Haze event monitoring and investigation in Penang Island, Malaysia using a ground-based backscatter Lidar

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Abstract. During 24th July 2013 to 1st August 2013, a haze event struck Penang Island, causing the visibility to decrease and increase in Air Pollution Index (API). A ground-based backscatter Lidar, operate at 355nm which was setup at the roof top of the School of Physics, Universiti Sains Malaysia. It was used to monitor and investigate the haze event. For this work, we studied the daytime variation of the aerosol intensity, distribution, planetary boundary layer (PBL) height and the aerosol optical depth (AOD) values during these days. We found that the aerosol are very intense during the first two days of the haze event and slowly decline as time passed. Finally the haze event died off on 1st August 2013. As for daily aerosol distribution, aerosols are generally more intense during the afternoon. Its intensity is slightly lower in the morning and evening. Similar trends were observed for AOD values as they increase from morning to afternoon and slowly decrease in the evening. Most aerosols are found contained below the PBL which generally found at around 1000 - 2000 m in height.

1. Introduction

During the past 20-30 years, haze events caused by trans-boundary biomass burning smoke increased significantly in the Southeast Asia region. The haze event occurs recurrently every year during the dry season, typically around June to September. This biomass burning smoke usually comes from forest clearance using fire which goes rampant and developed into uncontrollably burning wild-fires [1]. The smoke is then transported by the Southwest monsoon across the boundary into other countries.

In June 2013, a serious haze event struck Peninsular Malaysia. The air pollution index (API) reported by the Department of Environment Malaysia (DoE) rose rapidly and reaches unhealthy and very unhealthy levels within a few days especially in the central and southern part of Peninsular Malaysia. It is worth to mentioning that in Muar, a city in the south of Peninsular Malaysia had an API reading on 23rd June 2013 that even exceeds 700, which is categorized in hazardous level according to the DoE official web site (http://apims.doe.gov.my/apims/). However, northern part of Peninsular Malaysia such as Penang was less affected by haze. The API generally maintained at healthy level until the mid of June. After that, the API readings in Penang Island start to fluctuate around healthy, moderate and unhealthy level. Generally, haze was found in the atmosphere when the API readings hike up to moderate and unhealthy level. This situation continued until the end of August.

Haze event are generally highlighted by the high concentration of aerosols suspended in the air. A collection of particles, either solid and/or liquid suspended in a gas is the simplest form of aerosol. Many daily events such as smoke, smog, fume, dust, haze, fog, mist, and cloud are considered as aerosol [2]. In terms of radiative forcing of Earth's climate, aerosol will affect the Earth's radiation balance directly by absorb and scatter incoming and outgoing radiation, depending on the aerosols'

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chemical composition. Indirectly, the aerosols will act as cloud condensation nuclei (CCN) and hence altering the concentration of initial droplets, albedo, precipitation formation and lifetime of the clouds. Aerosols may comes from both natural sources, such as volcanoes, sea salts, storms, and air-borne dust, as well as anthropogenic sources such as fossil fuels combustion, biomass burning and gas-to-particle conversion process. [3-6]. Aerosol generally shows high spatial and temporal variation, depending on the emission and dispersion process, chemical evolution, as well as meteorological process. Hence, high spatial and temporal resolution measurements, such as Lidar are very useful in air quality research [7].

Recently, more and more research has been carried out using Lidar to study the atmosphere. For example, Lidar and ceilometers were used to obtain aerosol and PBL profile over Athens, Greece. Good agreement with the results were obtained from both instruments as stated in [8]. Next, two micro-pulse Lidars were used to study the properties of atmospherics aerosol vertical distribution in Lanzhou China as stated by [9]. The aerosol was found to be distribute quite evenly in the lowermost two km of atmosphere. Then their concentration gradually decreased with increasing height. Lidar is also one of the popular instruments to study dust transportation in many area around the world. In Greece, Lidar were to study the Saharan dust layer over Athens [10]; while on the other side of the globe, a group of researchers did a case study on dust aerosol radiative properties in Lanzhou, China [11].

In this study, we use a ground based elastic backscatter Lidar to monitor and investigate the haze event. During the operation of the elastic backscatter Lidar, a collimated laser beam is emitted into the atmosphere. Then, the laser beam will undergo multiple scattering processes in the atmosphere before returning to the Lidar sysem. A telescope, usually set up in a coaxial or biaxial configuration with respect to the laser emitter will capture the return signal (or so called backscatter signal in Lidar terminology). Due to the high temporal (in terms of seconds) and spatial (3-15 m) resolution of the Lidar system, it is very useful in visualizing the vertical distribution of aerosols, as well as the instantaneous PBL structure by using aerosols as passive traces [3-5, 12]. Hence, the Lidar system is used during the haze event to monitor the changes of a few parameters such as aerosol backscatter coefficient (β_{aer}), AOD, and PBL height.

AOD was chosen as one of the parameter to monitor because AOD is a measure of the degree of light extinction by aerosol through absorption or scattering in the atmospheric column [13]. Light scattering and absorption by aerosols will diminish the solar radiation and limit the visual air quality. Consequently, visibility will be reduced and the air quality will decrease. This makes the AOD an important parameter to measure [6]. On the other hand, PBL is the lowermost sub-layer of the troposphere. It is directly affected by the earth and solar radiance, as well as the anthropogenic activities on the earth's surface [8]. Moreover, heat and moisture from the earth's surface must first be well mixed before circulating in the free troposphere. Thus, aerosol concentrations in the PBL are generally higher compared to that in the free troposphere [8, 14]. Generally, most aerosols are concentrated in the PBL, since the PBL is in direct contact with the ground. Nearly all aerosol sources are coming from ground level [15]. Hence, PBL height data are vital in atmospheric dynamics studies [8].

Since the 2013 haze event in Malaysia can generally consider as a recurrence event, it is thoroughly important to study and obtain data which can help further understanding of the aerosol emission and dispersion, as well as its effect on regional and global climatology. The main objective of this study is to monitor the life of the haze event and investigate it using parameters such as aerosol backscatter coefficients, AOD and PBL height obtained from a ground-based backscatter Lidar.

2. Instrumentation

2.1 Lidar System
An eye-safe ground based backscatter Lidar system, model no. LB100-ESS-D200, manufactured by Raymetrics SA was setup on the roof top of the School of Physics, Universiti Sains Malaysia, Penang.

The location are shown in Figure 1. This elastic backscatter Lidar system are capable of profiling aerosols and clouds by transmitting laser pulses into the atmosphere and measured the return time of the backscatter signal. It is operate with a Nd:YAG pulsed laser that emit 355nm laser beam into the atmosphere. The pulse duration is 5.04ns, the energy emitted in each pulse is 33.4mJ with 20Hz repetition rate. The returned signal is then collected by a Cassegrain telescope with a diameter of 200mm, 1mrad field-of-view and a complete overlap height of 180m. The captured signal is then spectrally analyzed, filtered and focused on a photon multiplier tube (PMT), with a corresponding spatial and temporal resolution of 7.5m and 1 minute respectively. Next, the current generated from the PMT will be detected by the Licel transcient recorder and the analog Lidar signal is obtained and recorded. By using a combination of a powerful A/D converter (12 Bit at 40 MHz) with a 250MHz fast photon counting system, the photon counting Lidar signal is obtained and recorded.
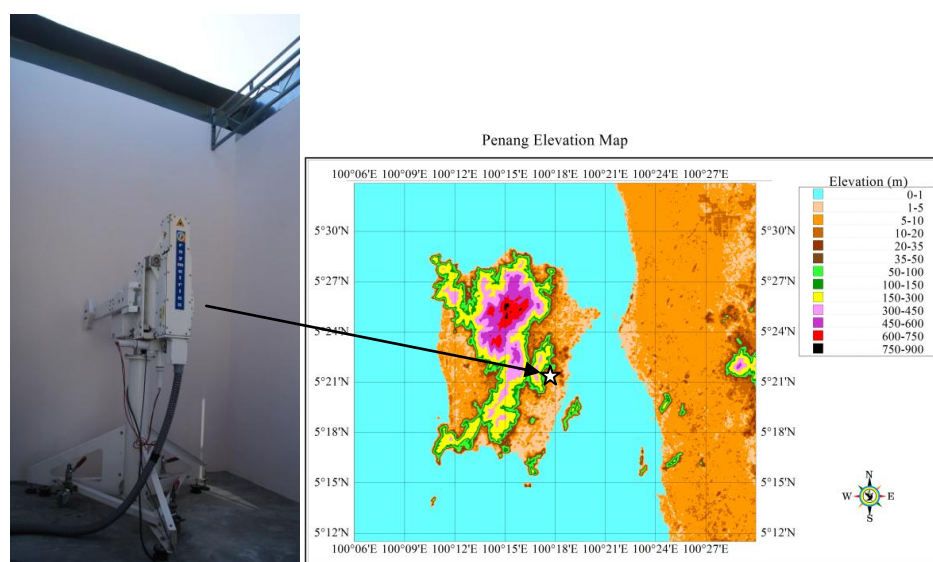

Figure 1: Topographic map produced from the global digital elevation model (GDEM) showing the high-mountain and low-plain regions in Penang. Five-edge star is point to the study site (Universiti Sains Malaysia, USM) where the Lidar system was deployed.

3. Methodology

3.1 Data Acquisition
The Lidar system was set to shoot at zenith on every weekday except on rainy day or public holiday. The acquisitions start from 0200 UTC to 1000 UTC, which correspond to 1000 to 1800 Malaysia local time. The Lidar system was set to an average of 1200 shots into a data file, which means that one data file will be produced every minute.

3.2 Data Pre-processing
The acquired data was being processed using Lidar Analysis.exe, which is the processing software provided by Raymatrics SA. Before starting the data processing, the usage of analog signal, photon counting signal or glued signal has to be determined, according to the conditions stated in [16]. Then, the background radiation is subtracted from the Lidar signal. If the photon counting signal or the glued signal is used, dead-time correction has to be further applied to the photon counting signal as given by [17]. Next, the range corrected signal (RCS) is obtained by applying the distance square law correction (z^2) to each data point to compensate for range-related attenuation from the atmosphere. After that, the temporal evolution of the RCS is plotted. This plot shows the general view of the atmospheric

conditions. Days with strong backscatter signals from the lower atmosphere, typically below 2000 m is selected and identified as hazy days. In this case, the hazy days lasted from 24/7/2013 until 1/8/2013.

3.3 Data Processing
When the pre-processing is completed, the aerosol backscatter coefficient (β_{aer}) is calculated with the aid of the Lidar Analysis.exe software. Here, the Klett inversion technique was used to retrieve the aerosol backscatter coefficient [18]. This was done using a simple numerical integration from the reference height until ground level (inward stepwise integration) since this method is more stable [19]. The reference height is a height where almost no aerosol backscatter signal is found, and the backscatter signal is mostly molecular [20]. To use the Klett inversion technique, an assumption has to be made on the Lidar ratio of the studied aerosol. In this case, the Lidar ratio was assumed to stand at 40 sr and remain constant throughout the haze periods. Although a Lidar ratio of 40 sr is slightly lower than the Lidar ratio for Southeast Asia aerosols and biomass burning aerosols, as stated by [21] and [22], but since Penang is a highly urbanized and industrialized city on an island, so that a certain degree of mixing between marine aerosols, Southeast Asia aerosols, as well as the biomass burning aerosols is expected, causing the Lidar ratio to be lower than the value suggested in the literature. After the aerosol backscatter coefficient was calculated, the temporal evolution of the aerosol backscatter coefficient was plotted.

Next, the hourly PBL height and hourly AOD were calculated. To determine the PBL height, the data files at each hour were selected. The Inflection Point Method (IPM) proposed by [14] was applied, where the minimum of the second derivative of the RCS gives the PBL height.

In addition for hourly AOD, the average light extinction effect by aerosols throughout a particular hour, assuming the aerosol loading in the atmosphere do not change very much throughout that hour was taken into account. Hence, the data files need to be averaged for that particular hour and AOD was calculated by formula below

$$AOD = \int_{R_0}^{R_{max}} \alpha_{aer}(r) dr \qquad (1)$$

where R_{max} is the reference height, R_0 is the height where the overlap is complete and α_{aer} is the aerosol extinction coefficient and α_{aer} is given by

$$\alpha_{aer} = L_{aer} * \beta_{aer} \qquad (2)$$

where L_{aer} is the aerosol Lidar ratio and β_{aer} is the aerosol backscatter coefficient.

4. Results and Discussion
The study period start from 24th July 2013 and end on 1st August 2013. A total of six daily measurements had been made during the study period, while the remaining days falls on weekends and public holiday where the Lidar is not operating. These measurements cover the whole life cycle of the haze event, starting from where the haze starting to be detect, right until the haze dies off. During these six days, significant differences in the aerosol distribution pattern are found during the haze event compared to the day where the haze dies off. This changes in aerosol distribution pattern will change the Earth radiative forcing and cloud formation in our atmospheric column, which ultimately will affect local and regional climate.

Aerosols are generally contained in the PBL, the first step was to determine the PBL height during the study period. Using the inflection point method suggested by [14], where the minimum of the second derivative of the RCS will provide information on the PBL height. The calculated PBL heights, in meter are shown in Table 1. Generally the PBL is located below 2000 m in height and will increase its height from morning to afternoon. Then its height will slowly decrease when approaching evening. This means that more aerosols will be loaded in the atmosphere in the afternoon compared to morning and evening.

Table 1: PBL height (m) evolution during the study period

Date/Time	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00
24/07/2013	1450	1370	1760	1190	1100	1020	1400	1270
25/07/2013	600	960	960	1120	1240	1330	1180	1450
29/07/2013	540	580	920	820	990	900	840	640
30/07/2013	470	930	1040	1400	1140	1060	1150	1090
31/07/2013	580	1390	1110	810	1100	700	630	1330
01/08/2013	400	340	340	440	840	740	300	560

Figure 2 shows the temporal evolution of the aerosol backscatter coefficient for the study period and the black colour line indicates the PBL height. Each calculated PBL heights are plotted in respective profiles at respective time, while PBL heights at other times are extrapolated. From the profiles, the daytime aerosol distribution pattern and the intensity of the aerosol loading in the atmosphere can be observed. During the study period, aerosols were generally contained under the PBL, except for 30th July 2013, where a residual layer was found above the PBL around 0200 UTC to 0300 UTC. This residual layer had a very low concentration of aerosols, given by the low backscatter coefficient and was very short lived. Hence it was suspected that a convection effect was responsible for making the aerosol load higher than the PBL and it slowly decent and mixed together with other aerosol in the PBL. Next, on 24th and 25th July 2013, there was a thick aerosol layer loaded under the PBL. This thick aerosol layer indicated that the amount of aerosol loading in the atmosphere was very high, which was further supported by the high aerosol backscatter coefficient on these two days. This also shows that the haze event was serious on these two days. Then, it was followed by two slightly clearer days on 29th and 30th July 2013, where the aerosol backscatter coefficients were quite low under the PBL. After that, the haze returned again as the amount of aerosol in the atmosphere again increased on 31st July 2013. However, the amount of aerosol loading in the atmosphere at this day was not as high as the first two days since the aerosol backscatter coefficients were not as high as those obtained during the first two days. The aerosol layer was thinner compared to the first two days. Finally, on 1st August 2013, only a thin layer of aerosols was found loading in the atmosphere with low aerosol backscatter coefficient, which indicated that the haze had finally died off.

Moving on to daily aerosol distribution, aerosols were generally distributed under 2000 m in height, which was bounded by the PBL. Relatively heavily polluted days will have a higher PBL height compared to the mildly polluted days as shown in Figure 2. For example, 24th, 25th and 31st July 2013, which were heavily polluted days; its PBL height was generally maintained around 1000 to 1500m in height. As for mildly polluted days, the PBL height was maintained around 500 m to 1000 m in height, as shown in profiles for 29th and 30th July 2013. Compared to polluted days, a clear day has an even lower PBL height. For example, on 1st August 2013, after the haze died off, the PBL height was generally found at 500 m height which is very close to the Earth surface. As for daily aerosol distribution, it is much dependent on the PBL height. During the study period, most of the aerosols were contained under the PBL, except when there was a residual layer. Hence the aerosol layer generally will increase its height together with the PBL from morning to afternoon and decrease its height together when approaching evening, unless the residual layer exist and cause the aerosol layer load to be higher than the PBL, as shown in aerosol backscatter profiles for 30th July 2013 from 0200 to 0300 UTC.
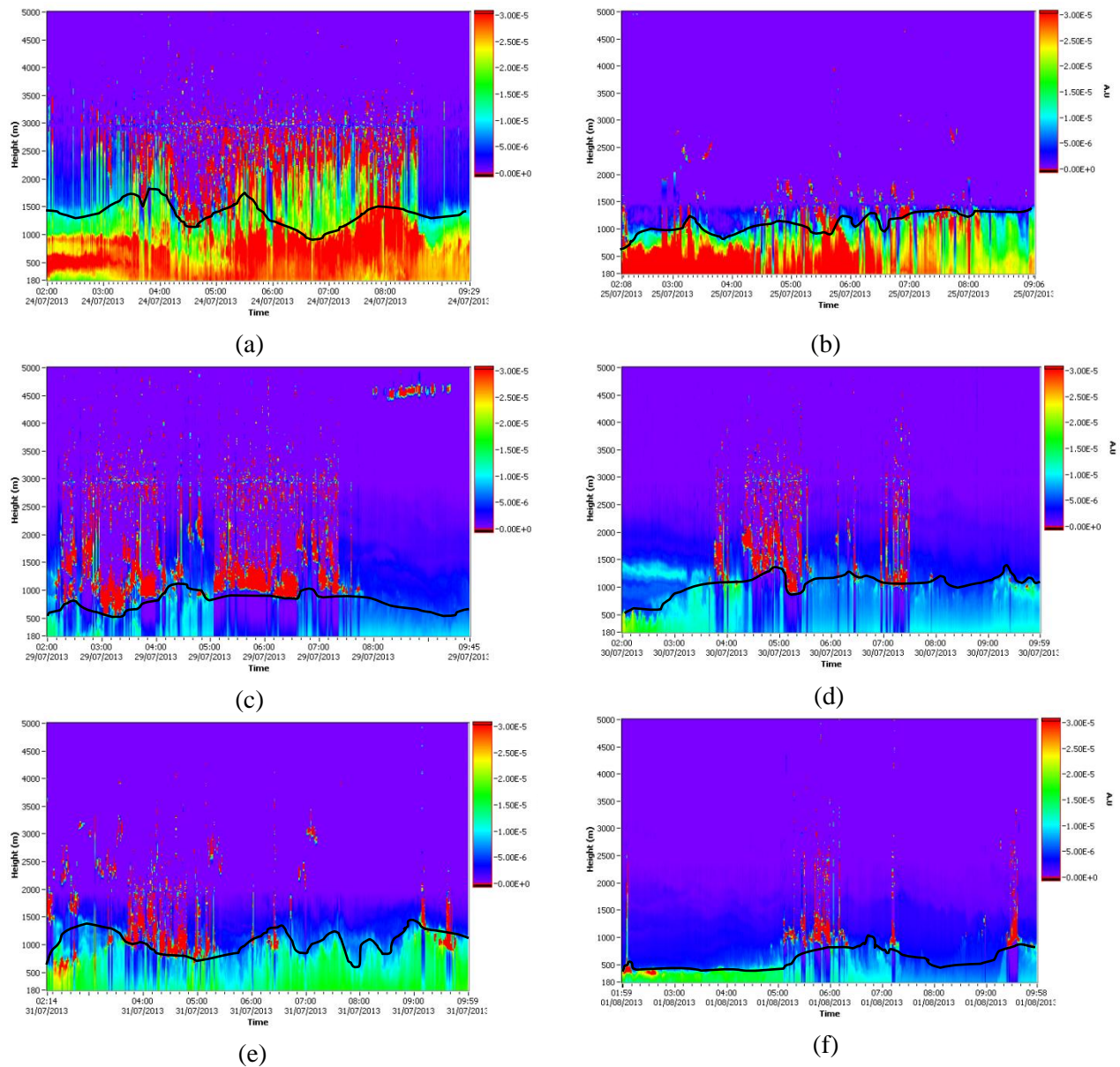
Figure 2: Temporal evolution of aerosol backscatter coefficient (m^{-1} sr^{-1}) on 24th July, 25th July, 29th July, 30th July 31st July and 1st August 2013. The black colour lines indicate the PBL height.

Figure 3 shows the vertical profiles of aerosol extinction coefficient. Based on the profiles, the aerosol extinction coefficient was decreasing very fast with increasing height. This proves that there was lesser and lesser aerosol with increasing height. It was found that the aerosol extinction coefficient is very low beyond 2000 m in height, which means that aerosols generally contained below 2000 m in height and only minor aerosols exist beyond that height. This suggests that most aerosols are concentrated under the PBL since the PBL height listed in Table 1 does not exceed 2000 m in height. As shown in Figure 3, the aerosol extinction coefficient for 25th July 2013 at 0235 UTC is the highest, followed by that of 24th July 2013 at 0305 UTC and 31st July 2013 at 0305 UTC. However, the aerosol extinction coefficient profile for 25th July 2013 at 0235 UTC is slightly different from that on 24th July 2013 at 0305 UTC and 31st July 2013 at 0305 UTC. The aerosol extinction coefficient for 25th July 2013 decreased very fast after 500 m in height and dropped even lower after exceeding 1000 m in height. For 24th July 2013 at 3.05 UTC and 31st July 2013 at 0305 UTC, the aerosol extinction

coefficient started to drop around 1000 m in height and fell to a very low aerosol extinction coefficient value at 2000 m. This shows that on 24th and 31st July 2013, the aerosol layer had a thickness around 2000 m, but for 25th July 2013, the aerosol layer was thinner where its thickness was just around 1000m. Besides that, on 25th July 2013, aerosols were loaded very low at a height around 700 m, given by the high aerosol extinction coefficient up to this height. Compared to 25th and 31st July 2013, the aerosols were loaded higher in the atmosphere, up to around 2000 m in height, given by the relatively high aerosol extinction coefficient value up to this height. However, the light extinction capability of the aerosol at 25th July 2013 was much higher than that at 24th July 2013 and 31st July 2013, given by the relatively higher aerosol extinction coefficient in the lower atmosphere compared to the other two days. This suggested that the aerosols may undergo a characteristics change from 24th to 25th July 2013 or there might be an aerosol intrusion during night time on 24th July 2013 when the Lidar was not operating and the aerosols were completely mixed up with local aerosols by the next morning. On 30th July 2013 at 0220 UTC, the aerosol extinction coefficient profiles had two peaks, one at around 500 m in height, and the other one at around 1300 m in height. This demonstrates that there were two aerosol layers presented during that particular time, which agrees well with what is shown in Figure 2.
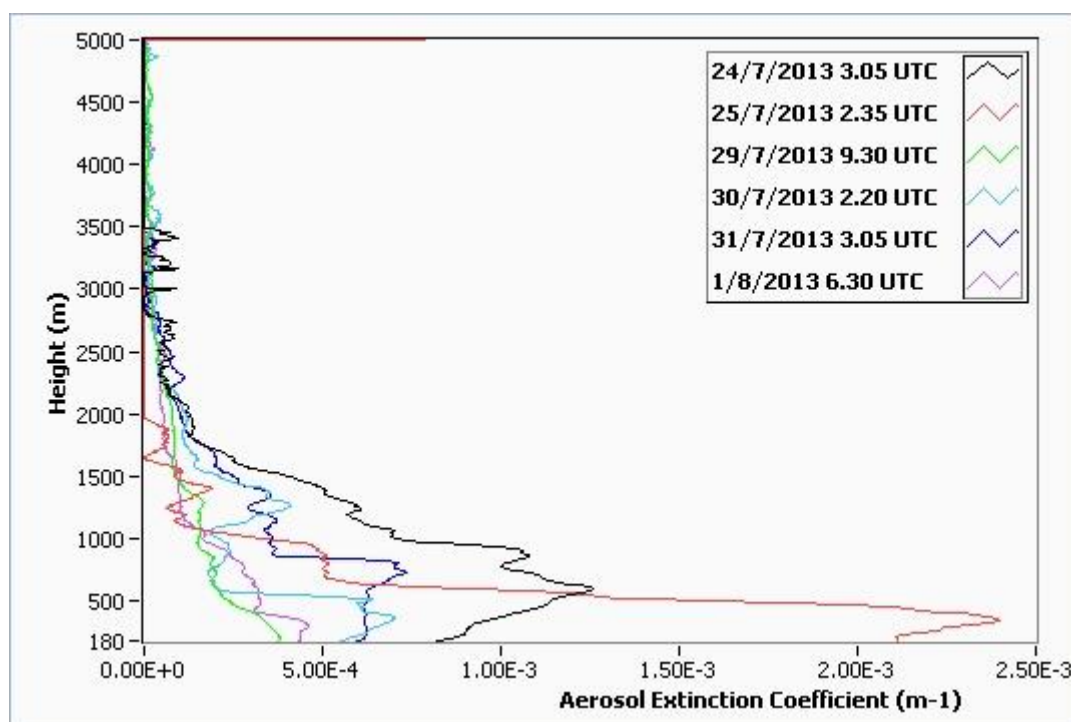

Figure 3: Aerosol extinction coefficient profiles (m^{-1}) for six different selected days and time during the study period.

Figure 4 displays the hourly AOD during the study period. Higher AOD generally means that there are more aerosols in the atmosphere, because these aerosols will obstruct the transmission of light either through absorption or scattering process. However, clouds are also considered as aerosols. Light will undergo a high degree of extinction when passing through clouds, causing an extremely high AOD. In the Southeast Asia region, AOD reading lower than 0.3 usually means that there is only minor aerosol contained in the atmosphere, while AOD reading higher than that represents polluted air. AOD reading higher than 2.0 is usually caused by cloud contamination. Based on Figure 3, 24th and 25th July were days with highly polluted air, marked by the high AOD reading. Then, 31st July 2013 was the day with moderately polluted air, as given by the lower AOD reading compared to 24th and 25th July 2013. Next, 29th and 30th July 2013 were days with slightly polluted air, stated by the low

AOD reading. Finally, 1st August 2013 was the day that the haze died off, as the AOD reading was very low. The hourly AOD distribution also showed a general view on how the aerosols were distributed in the atmosphere. Although the AOD distribution did not show a similar trend over the study period due to difference in aerosol concentration over the study period, but relatively high AOD was generally found at the afternoon, and lower AOD was found during the morning and evening, except that particular day was a highly polluted day, where high amount of aerosols were loaming around the sky all the time, causing the AOD to remain very high all the time. The AOD distribution trend means that more aerosols are distributed in the atmosphere during the afternoon compared to morning and evening. However, this pattern is similar during hazy days or a clear day. Although the AOD distribution trend might look similar to the PBL height evolution trend, but both trends are not identical. This is because AOD is a measure of the degree of light extinction in the atmospheric column by aerosols and it is much dependent on the types and composition of aerosol, as well as the age of the aerosol. However, PBL is more affected by the heat from the Earth and the sun, as well as the anthropogenic activity on the Earth surface. Direct heat from the sun during the afternoon together with peak human activity at that time will cause the PBL load higher than in morning and evening. Moreover, PBL is just a sublayer in the atmosphere where the aerosol concentration is a few magnitudes higher than that in the free troposphere, but the aerosols in the free troposphere is not negligible. These aerosols still contribute a significant value to the AOD reading causing the daily AOD trend to be different from the PBL height evolution trend.
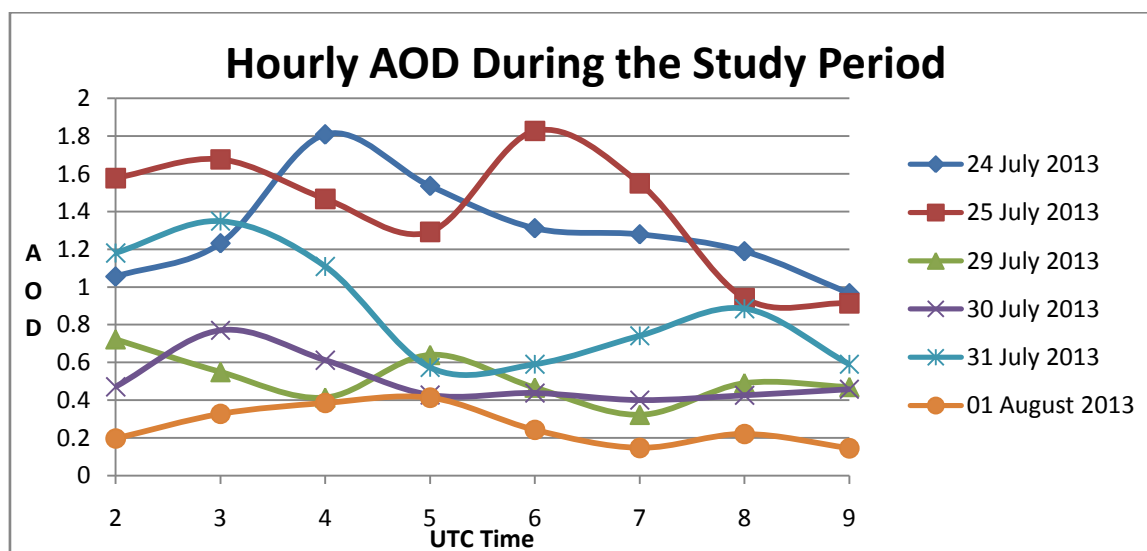

Figure 4: Hourly AOD Obtained using Lidar during the Study Period

5. Conclusion

In this study, a ground-based backscatter Lidar was used to study the haze event at Penang Island from 24th July to 1st August 2013. The PBL was found at a higher height in hazy days compared to the clear day after the haze dies off. Both the temporal evolution of aerosol backscatter coefficient and hourly AOD reading showed that high amount of aerosols were loamed under the PBL during the haze, particularly on 24th, 25th and 31st July 2013. These readings also showed that more aerosols were loaded in the atmosphere at morning and afternoon compared to evening, regardless of the atmospheric conditions. Overall, results from this study provide important results on aerosol variation and distribution during a haze event which is essential to future study on aerosol emission, growth, transportation and dispersion in Southeast Asia region. Future study should involve a synergy measurement which combines different in situ data such as particulate meter data, sunphotometer data, and satellite data into a more comprehensive result that allow us to study the haze event in details.

6. Acknowledgement

7. References

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