

## RETRIEVAL OF 24 HOUR AEROSOL OPTICAL DEPTHS FROM MIE LIDAR DATA

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### ABSTRACT

Temporal Aerosol Optical Depths (AODs) of Phimai district, Nakhon Ratchasima province in Thailand were retrieved from measured Mie lidar data on 17-20 February 2005 using Fernald method. The ground-based station was selected for its high and diverse local agricultural activities contributed to the aerosol content which allows for various parameters such as concentration, size distribution and aerosol optical properties to be investigated by Mie theory. The retrieval algorithm of 24 h AODs was performed in order to monitor regional impact of biomass burning emission on tropospheric aerosols. Results revealed that open biomass burning was a significant contributor to large carbonaceous aerosols in the vicinity of research site with AOD around 0.6-0.7. Furthermore, the prominence of open burning emission yielded short range aerosol transportation when fine and coarse aerosol particles were accumulated with the minimum and maximum average AODs of 0.2187 and 0.4291, respectively. In addition, the observation provided important insights into the physical and scavenging of aerosols under the influence of regional anthropogenic source and would be great knowledge of aerosol data development. By the lidar technique used in present work, the nocturnal AOD retrieval was advantageously available.

**Keywords:** Fernald Method, Lidar Technique, Aerosol Optical Depths, Biomass Burning

### 1. INTRODUCTION

During the past century, the amount of carbon dioxide in the atmosphere has increased by about 25% on account of human activities (fossil fuel/biomass burning) (IPCC, 1995; Meehl *et al.*, 1996). This has caused the surface temperature of the Earth to increase globally by about one Kelvin (Satheesh and Moorthy, 2005). In the recent years, both direct and indirect radiative influences of aerosols have continued to be one of the most significant sources of uncertainty in climate change. Also, changes in the greenhouse gas and aerosol content of the atmosphere affect the radiation balance of the climate system, it then will be useful for global environmental monitoring studies of anthropogenic aerosols especially by considering both their optical and physical properties.

Atmospheric aerosol optical depth is an important parameter for studies of atmospheric pollution, aerosol radiation-climate effects and so on (Qiu, 1998). Aerosol Optical Depth (AOD) is the extinction of light caused by atmospheric aerosols which exist in a variety of forms such as dust, fume and mist (Linyan *et al.*, 2008). AOD shows large spatial and temporal variations because of the various production, transport and removal processes and the prevailing meteorological conditions. Its values are related to concentration, size distribution and aerosol optical properties, since aerosol scattering varies in complicated manner depending on size distribution and indices of refraction of the aerosol particles (Iokibe *et al.*, 2005). It truly has an impact on climate and land surface environment in both regional and global scales, while

tropospheric aerosols, e.g., carbonaceous (black carbon and organic carbon), sulfate and soil dust have more influence on human health. On global basis, major source of carbonaceous aerosol is biomass burning (Reddy *et al.*, 2002). It is the burning of living and dead vegetation which includes the human-initiated burning for land clearing. Scientists estimate that humans are responsible for about 90% of biomass burning which releases large amount of particulates (solid carbon combustion particles) and gases, including greenhouse gas that helps warm the earth. Studies suggest that biomass burning has increased on a global scale over the last 100 years (NASA, 2001), yielding the deep impact on climate and human being.

Many methods have been proposed to retrieve AOD, several ground-based networks for aerosol optical properties have been operated in East Asia (Kim *et al.*, 2007) such as Aerosol Robotic Network (AERONET) sun/sky radiometer, SKYNET and the Asian Dust lidar Network (using Micro-Pulse lidar: MPL). Due to the direct aerosol effect on the earth's radiation budget in absorbing and scattering solar radiation, the investigation of AOD is usually performed during daytime using sunphotometer. However, the indirect aerosol effect plays a key role in physical and radiative properties of clouds. lidar technology is now mature enough to provide quantitative measurements of the optical properties of aerosols with high spatial and temporal resolutions and with a high level of accuracy (Pappalardo *et al.*, 2003). Recently, lidar is widely used as a tool for remote sensing of atmospheric aerosols and clouds (Reagan *et al.*, 1989).

## 2. MATERIALS AND METHODS

Although, there are several instruments for providing aerosol optical depth values, here in Thailand the lacks of instrumentation and available database for aerosol observation are persisted and constrained. The capability of Mie scattering lidar system installed in Phimai district, Nakhon Ratchasima Province, Thailand allows tropospheric aerosol observation from 6 m to 24 km height over 24 h. In the present work, we focus on AOD investigation for both diurnal and nocturnal periods particularly in the lower troposphere (0-4 km) whereas aerosols are condensed. The 24 hr dataset of 4 consecutive days during 17-20 February 2005 were selected because the farmers started the open biomass burning of agricultural wastes during harvest season, causing large amount of carbonaceous and soil dust

aerosols which was suitable to initially analyze clear and cloudy sky features and monitor aerosol optical property in Thailand.

### 2.1. lidar System and Observation

#### 2.1.1. Observation Site

**Figure 1** shows the location of Phimai district, Nakhon Ratchasima province ( $15^{\circ} 13' 0''$  N,  $102^{\circ}30' 0''$  E) where the lidar system was installed. It is about 300 km far-away from Bangkok. Phimai's major economic activity is agriculture in farming for example cassava, corn, rice, sugar cane and fruits. Due to 6-month long dry period and the local activities around Phimai, it is suitable for the anthropogenic aerosol study with an assumption that the man-made (biomass) burning is an important contributor to carbonaceous aerosol emission. Results of the retrieval of hourly instantaneous AODs from measured Mie lidar dataset (Ruangrungrrote *et al.*, 2008) had confirmed the reliability of retrieval algorithm and concluded that, there were extensive cassava cultivations as annual crop in Phimai region. It is also suggested that open biomass burning of agricultural wastes during harvest seasons can emit large amount of the mixture of carbonaceous and soil dust aerosols. Hence, the development of AOD retrieval database in Thailand is significantly required in order to observe nocturnal carbonaceous aerosol distribution and study their lifetimes in such region.

#### 2.2. Instrumentation

**Figure 2** shows the NIES Compact Mie scattering lidar system (Sugimoto, 2001) installed in Phimai, Nakhon Ratchasima province. The laser used in this lidar system is flashlamp pumped Nd: YAG laser with a second harmonic generator. A linearly polarized laser pulse with a wavelength of 532 nm is transmitted vertically into the atmosphere. The backscattered light from aerosols and clouds is received with a 20-cm Schmidt Cassegrain telescope. The receiver has a polarizing beam splitter to separate the backscattered light into two components, parallel and perpendicular to the transmitted polarization. Separated polarization components are detected with the two photomultiplier tubes. The output from photomultipliers yields an electronic signal proportional to the received light intensity. Hence, the lidar measures the backscattered intensity, which contains information on atmospheric optical properties, including the depolarization ratio, indicating the non-sphericity of aerosol particles.

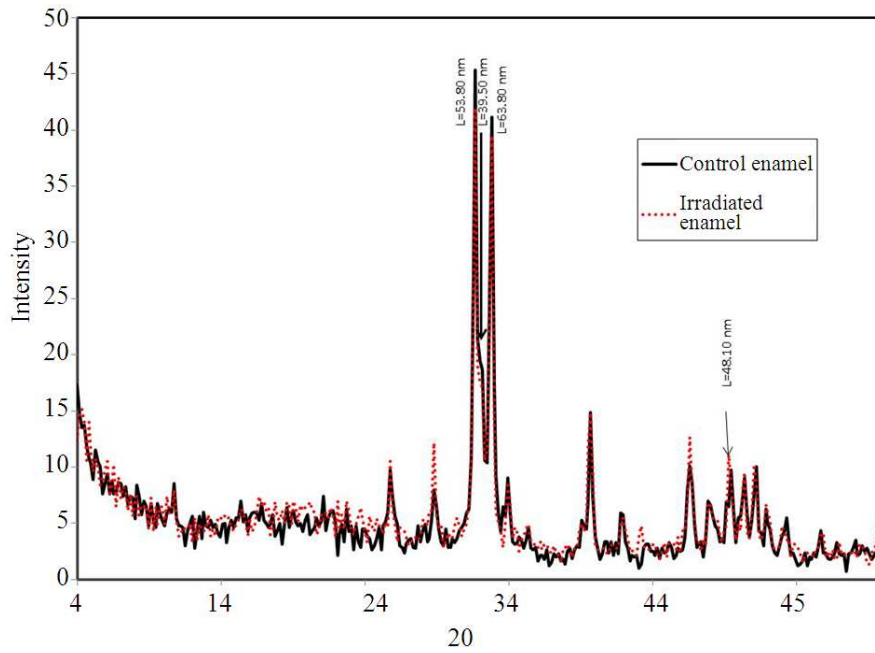


Fig. 1. The research site at Phimai district, Nakhon Ratchasima province

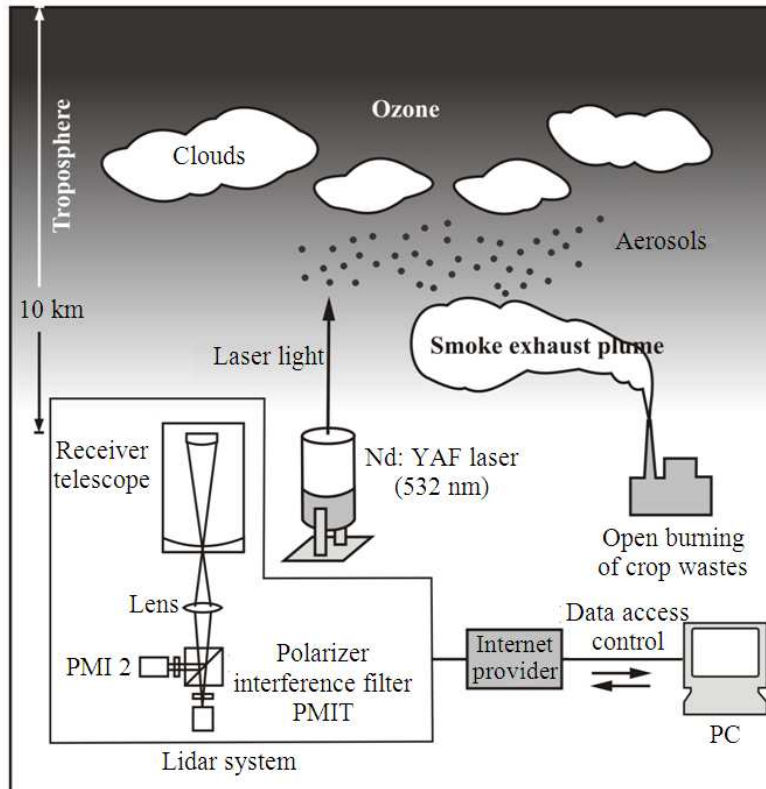


Fig. 2. Experimental setup for Mie scattering lidar

Mie scattering lidar was operated for a period of 5 min for every 15 min. After 5 min observation, the data was stored on the hard disk of the PC. Data from 6 m to 24 km were recorded with 6 m-height resolution over 24 h since most of atmospheric aerosol content is concentrated in the first few kilometers from ground level (Biral, 2003). The critical height ( $z_c$ ) which contains no aerosols, is suggested being as higher in the atmosphere as possible (Klett, 1985). Even though the consistency of aerosol observation can be performed from ground level up to stratosphere, the study of continental component as tropospheric aerosols was key objective. In this work,  $z_c = 15$  km was designated for aerosol-free layer within tropopause (Ruangrungrrote *et al.*, 2008) and high fluctuation of noise signals were detected beyond such height. Therefore, average of all returned lidar signals above  $z_c$  were calculated for a subtraction from the backscattered signals from 0- 4 km.

### 2.3. Retrieval Algorithm

#### 2.3.1. Particle Backscattering Coefficient

For a single-wavelength pulsed lidar and a vertically pointing lidar, the single scattering lidar equation can be expressed in the form:

$$P(z) = ECz^{-2} [\beta_a(z) + \beta_m(z)] T_a^2(z) T_m^2(z) \quad (1)$$

Where:

- $P(z)$  = Received power form height  $z$
- $E$  = Transmitted power from laser
- $C$  = Calibration constant of the instrument which includes losses in the transmitting and receiving optics and the effective receiver aperture
- $\beta_a(z)$  = Backscattering coefficient of aerosols at height  $z$
- $\beta_m(z)$  = Backscattering coefficient of atmospheric molecules at height  $z$
- $T_a(z) = \exp[-\int_0^z a_a(z) dz]$  = Aerosol transmittance
- $T_m(z) = \exp[-\int_0^z a_m(z) dz]$  = Molecular atmosphere transmittance
- $a_a(z)$  and  $a_m(z)$  and = Extinction cross sections of the aerosols and atmospheric molecules at height  $z$

The solution to Equation (1) for the aerosol backscattering coefficient  $\beta_a(z)$  can be determined using

the Fernald method (Fernald *et al.*, 1972; Fernald, 1984; Motoaki *et al.*, 2002) and given by equation:

$$\beta_a(z) = \frac{P(z)z^2 \exp \left[ -2(S_a - S_m) \int_0^z \beta_m(z) dz \right]}{P(z)z^2 \exp \left[ -2(S_a - S_m) \int_0^z \beta_m(z') dz' \right] - \beta_m(z)} \quad (2)$$

where,  $S_a = \frac{\alpha_a(z)}{\beta_a(z)}$  and  $S_m = \frac{\alpha_m(z)}{\beta_m(z)} = 8\pi/3$  sr, are the lidar ratios for aerosol and molecule, respectively. The value of  $S_a$  is assumed to be constant and independent of height in the calculation (Fernald, 1984). Here, the value of  $S_a = 35$  sr was used for dust aerosols (Karyampudi *et al.*, 1999). Then,  $a_a$  was calculated.

Now it is assumed that the aerosol backscattering coefficient at a specific height  $z_c$  (calibration height), i.e.,  $\beta_a(z_c)$  is known. Then, by solving Equation 2, the lidar equation can be expressed in the form:

$$\beta_a(z) + \beta_m(z) = \frac{X(z) \exp \left[ -2(S_a - S_m) \int_{z_c}^z \beta_m(z) dz \right]}{\beta_a(z_c) + \beta_m(z_c)} - 2S_a \int_{z_c}^z X(z) \exp \left[ -2(S_a - S_m) \int_{z_c}^z \beta_m(z') dz' \right] dz \quad (3)$$

where,  $X(z) = P(z)z^2$  is the range normalized signal at the heights  $z_c$  and  $z$ .

In this study,  $z_c$  is referred to critical height and set at 15 km which means that  $\beta_a(z_c) = 0 \text{ m}^{-1} \text{ sr}^{-1}$ . Next,  $\beta_m(z_c)$  was calculated, yielding  $\beta_m(z) = \beta_m(z_c)$  due to atmospheric homogeneity. By using Equation (3),  $\beta_a(z)$  could be obtained with the initial values of  $S_a$ ,  $S_m$  and the known  $X(z)$ .

#### 2.4. Depolarization Ratio

The linear depolarization ratio  $\delta(z)$  is the ratio of perpendicular polarized signal to parallel polarized signal as given by Equation (4) (Iokibe *et al.*, 2005):

$$\delta(z) = \frac{P_{\perp}(z)}{P_{\parallel}(z)} \quad (4)$$

where,  $P_{\perp}(z)$  and  $P_{\parallel}(z)$  are the received powers of the backscattered light (as a function of height  $z$ ) with linear polarization perpendicular and parallel, respectively, in respect of the transmitter polarization axis. The depolarization ratio is a measure of the non-sphericity of aerosol and cloud particles. Spherical particles like water droplets cause no depolarization ratio with  $\delta = 0$ , whereas non-spherical particles, such as ice clouds and mineral dusts do produce depolarization, so that  $\delta > 0$ .

Thus the depolarization ratio describes degree of polarization which can be used to distinguish aerosols from clouds and classify their types in atmospheric science applications. Clouds with  $\delta < 0.15$ , are classified as water clouds. Depolarization ratio of clear air is low and affected by photon counting statistics, while depolarization ratio measurements are induced by presence of multiple scattering of dense clouds. The change from ice to water is noticeable as a drop in the depolarization ratio.

## 2.5. Aerosol Optical Depth

The aerosol lidar ratio ( $S_a$ ) is proposed to be constant and independent of height (Fernald, 1984). From the relation of  $a_a(z) = S_a(z) \beta_a(z)$  where both values are known and assumed to be constant for every 6-m height resolution, the  $a_a(z)$  could be solved. Aerosol Optical Depth ( $\tau_a$ ) corresponds to the path length ( $\xi$ ), defining in terms of Equation (5):

$$\tau_a = \int_0^{\xi} \alpha_a(z) dz \quad (5)$$

The condition of constant AOD for every 6-m height was also introduced to determine hourly  $\tau_a$ . The vertical profiles of  $X(z)$ ,  $\delta(z)$  and  $\beta_a(z)$  are plotted to indicate different features between cloud and aerosol for both clear and cloudy skies. Since the cloud layers have apparent sharp peak of all three parameters due to large multiple scattering, yielding the selective path length for aerosol region identification below cloud layers. Specifically, the maximum peak of aerosol backscattering coefficient could be used to analyze optimal path length for the implicit cloud appearance.

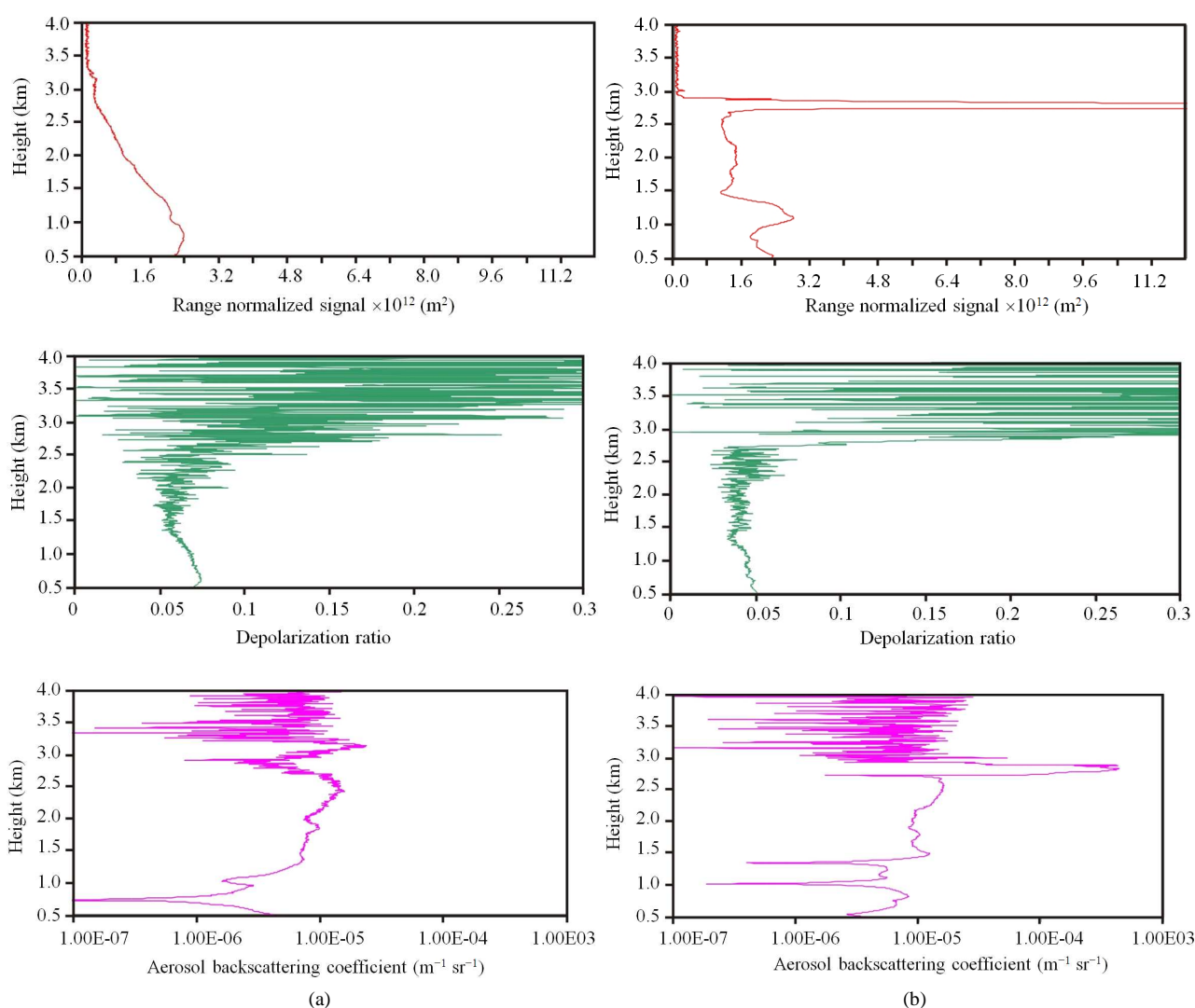
## 3. RESULTS AND DISCUSSION

**Figure 3** shows the typical results of vertical profiles at a height below 4 km of  $X(z)$ ,  $\delta(z)$  and  $\beta_a(z)$  for clear sky at 12.00 and cloudy sky at 21.00 on 19 February 2005. It is noted that all vertical profiles of three

parameters, can distinguish aerosol and cloud layers and provide the optimal path length ( $\xi$ ) for 24 h AOD determinations. For clear sky condition in **Fig. 3a**, large depolarization ratio around 0.25 of the coarse aerosol particles is noticeable above 2.5 km high with a confirmation of sharp peak  $\beta_a$  at 2.8 km as the optimal path length ( $\xi$ ) for AOD determination. For cloudy sky in **Fig. 3b**, the sharp peaks of three parameters caused by multiple scattering from cloud base above 2.5 km is observed, giving the path length ( $\xi$ ) at 2.5 km with  $\delta(z)$  less than 0.1 of existed fine soil dust aerosols.

Dataset of 4 consecutive days during 17-20 February 2005 representing the biomass burning contribution by the locals, was further investigated in order to monitor aerosol lifetime. **Figure 4** shows daily temporal and height cross sections of  $\delta(z)$  and  $\beta_a(z)$  with color scales. The higher value  $\delta(z)$  of coarse aerosol particles drifted in the atmosphere shows similar trend as discussed on **Fig. 3a**. This represents an evidence of aerosol loading caused by anthropogenic source which can be considered as a group of large emission of soot aerosols (carbonaceous aerosol as black and organic carbons) resulted from open burning of crop wastes in the immediate vicinity. Values of  $\beta_a(z)$  in the order of  $10^{-5}$  and  $10^{-6} \text{ m}^{-1}\text{sr}^{-1}$  are related to cloud and aerosol, respectively (Iokibe *et al.*, 2005). In **Fig. 4**, the  $\beta_a(z)$  of  $4 \times 10^{-6} - 3 \times 10^{-5} \text{ m}^{-1}\text{sr}^{-1}$  with  $\delta(z)$  of 4-5% illustrate the dark blue islands of lower coefficients of  $\beta_a(z)$  in the green sea of higher  $\beta_a(z)$ . This implies that high value of obtained atmospheric column AODs were composed of a mixture of biomass burning and soil dust aerosols.

Finally, daily average of AODs ( $\tau_a$ ) in the same period are reported in **Table 1** with the minimum of 0.2187 and maximum of 0.4291. These correlate to the continental polluted aerosol of 0.327 AOD, predicted by the software OPAC (Hess *et al.*, 1998). **Figure 5** shows both diurnal and nocturnal AODs in an attempt to display the specific appearances when the distinct evidences were observed. The aerosol populations are noticeable of high AODs up to 0.6-0.7 of larger size aerosol and later being declined during late nights. During 17-18 February 2005, there existed quite low AODs in comparison with the other two days, while their depolarization ratios were high due to coarse aerosols. Meanwhile, AODs were rather high on 19-20 February 2005 with low depolarization ratios due to dense fine aerosols. The prominence of open biomass burning emission during this period would result in short range aerosol transportation as seen in a day by day accumulation of fine and coarse aerosol particles.



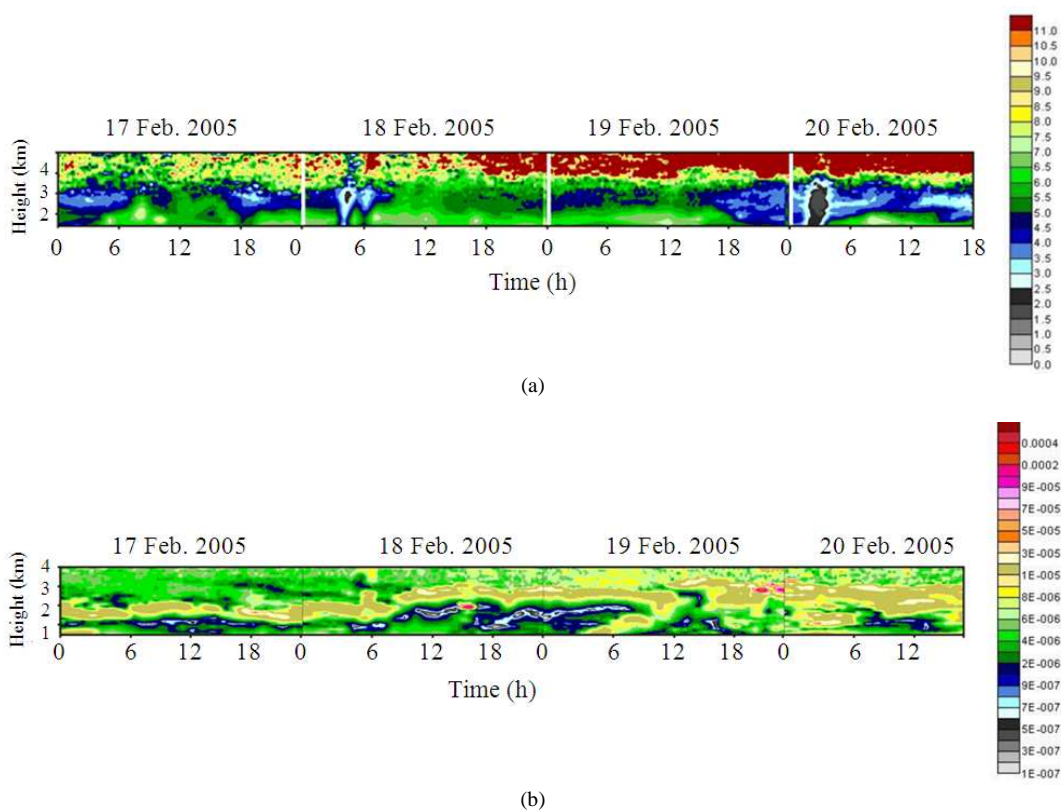
**Fig. 3.** The 19 February 2005 vertical profiles of range normalized signal, depolarization ratio and aerosol backscattering coefficients at: (a) 12.00 and (b) 21.00 LST, respectively

**Table 1.** Daily average of  $\tau_a$  for 4 consecutive days from 17-20 February 2005

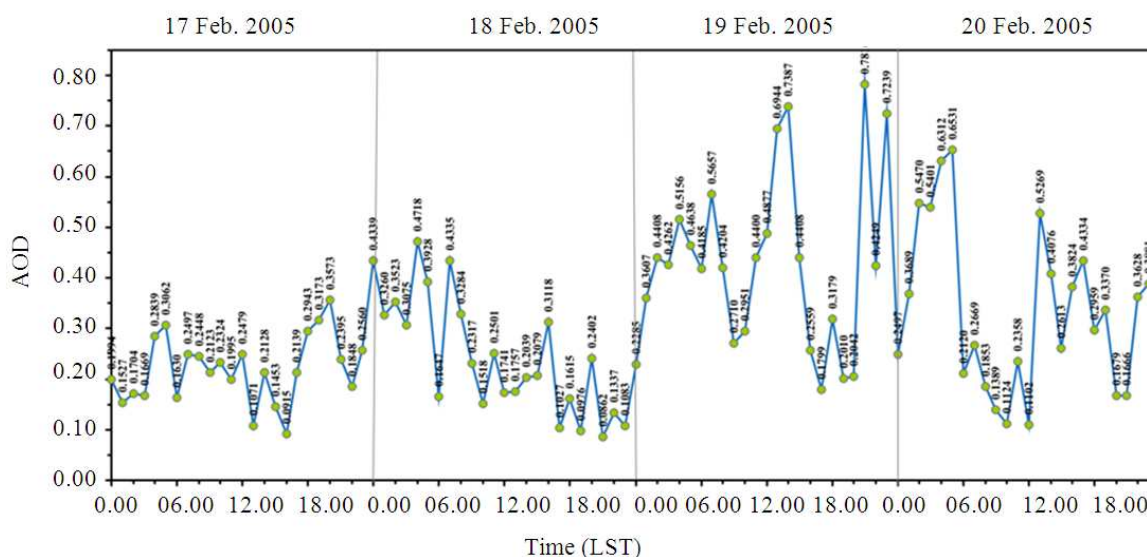
Date in February 2005	Daily average of $\tau_a$
17th	0.2187
18th	0.2437
19th	0.4291
20th	0.3326

To be more specific, in the junctions of 3 adjacent days during 18-20 February 2005, the transports of aerosol appeared and AODs rose in the first half of the day, later

dropped off during the midday and rose again in the afternoon so the same behavior did in the evening and late night. Importantly, from the 19-20 February 2005 results, it implied that the lifetime of biomass burning aerosols was slightly short within few hours since their depolarization ratios decreased from 18.00 pm onwards. This caused by the effects of daily biomass burning emission due to farmer’s routine behaviors and the practice of villagers to light open campfires for making warm and expelling insects during winter nights as being confirmed by each bump of high green depolarization ratios in **Fig. 4**.



**Fig. 4.** Daily temporal and height cross sections of: (a) depolarization ratio and (b) aerosol backscattering coefficients on 17-20 February 2005 are shown with color scales



**Fig. 5.** 24 h atmospheric column of AODs retrieved from Mie lidar dataset for 4 consecutive days from 17-20 February 2005

The obtainable results suggested that the lifetime of soot aerosols would last only for few hours when should possibly be the actual lifetime of aerosols. It might be under the influence of wind effect and nighttime high relative humidity yielding an increment of the extinction efficiency which had a partial effect on AOD enhancement.

#### 4. CONCLUSION

In summary, the depolarization ratios of various periods are very interesting aspect for a classification of aerosol size distribution and cloud trend. The observation of either short lifetime or wind effect of carbonaceous and soil dust aerosols will be achievable if longer periods of retrievals are obtained. Yet, this work is preliminary for a validation of analytical retrieval algorithm and alternatively providing 24 h atmospheric column of AOD by the available Mie lidar at wavelength 532 nm in the region where aerosol data are sparse. It then would be useful for atmospheric science study in order to obtain the comprehension on aerosol characteristics in Thailand. For future work, we intend to create a software program for a custom lidar calculation especially for aerosol lidar ratio determination in order to profoundly study the characteristic of tropospheric aerosols in Thailand.

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