Comparison of Aerosol optical depth (AOD) derived from AERONET sunphotometer and Lidar system

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Abstract. Aerosol optical depth (AOD) is the measure of aerosols distributed within a column of air from the instrument or Earth’s surface to the top of the atmosphere. In this paper, we compared the AOD measured by the Raymetrics Lidar system and AERONET sunphotometer. A total of 6 days data which was collected by both instruments were compiled and compared. Generally, AOD value calculated from Lidar data are higher than that calculated from AERONET data. Differences and similarities in the AOD data trend were observed and the corresponding explanations were done. Level 1.5 data of AERONET is estimated to have an accuracy of ±0.03, thus the Lidar data should follow the trend of the AERONET. But in this regards, this study was conducted less than one month and was very difficult to justify the differences and similarities between AOD measured by the Raymetrics Lidar system and AERONET sunphotometer. So further studies for an extended period will be needed and performed with more comprehensive LIDAR measurements. The slope of the best-fit straight line for the data points between the AOD values retrieved from LIDAR and the AERONET measurements is the closest to unity and the coefficient of determination is high (above 0.6692). Factors which affect AOD data were discussed. As a conclusion, the trends of the AOD of both systems are similar. Yet due to some external factors, the trend will be slightly different.

1. Introduction
In the atmosphere, there are atmospheric aerosols which play a very important role in most atmospheric processes, such as the air quality, visibility, clouds, precipitation and chemical processes. Aerosols originate from natural (sea salts, air-borne dust, volcanoes, and storms) and anthropogenic sources (fossil fuels combustion, biomass burning and gas-to-particle conversion) [1], [2], [3], [4]. They have different residence time, physical properties, chemical composition, refractive-index characteristics and climate-relevant properties due to the different sources and meteorological processes. In terms of Earth’s radiative forcing, aerosols will affect the Earth’s radiation balance directly by absorbing and scattering incoming and outgoing radiation and indirectly by acting as cloud condensation nuclei (CCN), which will then change the concentration of initial droplets, albedo, precipitation formation and lifetime of the clouds [1], [2], [3], [4]. Thus, measurements of these physical and optical properties of the particles (aerosols) are of great interest. To do so, we can use the Lidar [5] or AERONET sunphotometer [6].
Light detection and ranging also known as Lidar is a technique whereby a beam of light is used to make range-resolved remote measurements. Lidar is used extensively in measuring the properties of the earth’s atmosphere and also in ocean research [7]. Lidar also has a few military applications, including chemical [8] and biological agent detection [9]. For this study, we will only focus on atmospheric Lidar. Atmospheric Lidar makes use of the interaction, scattering and absorption of a beam of light with the particles or constituents in the atmosphere. A variety of atmospheric parameters can be measured, including aerosol and cloud properties, temperature and etc., which depends on the design of the Lidar. The paper entitled “Lidar observations of the vertical aerosol flux in the planetary boundary layer” shows two different Lidar systems i.e. Doppler wind Lidar for measuring the vertical wind velocity and a Raman Lidar to measure aerosol parameters [10].

AERONET which is also known as Aerosol Robotic NETwork program is a federation of ground-based remote sensing aerosol networks collaborated on by national agencies, institutes, universities, individual scientists and partners. This program provides a long term, continuous and readily accessible public domain database of aerosol optical depth, microphysical and radiative properties for aerosol research and characterisation, validation of satellite retrievals, and synergism with other databases [11]. Holben et.al described the concept and description of AERONET in detail in their paper [12].

Lidar uses a single wavelength to detect the optical depths of the atmosphere at different heights. Meanwhile, AERONET uses a sun photometer that delivers integrated optical depths of the atmospheric column at multiple wavelengths. The different measurement techniques of the two systems are as shown in Figure 1. The sunphotometer always points towards the sun using the incorporated sun-tracker, while the Lidar system points vertically into the atmosphere (Zenith angle of 90°). If a cloud is detected by the Lidar system, the sunphotometer which points in another direction may miss it.

![Figure 1: Simulation of the measurement techniques of the Lidar system and sunphotometer.](image)

Although the two systems have different methods, the sunphotometer can be used to reinforce the aerosol profiling capabilities of a Lidar [13]. In the past, a few studies have been made to compare between the two systems [14], [15]. Most of the studies that were found did not compare the two systems in much detail. Therefore, this study will solely focus on comparing the two systems. And, the data of comparison is the aerosol optical depth (AOD). By definition, Aerosol Optical Depth (AOD) is the measure of aerosols (e.g. urban haze, smoke particles, desert dust, sea salt) which are distributed within a column of air from the instrument or Earth’s surface to the top of the atmosphere.

2. Methodology and data collection

2.1. Lidar system

The Lidar system used is the Raymetrics LB100-ESS-D200 Eye-Safe Scanning Lidar System. Laser of wavelength 355nm was fired into the atmosphere at a zenith angle of 90° and azimuthal angle of 0°. Energy emitted per pulse for the lidar system is 6.50J. The laser pulse repetition rate is 20Hz. For this
study, the laser pulse was set at 1200 shots per minute where data will be collected every minute throughout the whole operation of the Lidar system. The data retrieval was held throughout the weekdays of the month of December 2012. Each session was about 6 to 7 hours per day from 10.00 am till 5.00pm. All the data used in this study were only taken on sunny or cloudy days. In the case of rainy days, no data collection was done.

The laser system is placed on the rooftop of the School of Physics, USM, Penang, which is at a height of 50m above sea level. The position of the system is at longitude of 100.30 and latitude of 5.40. The temperature in the laser system is set to be 30 °C and the pressure is set as 1 atm. The temperature is set as so because the temperature in Penang, Malaysia has an average of 30 °C, where the temperature from morning (around 9am) till evening (6pm) would fluctuate from 23 to 32 °C (based on weather station data).

2.2. AERONET sunphotometer
For AERONET, the instrument used is the CIMEL Electronique 318A spectral radiometer (sunphotometer). It makes direct sun measurements in eight spectral bands between 340nm and 1640nm [12]. The radiometer is placed at the rooftop of School of Physics, USM, Penang. Its location is at a longitude of 100.302 and latitude of 5.358. Data is collected every day at a scheduled routine.

2.3. Method
Data of AERONET used are all of level 1.0 (unscreened data) and level 1.5 (cloud-screened data with an accuracy of the order of ±0.03 using the cloud-screening and quality control algorithm by Smirnov A. et al. [16]). However, the data are not quality assured as the final calibration is not applied. Level 2.0 cannot be downloaded, as the data is still in process and not available yet. Thus, for this study, data of level 1.0 and level 1.5 are used. AOD 355nm can be obtained from AOD 380nm and AOD 340nm using Equation 1 and Equation 2. We will first obtain the Angstrom coefficient, \( \alpha \) by dividing the ln component of the AODs with the ln component of the corresponding wavelengths using Equation 1. Then, we get the AOD of 355nm through Equation 2. For Equation 2, either AOD 340 or AOD 380 can be used to calculate the final AOD 355.

\[
\alpha = \left[ \frac{\ln(AOD_{340})}{\ln(\lambda_{340}/\lambda_{380})} \right] 
\]

\[
AOD_{355} = AOD_{340} \times \left(\frac{\lambda_{335}}{\lambda_{340}}\right)^{-\alpha}
\]

Data obtained from the Raymetrics lidar system was analysed using the software provided, which is the Advanced Viewer. The Inver Klett-Fernald method is used by the software to obtain the value of the Extinction coefficient before solving it to get the AOD value for each specific time. For this method, we had to estimate the Lidar ratio. Since we do not have data for the Raman channel yet, we used the AERONET data as a guideline to choose the best Lidar ratio. As such, we chose Lidar ratio of 35 as this is the value where the Lidar AOD is almost the same as the AERONET AOD. This Lidar ratio also indicates that the atmosphere in Penang consists of mixed aerosols that are marine and anthropogenic aerosols.

| Time(hh:mm:ss) | AOD_380 | AOD_340 | Angstrom coeff, \( \alpha \) | AOD_355 | Lidar AOD |
|---------------|---------|---------|-----------------------------|---------|----------|
| 10:40:59      | 0.240795| 0.28515 | 1.520057929                 | 0.267038049 | 0.377    |
| 10:55:59      | 0.35596 | 0.394419| 0.922408138                 | 0.379020932 | 0.27     |
3. Results and Discussions

The AOD values for AERONET (the average of AOD 380nm and AOD 340nm) and Lidar (355nm) are compiled and the data of AERONET for Level 1.0 and Level 1.5 are compared with the data of Lidar respectively.

3.1. Comparison of Lidar AOD and AERONET AOD (Level 1.0)

Generally, the Lidar AOD is larger than the AERONET AOD. The difference is generally quite small except for some specific AOD points. The reason Lidar data is higher than the AERONET AOD may be due to the slight misalignment of the far-range sensing causing some signal noise in the lidar data. Noise present in the Lidar data are generally due to the large field-of-view of the Lidar system. The noise results from the interference from background light [17].

For AERONET AOD which is much higher than the Lidar AOD, as seen in Figure 2 (indicated by the circle), it is due to the presence of high clouds which are only detected by the sunphometer but not the Raymetrics LB100-ESS-D200 Eye-Safe Scanning Lidar System. The sunphometer measures the direct solar radiance up to the whole atmosphere column which might be contaminated with clouds while for the Lidar, it is only the integral of the extinction coefficient from the ground level till around 15km of height in the atmosphere. The presence of clouds is confirmed by the low or approximately 0 Angstrom coefficient obtained from AERONET.
For Level 1.0 data, which might be cloud-contaminated, most of the peaks shown in the AOD graphs for both AERONET and Lidar are represented by clouds (low and middle clouds) that exist in the sky. This was confirmed through our inspection of the time evolution graph for the total backscatter coefficient of the Lidar system. Clouds are the main factors of affecting the values of AOD. Thus there is an importance of comparing data which have undergone cloud-screening so that we can investigate the AOD value in the atmosphere.

3.2. Comparison of Lidar AOD and AERONET AOD (Level 1.5)

On average, the AOD for the atmosphere in Penang is less than 0.5. The peak of the AOD is mostly in the noon or afternoon as shown in Figure 3 and Figure 4. Peaks in the morning (11:31:12) and noon (13:26:24) may indicate the heavy traffic and activities around that particular time.
On the 12th of December (Figure 5), we get a peak of around 0.71 of Lidar AOD. The sunphotometer also showed AOD of 0.6. This may be due to dust or aerosols coming from other parts of the country, which mix with the local anthropogenic aerosols and thus cause the AOD to increase more than normal. According to the weather station data, the weather at 1pm was cloudy while haze was occurring at 2pm. When analysing these data, we find a problem where the temporal variation between each data point is quite big. This is due to the cloud screening algorithm applied by AERONET \.[16] The data which is suspected to be clouds will be completely screened off. Since Malaysia has a very cloudy weather, most of the time, the data for Level 1.5 and Level 2.0 will only be left with a few points after undergone cloud-screening. This will be a problem as the actual value of AOD at a particular time cannot be identified and is only estimated by connecting the data points, as for here, the data at 13:43:37 is connected with the data at 15:43:36. Although the Bayan Lepas weather station (~9km away from the Lidar and sunphotometer location) stated that there is haze, yet we cannot determine if it is true as there is only one data between 1pm to 3pm. We only have data at 13:43:37. The data for other time is removed due to contamination of clouds.

As mentioned before, AERONET AOD has an accuracy of an order of $\pm 0.03$. Thus, the trend of the AOD of Lidar should be similar to the AERONET. Although the values are slightly different, the trend is still quite similar. Referring to Figure 6, the slope of the best-fit straight line for
the data points between the AOD values retrieved from LIDAR and the AERONET measurements is the closest to unity and the coefficient of determination is high (above 0.6692). This shows that the agreement between the two systems is good. However, the differences in the AOD should be noted and discussed.

![Lidar AOD vs. AERONET AOD](image)

**Figure 6:** Best-fit straight line for Lidar AOD and AERONET AOD.

It is also found that the AOD data for both AERONET and Lidar are typically higher in the afternoon compared to in the morning. This suggests the presence of higher concentrations of aerosol in the afternoon. This is similar to the explanation of Yang Xun where as he investigated, the AOT value in the afternoon was mostly higher than in the morning [18]. The reason for the concentration of AOD in the afternoon is higher than in the morning may also suggest the effect of temperature on the aerosol distributions. Based on the weather conditions obtained from the nearby weather station, we can see that the temperature in the afternoon is higher than the temperature in the morning. On the whole, when the temperature increases at 12pm in the afternoon, the AOD graphs also show a trend of increasing in value after 12pm. This shows that temperature affects the concentration of AOD. This is consistent with the fact that, as the air in the planetary boundary layer (PBL) warms during the morning, the height at which thermal equilibrium occurs increases. Thus the depth of the PBL increases from dawn to several hours after noon. Since the PBL depth increases, there is a higher rate or possibility for aerosols to be distributed in the atmosphere.

4. Conclusion

All in all, the trend of the Lidar AOD and the AERONET AOD agree well and is almost similar. The differences in AOD of both systems may be due to presence of noise in Lidar data and presence of clouds in AERONET data. Due to the cloud-screening algorithm of AERONET, the points obtained for Level 1.5 is limited and thus the actual condition of the atmosphere may not be determined accurately. The AOD for Penang is normally less than 0.5 except on the 12th of December where there is haze. The slope of the best-fit straight line for the data points between the AOD values retrieved from LIDAR and the AERONET measurements is the closest to unity and the coefficient of determination is high (above 0.6692). The aerosol distribution may be affected by temperature. Further observations should be made and a more consistent and long term data collection should be done. This is so to more accurately observe the conditions of the atmosphere in Penang.

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