitude range 25-40km is introduced, and the primary structure of the Lidar and the inversion method of atmospheric density, pressure and temperature in the altitude range 25-40 km at Hefei are described. Meanwhile, the inversion results are compared with the data of sounding balloon, and the reasons of this difference are discussed in this paper.

2 Lidar system

The middle atmospheric Rayleigh Scattering Lidar, located at Hefei (31.9°N ;117.16°E), China, is composed of transmitter, echo signal receiver and data acquisition and control. The system structure is show in Fig. 1.



1.expander 2.receiving optical system 3.diaphragm aperture 4.spectrometer 5.collimating optical system
Fig. 1. Structure of Rayleigh Lidar system

The lidar system employs the Q-switched Nd-YAG laser at 532 nm with a pulse repetition rate of 10Hz. Laser pulse energy of 400 mJ is enough to measure the temperature profiles up to the height range 40 km. The divergence of transmitted beam is about 0.3 mrad, being directed vertically into atmosphere via the gimbal-mount mirror. There is little aerosol above 25 km in the clear background area, so the Lidar echo signal completely come from the Rayleigh scattering of high atmospheric. That is why the Rayleigh Lidar is especially for the middle atmospheric remote sensing. A Cassegrain telescope with a diameter of 0.4m which collected the backscattered photons of 532 nm is used as the receiver. The field of view of the telescope was set to be 1.5 mrad via a field-stop iris at the focal plane. The diverging return light from the focus is collimated to pass through an interference filter, and then detected by a photomultiplier tube (PMT).The output pulses from the PMT are gathered by a multichannel scaler connected with a data acquisition computer. The PMT is equipped with a refrigerator, in order to reduce the thermal noise and dark current. To prevent PMT saturation induced by the low-altitude returns, an electronic gating in the PMT housing is used to block the strong returned signals from lower altitudes. A narrow band interference filter with full-width at half-maximum (FWHM) of 1 nm is used to reject much of the background light. After the return signals were filtered, they are detected by the PMT and then counted and saved by the data acquisition computer. The main parameters of the Rayleigh lidar are given in Table 1.

Table 1 Technical parameters of the Rayleigh lidar

Lidar system	**Specification**
Transmitter	
Laser	Nd:YAG
Wavelength	532nm
Repetition rate	10Hz
Pulse energy	400mJ
Beam divergence	0.3mrad
Receiver	
Telescope type	Cassegrain
Telescope diameter	400mm
Field of View	1.5 mrad

Hence the Rayleigh scattering signals from the air molecules between 25 and 40 km are strong enough to permit the calculation of the atmospheric density , pressure and temperature in this region.

3 Method

In general, the density, pressure and temperature measurements by using the Rayleigh lidar above 25km or 30 km is based on the inversion of pure molecular Rayleigh scattering. The Rayleigh lidar method assumes that only a negligible amount of aerosols exist above 25km and the scattered light is only due to the pure molecular scattering and that Mie scattering due to aerosols is negligible above 25km. [5]

The backscattering signals for a single wavelength Rayleigh lidar is described by the lidar equation as follows. [6][7]

$$P(z)=\frac{C}{z^2}\rho(z)\frac{R}{k}\sigma_{Ray}T^2(z)+n_{SB}(z) \qquad (1)$$

where $P(z)$ is the number of photons received from altitude z, C is the Lidar system constant, $\rho(z)$ is the atmospheric density, σ_{Ray} is the mean Rayleigh backscattering cross section of air molecular, $T(z)$ is the Atmospheric Transmittance, $n_{SB}(z)$ is the background noise photon count (consisting of the photomultiplier dark count and the sky background); k is the Boltzmann constant, R is the universal gas constant.

Thus atmospheric relative density profiles can be acquired from the return signal detected by lidar. The atmospheric density profile can be show as follows.

$$\rho(z)=\frac{z^2k}{CRT^2(z)\Delta Z\sigma_{Ray}}(P(z)-n_{SB}) \qquad (2)$$

It is clear that the received signals due to molecular scattering is directly proportional to the density of the atmosphere. If it want to get the absolute value of the atmospheric density, it must accurately determine the parameters of the radar system and the transmission coefficient of the atmosphere. These parameters are not only difficult to measure, but also are easy to be affected by the factors of working environment. Usually, Normalization method of Rayleigh scattering signal were used, to calculate the density.

Firstly，the relative distribution of the atmospheric density is obtained from the laser radar equation. Secondly，molecular number density at the reference point is measured by other methods. Then, the absolute distribution of the atmospheric density is obtained by using the value of the calibration. Thus，if atmospheric density at the reference height z_0 is obtained from other instruments, the atmosphere density above 25 km can be expressed as

$$\rho(z)=\frac{z^2\rho(z_0)(P(z)-n_{SB})}{z_0^2(P(z_0)-n_{SB})} \qquad (3)$$

Where $\rho(z)$ is atmosphere density at the height z, z_0 is the normalization altitude, $\rho(z_0)$ is atmosphere density at the reference height z_0，$P(z)$ is the returned photon counts at the height z, $P(z_0)$ is the returned photon counts at the reference height z_0. The reference height should be as high as possible and the signal to noise ratio should be over 5. And the atmosphere density at the reference height z_0，can be obtained from the standard atmospheric model or radiosonde data.

In this paper, the atmospheric transmittance is considered as a constant. For the 532nm wavelength, the change of atmospheric transmittance from 25 km to 40 km is less than 0.5%, which can be considered that the atmospheric transmittance is approximately equal to 1. And the error of inversion result caused by approximate value of atmospheric transmittance is about 1% ~ 2%.[8]

Because the pressure and temperature profiles can be obtained by measuring the relative atmospheric density, basic assumptions to measure middle atmosphere temperature and pressure with the Rayleigh scattering theory include the following two items. Firstly, it is assumed that the middle atmosphere is in a static equilibrium state, and it is in accordance with the ideal gas law. Secondly, it is assumed that the proportion of the various components in the atmosphere is constant. According to the above two mentioned assumptions, we can get the temperature profile in the middle atmosphere through the relative density profile.

The ideal gas law

$$\rho = \frac{pM}{RT} \tag{4}$$

The hydrostatic equation

$$dp = -\rho g dz \tag{5}$$

The temperature can be obtained

$$T(z) = \frac{M}{R}\frac{p(z)}{\rho(z)} \tag{6}$$

And the pressure can be gained by integrating the hydrostatic equation

$$p(z) = p(z_R) + \int_{Z_R}^{Z} (-g(r)\rho(r))dr \tag{7}$$

Based on the above two equations, the temperature at the height z can be expressed as the follow equation.

$$T(z) = \frac{T(z_0)\rho(z_0)}{\rho(z)} + \frac{M}{R}\int_{Z}^{Z_0} \frac{g(r)\rho(r)}{\rho(z)}dr \tag{8}$$

Where $T(z)$ the atmospheric temperature at the height z, $p(z)$ is the atmospheric pressure at the height z, $T(z_0)$ is the atmospheric temperature at the reference height z_0 , M is the average molecular weight of atmosphere, $g(r)$ is the acceleration of gravity.

4 Observation Results and Discussion

The lidar usually operates on all the clear nights starting from 21:30 to 05:00 local time (LT). For the present study, data were collected on the clear nights from May 22,2015 to May 23,2015, in the western suburbs of Hefei. The typical echo curve of this Lidar is as shown in Fig. 2.It can be seen that the effective return signal at the height approximately 40km can be obtained by the lidar, where the signal to noise ratio is more than 1.And there is only the background noise above 40km.

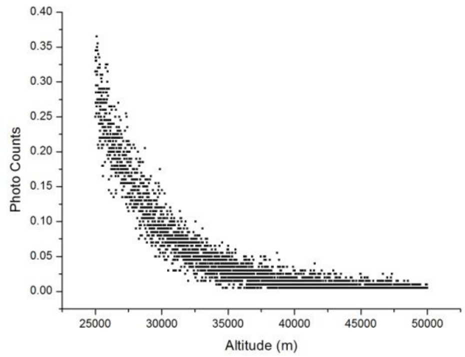


Fig. 2 Typical echo curve of the Rayleigh Lidar (time resolution 30 min, spatial resolution 150 m)

The time resolution of the sampling is 30 min, the spatial resolution is 150 m, and the maximum height of the sampling is 120 km. Cumulative 4000 pulses echo signals are used to improve the SNR. During data processing, the atmospheric echo between 60 km and 90 km can be seen as background noise. Using original echo subtracts above background noise, the echo profile deducted background noise can be obtained. Considering the fluctuation of the echo signal caused by the fluctuation of the atmosphere, the original echo signal is smoothed by moving average, and the width of the smoothing window is 300 m.

In order to verify the performance of the lidar and the reliability of the data processing method, the observation results of lidar and radiosonde balloon measurement results were analyzed. The sounding balloon is discharged at a distance of 100m from lidar site, on May 23, 2015 at 1 am. Because the changes of stratospheric density, pressure and temperature in a small horizontal range and in short time is not obvious, we can compare the measurement results of lidar and the sounding balloon near the lidar to verify our lidar system and inversion method. The radiosonde date on May 23, 2015,at 7AM are selected to compare with the result of lidar in same time. Here the reference altitude is 37 km, where the SNR is above 5, and the reference values of density and temperature in designated altitude chosen from the sounding balloon.

According the data obtained by the Rayleigh Lidar during 8 hours, the distribution of middle atmospheric density variations with increasing altitude at night in local area is as show in Fig. 3. The black dot in Fig.3 is the density profile obtained by the actual measurement data inversion. The red dot in the figure is the results derived from sounding balloon.

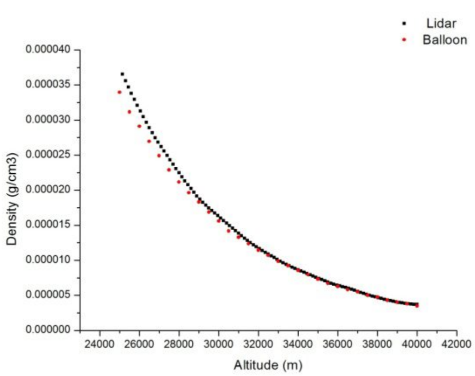


Fig. 3 Middle atmospheric density profile (time resolution 8 hours)

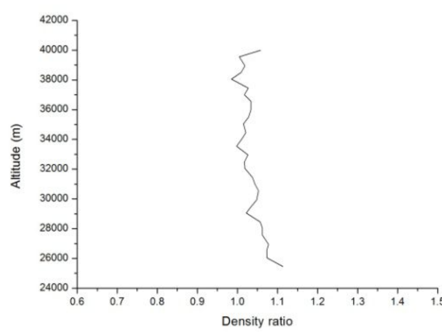


Fig. 4 Density ratio profile of the retrieved density to sounding balloon

It can be seen from Fig. 3 that the results of the atmospheric density inversion is in good agreement with those of sounding balloon. Fig. 4 presents the density ratio profile of the retrieved density to the sounding balloon. The density relative ratio profile of the retrieved density to the sounding balloon is between 0.98 and 1.10 mostly. And the density relative ratio profile of the retrieved density to the sounding balloon from 29km to 38km is about 1.0,which show that the lidar measured value is very close to the measured data of sounding balloon. The density relative ratio below 29km and over 38km deviates from 1.0. The main reason may be that there is aerosol below 29km and the SNR above 38km is small which may cause errors.

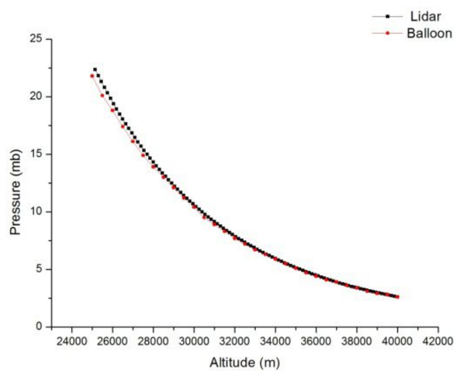


Fig. 5. Middle atmospheric pressure profile

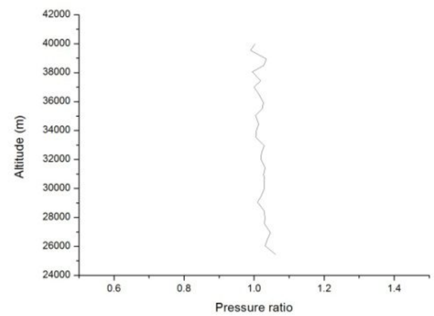


Fig. 6 Pressure ratio profile of the retrieved density to sounding balloon

According to the equation (7), the distribution of middle atmospheric pressure is show in Fig. 5, and the pressure ratio profile of the lidar to the sounding balloon is show in Fig. 6.As can be seen from Fig. 6,the result of lidar measurement is agreement with the data of sounding balloon. The pressure relative ratio profile of the retrieved pressure to the sounding balloon is between 0.99 and 1.06.

Fig. 7 presents the middle atmospheric temperature distribution measured by lidar. The temperature deviation profile of the lidar to the sounding balloon is show in Fig. 8.The temperature data measured by sounding balloon was processed by the part of the linear insertion, lest the discontinuity of the calculated results. Then the relative deviation of the results detected by lidar and sounding balloon can be calculated. However, comparing the results derived from the sounding balloon, the temperature measured by the Lidar still exist a certain error. Based on analysis and comparison, it can be found that the temperature mean error is about 3.5K from 25km to 40km, which the mean error from 25km to 28km is about 7.6K and the mean error from 28km to 40km is about 2.4K.

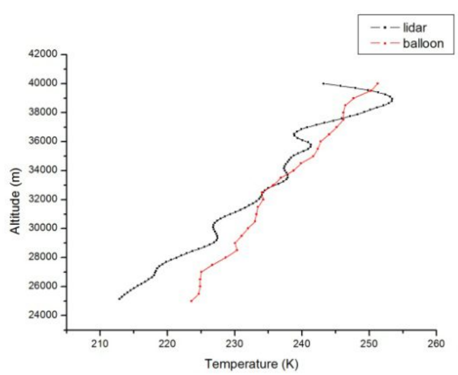


Fig. 7 Middle atmospheric temperature profile

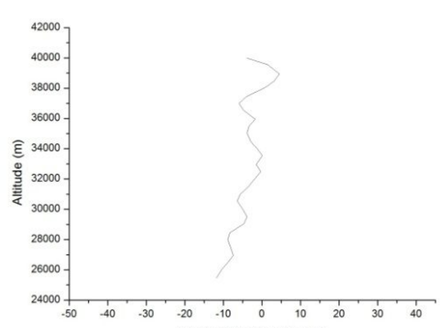


Fig.8 Temperature deviation profile of the lidar to sounding balloon

The temperature deviation of lidar mainly resulted from the uncertainty of the reference temperature value. The temperature measured by lidar below 28km is obviously higher than the data of sounding balloon. That is atmospheric transmittance is assumed to be 1 in the inversion, which means the influence of aerosol and ozone below 28km in the temperature retrieval are neglected. Especially, it is difficult to correct the atmospheric transmittance in the lower troposphere due to the fluctuation of aerosol. Similarly, there is also the temperature results by lidar was higher than the radiosonde in middle and lower troposphere reported in some literatures[9][10][11].In the altitude over 38 km, because only a small number of photos can be detected near the upper detected limit and background noise is difficult to be deducted, the temperature error is relatively large. Otherwise, the difference of measured atmosphere and time between lidar and sounding balloon, which the lidar detected the vertical distribution of atmospheric temperature between 1 hour or 1.5 hours and the sounding balloon measured the temperature distribution in its flight path within a short time, caused the measurement variation.

In general, the result measured by lidar are consistent well with the result of sounding balloon within a reasonable relative error range, which indicates that the inversion result is basically reasonable.

5 conclusion

It could be concluded that the lidar is effective and convenient in detecting atmospheric density, pressure and temperature in the altitude range 25km-40km. Under the condition of time resolution 8 hours and spatial resolution 150 m, the result by lidar agree well with the data by sounding balloon. The density relative ratio profile of the retrieved density to the sounding balloon is between 0.98 and 1.10 mostly, and the pressure ratio is between 0.99 and 1.06 mostly. The detection deviation of the temperature in the altitude range 25-40 km is about 3.4K, and there is little larger error in the altitude range 25-28 km and over 40km.It may be that the approximative value of atmospheric transmittance which is considered to be 1 in temperature inversion, and the uncertainty of the reference temperature value and the fluctuation of aerosol caused the temperature deviation in the altitude range 25-28 km. Over 40km,the main reason for those differences may come from the fact that with the increase of altitude, the signal to noise ratio of the laser radar echo is decreased, which make the error of lidar become larger.

In order to improve the precision of lidar measurement, it can be compensate the error caused by aerosols and ozone in the atmospheric parameters inversion and improve the SNR of the lidar return signals. The study results show that the Lidar is an effective means in middle atmospheric research. It can provide the distribution characterizes of the middle atmospheric density, pressure and temperature in Hefei area through long-term, systematic observation of the lidar. From the measured data provided by lidar, researcher can study the variation of the stratospheric atmospheric parameters and establish the atmosphere model of China.

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