RAINFALL DROPLET MEASUREMENT BY A PORTABLE AUTOMATED LIDAR (PAL)

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ABSTRACT

The development of a compact portable automated lidar (PAL) system is constructed for the purpose of continuous monitoring of the boundary layer (BL) activity in Shizuoka area, where strong wind dominates BL characteristics. The constructed system is described, and as a future example of continuous operation of the PAL system, observed streaks of light rain formed by falling raindrops in a time-height-intensity graph is shown using another PAL in Ichihara. From these streaks, we demonstrate that the PAL data can be utilized to calculate the raindrop size of falling raindrops.

1. INTRODUCTION

Hamamatsu, in Shizuoka Prefecture, Japan is well known for having larger fraction of clear days and stronger wind. Wind roll-up of sand affects the regional coastal zone. Because of this, the monitoring of sand transportation by wind in the boundary layer (BL) demands the use of lidar. The boundary layer is the region in space where the atmosphere is in direct contact with the surface of the earth. In this boundary layer, the atmosphere is “directly influenced by the presence of the earth’s surface, and responds to surface forcings with a time scale of about an hour or less” [1]. These time scales can be in minutes, as in the case of aerosol oscillations [2]. Thus, whenever there is a need to observe rapidly varying phenomena in BL, the need to develop a sensor capable of measuring fast changing atmospheric parameters is inevitable.

In the field of ground based remote sensing, a continuously-operated portable lidar system is the best candidate for detecting sand transportation as well as aerosol motion in the lower troposphere. Examples of the dynamics of these scatterers are the downward and upward motions of sand and aerosol particulates. The downward and upward motions are usually attributed to the cooling and heating of the ground surface, respectively. During the updraft motion, the air and together with the particulate rise and expand. The air temperature decreases with height forming, at times, clouds at the top of the updraft [3]. When these water particles increase in size, raindrops are formed.

The formation of rain in the atmosphere occurs when water droplets grow in size by collision and coalescence [4]. Raindrops vary in size depending on the type of interaction that exists among water droplets and on the prevailing atmospheric conditions. At certain size range, these droplets can effectively backscatter light. Thus, when they are hit by laser, their path can be traced in the time series graph (e.g., time-height-intensity graph) and their motion can be studied. This will lead to the measurement of the raindrop radius. At present, other ways of measuring raindrop size and rainfall speed include the use of optical disdrometer [5] and radar.

The purpose of this paper is to describe the PAL system in Hamamatsu and using another PAL system, to discuss the measurement of raindrop size from the data acquired by the PAL during slight rain conditions.

2. THE LIDAR SYSTEM

Presently, a PAL is constructed at the northern part of Hamamatsu city (34.80^{o}N, 137.73^{o}E, about 90 km southeast of Nagoya), a northern industrial park of Hamamatsu city, 15 km from the Pacific Ocean. The system is placed at the Central Research Center of Hamamatsu Photonics, Inc., 20 m above the ground level (100 m ASL). During operation, the beam is pointed north with an elevation angle of 44^o. The location of the PAL system is ideal for studying the sand transportation by south wind from the coast and also urban atmospheric pollution from city center.

2.1 The lidar instrument

The laser head consists of 2W laser diode, lenses, Nd:YAG, KTP, AOM, and the output coupler. The output laser beam is enlarged 25 times by a beam expander, and is bent by a couple of prisms and transmitted to the atmosphere. The backscattered signals are collected by a 20 cm Cassegraine telescope and are incident to the PMT through the iris, the narrow bandwidth filter and the lenses. A narrow field-of-view angle of 0.2 mrad is utilized to reduce the background skylight radiation during daytime. The data are analyzed by the scaler (Hamamatsu M8205), accumulated for 20 s and are stored in the PC. Fig.1 shows the diagram of the portable automated lidar system.

Inside the laser, the laser diode pumps the Nd:YAG crystal generating a 500 mW laser power. The laser beam is Q-switched by the AOM operated at 2.5 kHz resulting to a pulsed output of 100 μJ/pulse at1064 nm. The KTP crystal inside the cavity generates the 532 nm laser beam at 15 μJ/pulse. Table 1 summarizes the specification of the PAL system.

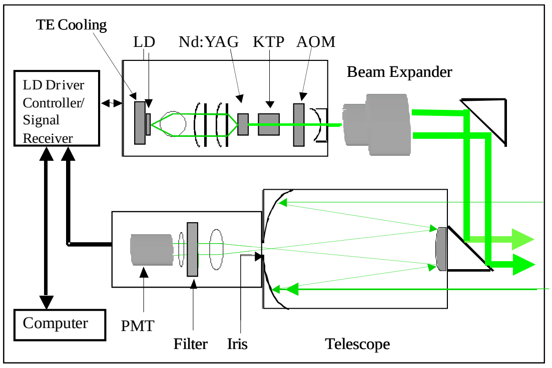

Fig. 1. The schematic diagram of the portable automated lidar system (PAL). The laser head is placed on top of the telescope.

Table 1. Specification of the PAL system

Transmitter	
Laser	LD-pumped Q-switched Nd:YAG
Wavelength	532 nm
Laser pulse width	30 ns
Repetition rate	2.5 kHz
Laser pulse energy	15 μJ
Laser beam divergence	50 μrad
AOM carrier frequency	80 MHz
Receiver	
Telescope type	Cassegrainian
Telescope diameter	20 cm
Field of view	0.2 mrad
Detector	PMT
Model	HPK-H7360MOD
Quantum efficiency	10-25%

2.2 Eye safety

The laser is not eye safe at the exit of the laser beam. Near the beam expander, the laser's energy density per pulse is around 18 times the standard maximum permissible exposure (ANSI Z136.1-1986), which is 1.16×10^{-7}Jcm^{-2}. However, at a distance of 340 m along the laser path, the beam is already eye-safe and does not obstruct aviation traffic.

2.3 The alignment procedure

Because of the small field of view (FOV) of the receiver, a small change in the optical alignment between the laser and telescopes' axes causes a significant deterioration to the signal. These misalignments are mainly due to daily and seasonal temperature changes. The other cause is mechanical disturbance (e.g., earthquake). The actual amount of temperature distortion can be evaluated using the lidar overlapping function [8].

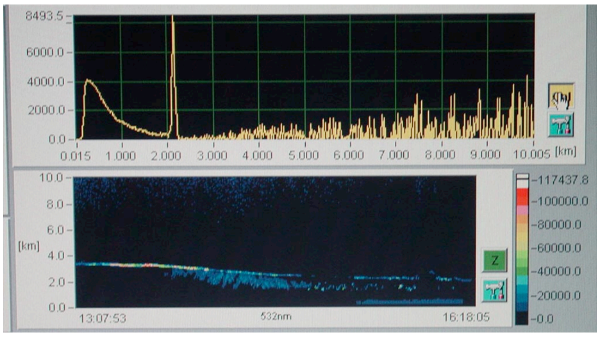

Fig.2 An example of an instantaneous monitoring of aerosol and a cloud (upper) The signal comes from an A-scope with 20 s integration. The lower graph is the THI indication of cloud and aerosol.

To prevent frequent optical misalignment, an actuator is installed to hold the upper prism. A computer program is made to control the actuator holding the upper prism and the acquisition of the data. The controlled motion of the prism effectively controls the optical automatic alignment of the system. During the continuous acquisition of data, alignment procedure is done every 15 min. For the duration of the alignment, the computer instructs the controller to move the actuator (for the vertical and then for horizontal motion) backwards by 10 unit steps, and then forward by 1 unit step. During the 1 unit step motion, the signals are integrated for 1 s until a total of 20 steps are completed. A unit step of the actuator corresponds to 50 μrad change in the tilt angle of the laser beam. The integrated signals are stored in the PC during the forward motion. The peak signal location is the position where the actuator will be repositioned after moving 20 steps. A total of roughly 90 s is needed to complete the whole alignment process. An example of measurement is shown in Fig. 2.

3. METHODOLOGY

As an example of future measurement, we explain the monitoring of light rainfall.

A well-aligned PAL system can effectively trace the dynamics of the atmosphere since the dynamics of the lower troposphere can occur in less than a minute. In the case of the PAL system, data are acquired every 20 s. During a slight rain condition, falling raindrops are effective reflectors of 532 nm laser beam and are well detected by the PAL system. These raindrops form streaks when the PAL data are graphed in time series. These streaks give an approximation of the vertical velocity of the raindrops. From the velocity approximation, the radius of the droplet can be estimated using Eq. 1 [7]:

$$r = \left[\sigma \pm \sqrt{\sigma^2 - \left(\frac{32\varepsilon\sigma^3}{3g}\right)v}\right] \cdot \left[\frac{16\varepsilon\sigma^3}{3g}\right]^{-1} \quad (1)$$

where

$$\sigma = \frac{2}{3}\left(\frac{\rho_d}{\rho_a}\right)^{\frac{2}{3}}\left(\frac{g^2}{3\eta}\right)^{\frac{1}{3}} \quad (2)$$

is the falling rate (in s^{-1}); g(=9.8 ms^{-2}) is the acceleration due to gravity; ρ_d(=1 gcm^{-3}) is the water density; ρ_d(=0.856×10^{-3} gcm^{-3}) is the air density at 2-3 km above the ground; $\varepsilon=\rho_m/4\rho_d$ and ρ_m(=10^{-6} gcm^{-3}) is the mist density; η(=0.206 cm^2s^{-1}) is the kinematic viscosity of air; and v is the terminal velocity of the droplet.

The observed data relating the water droplet's terminal speed and its radius can be found elsewhere [9]. Accordingly, when the radii of the falling droplet range is from 0.4 mm to 0.8 mm, the terminal velocities range is from 3.27 ms^{-1} to 5.65 ms^{-1} [4].

Approximations are also done to relate the terminal velocity and the radius of the falling water droplet [4]. If r is the droplet radius, Eqs. 3-5 give the relationship between the velocity and radius of a falling raindrop that are valid in the following regions: a) for r < 40 μm, b) for 40 μm < r < 0.6 mm, and c) for 0.6 mm < r < 2 mm:

$$v = k_1 r^2 \quad (3)$$

where k_1=1.19×10^8 $m^{-1}s^{-1}$;

$$v = k_2 r \quad (4)$$

where k_2=8×10^3 s^{-1}; and

$$v = k_3 r^{\frac{1}{2}} \quad (5)$$

where $k_3=2.2\times10^2\left(\frac{\rho_o}{\rho}\right)^{\frac{1}{2}}$ $m^{1/2}$ s^{-1}, respectively. In Eq. 5, ρ and ρ_o are the air density and reference density (=1.2 kgm^{-3}), respectively. For a slight rain condition, Eq. 4 can be utilized to relate the droplet speed to the droplet size.

4. RESULTS AND DISCUSSIONS

The following discussion deals with the measurements of the size of the rainfall droplets from PAL data, which is taken in Ichihara city (35.52°N, 140.07°E, about 40 km southeast of Tokyo), an industrial area of Chiba city, along the coast of Tokyo bay. The system is placed at the Chiba Prefectural Environment Research Center (CERC) for the purpose of comparing lidar data with ground based data [6]. The operation of the PAL system in Ichihara city since December 2002 up to the present has produced voluminous amount of data. These data give daily image of the dynamics of the atmosphere throughout the year.

Figure 3 shows the PAL data with streaks formed during a slight rain condition. These data were taken on April 23, 2003 from 22:00 to 23:00 Japan standard time (JST). During this time interval, the recorded ground precipitation in Chiba city and Kisarazu city (taken from the Japan Meteorological Agency) were less than 0.5 and 1.0 mm, respectively. The ground measured relative humidity ranged from 76% at 22:00 and increased gradually to 91% at around 00:00 of the next day. The ground temperature was from 16.5°C to 16.1°C. The wind speed was from 6.9 to 7.3 ms^{-1}. The wind direction was SSW to S.

Based on the observed streaks, the vertical speed of the water droplets is around 4.2 ms^{-1}. Using Eq. 1, the estimated raindrop radius is around 0.5 mm. This value is consistent with the observed radius mentioned in [4] and with Eq. 4.

Figure 4 shows the PAL data taken on June 28, 2003 at Ichihara city from 00:00 to 02:00 (JST). The graph shows the presence of several streaks formed by falling water droplets. During this time, the ground temperature and relative humidity ranged from 21°C to 22.3°C and 88% to 92%. The wind speed ranged from 1.8 to 2.1 ms^{-1}. The wind direction was SE and was constant from 00:00 to 05:00 JST. The Japan Meteorological Agency data showed that Chiba city registered a ground precipitation from 0.0 to 0.5 mm. In Kisarazu city, the recorded ground precipitation ranged from 0.0 to 1.0 mm.

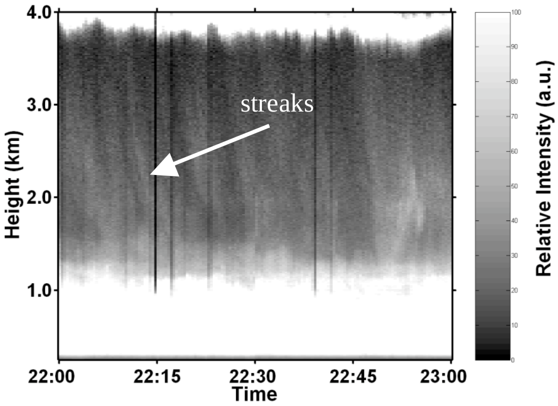

Fig. 3. Lidar data taken on April 23, 2003 showing streaks formed by falling rain droplets.

Based on the streaks from the graph, the vertical speed of the falling water droplets is approximately 4.8 ms^{-1}. This gives a radius of 0.6 mm using Eq. 1. This is, again, consistent with Eq. 4. The ratio of the terminal speed and the droplet radius is around 8000 s^{-1}, and is the same as k_2.

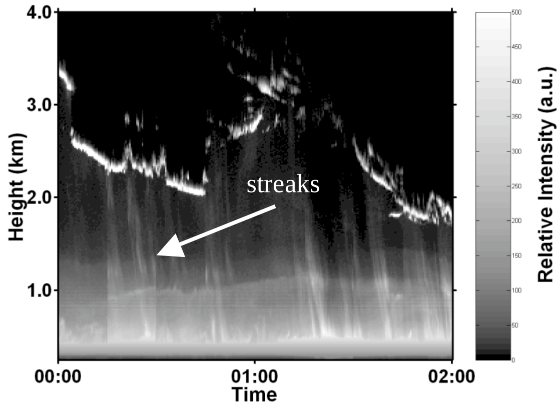

Fig. 4. Lidar data taken on June 28, 2003 showing streaks formed by falling rain droplets.

5. CONCLUSION

The operation of the PAL system has proven that it can detect changes in the atmosphere in the time scale greater than 20s. This rapid detection is able to distinguish atmospheric changes that occur in this time scale. During light rain conditions, the PAL system can clearly detect falling raindrops. This is manifested by the presence of streaks in the time-height-intensity graph of the PAL data. From the streaks formed in the graph, the average vertical speed of the rain can be approximated. The two sets of data presented above show that the values of the approximated radii are consistent with previous well established estimates and observed data. Thus, the observed streaks provide us with the information of the behavior and characteristics of water droplets as they fall to the ground.

The capability of obtaining the radius of the droplets is hindered during extensive rainfall condition. In this situation, the rain clouds are optically thick and are situated near the ground. The laser light can not penetrate through the cloud and no data can be retrieved above the thick cloud.

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