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Measurement of Cloud Optical Depth Using Sunphotometer Calibrated by Pdm Algorithm

Nur Hasinah Najiah Binti Maizan, Rubena Binti Yusoff, Jedol Dayou

Energy, Vibration and Sound Research Group (e-VIBS), Faculty science and Natural Resources, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia.

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ABSTRACT

One of the useful information to predict earth climate change over a long time is the thin ice cloud microphysical properties such as cloud optical depth (COD). It is a measure of cloud transparency in atmosphere and it depends on the cloud thickness of vertical depth and moisture density. Many algorithms have been developed to measure cloud optical depth but development of calibration constant algorithm for ground based COD retrieval is still lacking. Previously, Langley calibration method was used to calibrate ground based instrument, but this calibration method have a few limitation for long time monitoring purpose. Therefore, combination of clear-sky detection model, Perez- Du Mortier (PDM) algorithm was developed for near sea level calibration purpose and this method have been successfully used to calibrate ground based spectrometer for Aerosol Optical Depth (AOD) retrieval. This paper reports the results of investigating the feasibility of PDM algorithm in calibrating instrument for COD retrievals at near sea level. Calibration constant obtained is then applied to cirrus cloud observed at University Malaysia Sabah, Kota Kinabalu, Sabah. It was found that the proposed calibration method can be used in calibrating ground instrument to measure cloud optical depth at low altitude.

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INTRODUCTION

Clouds is made up of water drops or ice crystals floating in the atmosphere at altitudes ranging up to several miles above the sea. Information on the clouds formation is important as clouds play significant role in earth's radiation budget system by cooling and warming the earth that subsequently give an impact to earth's climate changes [19]. Clouds cool the earth by reflecting incoming sunlight and warm the earth by absorbing infrared radiation emitted from earth surface, and reradiating it back down. This redistribution of the radiant energy in the atmosphere depends on three factors. The presence of clouds, the fraction of the sky covered by clouds and the cloud phase and its optical depth [18]. Cloud optical depth (COD) τ, is a measure of cloud transparency in atmosphere and it depends on the cloud thickness of vertical depth and moisture density. A long term measurement is useful and may be used to understand the climate changes over time.

COD are normally measured using three popular methods, retrieval with satellite data, Lidar and ground based instrument. Different approach can be selected depending on the purpose. Satellite is the most accurate option for COD retrieval because the accuracy in the measurement of solar radiation is very high. A simple model has been developed by [14] to measure global and diffuse irradiance by using geostationary satellite visible image. The model is particularly efficient at correcting possible distortions for global and diffuse irradiance measure by ground based instrument. Satellites can also be used to retrieve COD for snow area. This method is relatively new and it uses the sensitivity of top-of-atmosphere (TOA) reflectance in the oxygen A-band to get the COD value [17].

Lidar is a remote sensing technology that measure distance by illuminating a target with a laser and analyse the reflected light [7]. In the process of retrieval of COD for cirrus cloud, laser have been transmit through the cirrus cloud for where the COD want to be retrieved and analyse the back scattered signal using certain

Corresponding Author: Jedol Dayou, Energy, Vibration and Sound Research Group (e- VIBS), Faculty Science and Natural Resources, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia.
Tel: +0688-320000; Faks:+6088-435324; Email: jed@ums.edu.my.

algorithm [13]. An advantage using Lidar is, it can detect optically thin cloud layer [10]. Lo *et. al.* [10] used Micropulsed Lidar (MPL) to retrieve short- wave COD and as well as Wu *et. al.* [20] who used Raman-Mie Lidar to retrieve optically thin cloud. Another research have conducted by Cadet *et. al.* [5] which focus on improvement method measuring COD for thin cloud by applying two Lidar methods named as Molecular integration (MI) method and Particle integration (PI) method.

Retrieval cloud optical depth by using ground instrument will measure cloud optical depth by using solar irradiance whether spectra irradiance or broadband irradiance [12, 16, 3]. As time passed by, many algorithms to retrieve COD has been developed from the complicated to the simplest and recently, Barnard *et. al*. [1] has proposed a simple empirical equation to calculate cloud optical depth using shortwave broadband measurement and this algorithm has been emphasis on thick cloud [1] and thin ice cloud [2]. To increase the accuracy of COD retrieval, instrument must be properly and regularly calibrated as instrument's calibration may deviate after long term measurement.

Langley calibration method was widely used to calibrate ground based instrument, but this calibration method have to take place at high altitude for clear sky condition and stable atmosphere. For long time COD monitoring purpose, this calibration method is not efficient in terms of accessibility and economic prospect because this method have to takes place at high altitude for clear and stable atmosphere. Therefore, Chang *et. al.* [6] has developed new Langley calibration method as an alternative for near sea level calibration purpose. This method had been successfully used to calibrate ground based spectrometer for Aerosol Optical Depth (AOD) retrieval at near sea level [6].

1) Perez- Du Mortier (PDM) Calibration Algorithm:

Clear sky condition at high altitude can be accurately approximate by using PDM algorithm [6]. PDM algorithm is a combination of clear- sky detection model between Perez model and Du Mortier model. The Combination of these model are able to ascertain only cloudless and clear data is selected for development of calibration constant in Langley regression. In previous, PDM had been used to determine aerosol optical depth calibration constant [6], calibration of visible range solar spectrum intensity [4], estimation of daylighting under different orientation [8].

By using clearness index as an indicator, sky type for this model can be classified into three types which is clear sky, intermediate blue and cloudy overcast. The perez's index for irradiance can be computed using the relationship between the diffuse I_{ed} and global I_{eg} horizontal irradiance as shown [15],

$$\varepsilon = \frac{(I_{ed} + I_{dir} / I_{ed}) + 1.041\phi_H}{1 + 1.041\phi_H}, \quad (1)$$

where, I_{dir} is the direct irradiance and ϕ_H is the solar zenith angle in radian.

In Du Mortier model, sky type is classify into five types namely blue, intermediate blue, intermediate mean, intermediate overcast, and overcast. This classification using Nebulosity index (NI) as indicator and can be computed by [21],

$$NI = \frac{1 - I_d / I}{1 - CR}, \quad (2)$$

where, I_d is the diffuse irradiance, I is the global irradiance. CR is the cloud ratio given by

$$CR = \frac{I_{d,cl}}{\left[I_{d,cl} + \exp(-4mAr)\sin\alpha\right]}, \quad (3)$$

where, $I_{d,cl}$ represents the clear sky illuminance and α represents the solar altitude. $I_{d,cl}$ is calculate using equation

$$I_{d,cl} = 0.0065 + (0.255 - 0.138\sin\alpha_o\ ), \quad (4)$$

where, Ar is the Rayleigh scattering coefficient written as

$$Ar = \{5.4729 + m[3.0312 + m\{-0.6329 + m(0.091 - 0.00152\,m)\}]\}^{-1}, \quad (5)$$

With m as the optical air mass. The Perez's and Du- Mortier model are used together in this paper to form a combined sky classification as shown in Table 1 [6].

Table 1: Perez and Du Mortier model classification of sky condition.

Value of Indices		Sky Condition
Clearness index, ε	Nebulosity index, NI	
$\varepsilon \geq 4.50$	$0.95 \leq NI \leq 1.00$	Ideal clear sky
$1.23 < \varepsilon < 4.50$	$0.70 \leq NI \leq 0.95$	Intermediate blue
$*\varepsilon \leq 1.23$	$0.20 \leq NI \leq 0.70$	*Cloudy overcast/ Intermediate mean
	$0.05 \leq NI \leq 0.20$	*Cloudy overcast Intermediate overcast
	$0.00 \leq NI \leq 0.05$	*Cloudy overcast/ Overcast

2) Cloud Optical Depth (COD) Algorithm:

COD equation presented here is to determining cloud optical depth and developed by Barnard *et. al*. [2]. This algorithm has been successfully used to measure COD of thick and thin cloud. In addition, this algorithm also can be used to estimates optical depth for both liquid water and ice at various locations [2].

$$\tau = \frac{\left(\frac{1.16}{r} - 1\right)}{(1-A)(1-g)}, \qquad (6)$$

Based on Eq. (6), $r = (T/C)/(\mu_o)^{1/4}$ and r is proportional to the atmospheric transmission T/C throughout the entire atmospheric column that includes clouds and clear air. C is a clear sky irradiance that should be measure in the absence of clouds and T is measured total irradiance. A is the surface albedo and value for A is set to 0.31 as it was the average value for Earth's surface albedo. The value of g is depending on the ice crystal habit and the ice particle size distribution. Based on previous research, recommended value of g is 0.87 for liquid water cloud, 0.8 for ice cloud and intermediate value could be chosen for mixed phase cloud [2]. So, value of g is set to 0.8 because this research will conducted on thin ice cloud.

Experimental Methodology:

Development of calibration constant and retrieval of cloud optical depth were conducted for three wavelength, λ_1 = 470 nm, λ_2 = 500 nm, and λ_3 = 550 nm by using ASEQ LR- 1 Spectrometer. There was two location of studies selected in Kota Kinabalu, Sabah. For development of calibration constant, the measurement was conducted at an open space near Tun Mustapha Tower, Kota Kinabalu or formerly known as Yayasan Sabah $116^o E, 6^o N$. This site was selected due to its location, which is near sea level with an altitude 7.844 m. Location for retrieval of COD was conducted in Faculty of Science and Natural Resources (FSSA) inside the University Malaysia Sabah's (UMS) compound $116^o 7' E, 6^o 2' N$. These site is selected because it higher than ground level and not blocked by any irrelevant object, thus gave the constant availability of solar radiation.

Range of air mass chosen for development of calibration constant in this reaserch is from 2 to 6. Air mass is chosen within this range because lower air mass tends to have slower rate of change, therefore it will increase the chance for atmospheric condition to change and this situation will affect the regression line [6]. In order to fulfil the requirement range of air mass, data collection of global and diffuse irradiance was started from 0640 to for every 3 minutes averages within the selected air mass ranges. Data is collected as much as possible during April 2012- May 2012 unless it was raining or the sky is highly overcast. For the measurement of cloud optical depth this step was started with measuring global irradiance T, in February 2014 from 0900 to 1400 with time interval of 10 minute for 5 days.

RESULT AND DISCUSSION

1) Development of Calibration Constant:

740 of data had been collected during 2 month period. However, these data may contain cloudy and overcast data. All the cloudy and overcast data need to be identify and removed using PDM model and the filtration process were conducted as follow.

Data filtration start with wavelength 470 nm. Each obtained data is labelled as D_n , where n represents the number of observations and corresponding clearness index and nebulosity index for each data will be calculated using Eq. (1) and Eq. (2) respectively and they were listed as follows:

$$\begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{bmatrix} = \begin{bmatrix} \varepsilon_1 \; NI_1 \\ \varepsilon_2 \; NI_2 \\ \vdots \;\; \vdots \\ \varepsilon_n \; NI_n \end{bmatrix} \qquad (7)$$

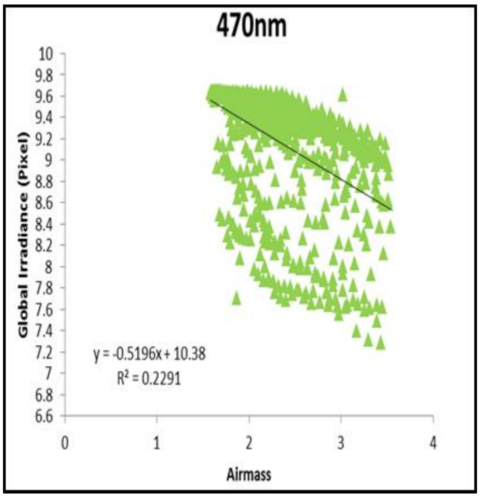
This raw data in Eq. (8) is known as clearness- nebulosity index (CNI). These CNI values were inserted into repetitive regression algorithm for data filtration using permutated criteria, $C_{p,q}$ which is illustrated in Eq. (8) *p* and *q* represent the criteria index where the range for *p* is between 1.23 until 1.89, and *q* is between 0.70 until 0.99. As a result, with corresponding conditional value of *p* and *q*, 2010 criteria were generate. The permutated criteria $C_{p,q}$ as started with $p \geq 1.23$ and $q \geq 0.70$ and continue to the other value of p with the step of 0.01 and these is illustrated in Eq. (9).

$$[\varepsilon_p NI_q] = \begin{bmatrix} C_{1,1} & C_{2,1} & \cdots & C_{67,1} \\ C_{1,2} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ C_{1,30} & \cdots & \cdots & C_{67,30} \end{bmatrix} \qquad (8)$$

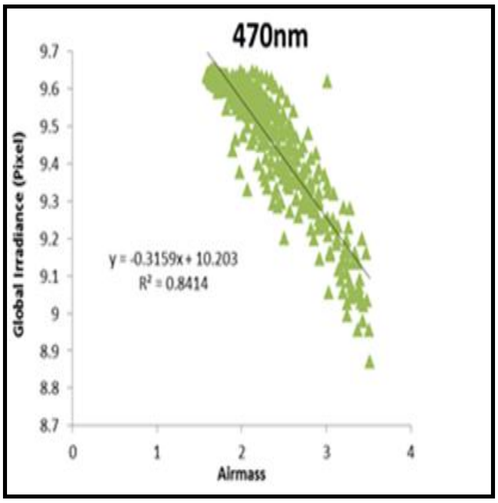
$$\lfloor \varepsilon_p NI_q \rfloor = \begin{bmatrix} \varepsilon_1 \geq 1.23, NI_1 \geq 0.70 & \varepsilon_2 \geq 1.24, NI_1 \geq 0.70 & \cdots & \varepsilon_{67} \geq 1.89, NI_1 \geq 0.70 \\ \varepsilon_1 \geq 1.23, NI_2 \geq 0.71 & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ \varepsilon_1 \geq 1.23, NI_{30} \geq 0.99 & \cdots & \cdots & \varepsilon_{67} \geq 1.89, NI_{30} \geq 0.99 \end{bmatrix} \quad (9)$$

For every criteria $C_{p,q}$ only global irradiance data D_n with value of $\varepsilon_1 \geq p$ and $NI_1 \geq q$ will be used to form a Langley plot against air mass and corresponding data of $C_{p,q}$ that not fulfil this condition will be filtered out. After using Eq. (7- 9), a total of 2010 criteria were permutated for the clear sky filtration and highest correlation of R^2 = 0.8414 is obtained at criteria of $NI \geq 0.96$ and $\varepsilon \geq 1.51$. By referring to Table 1, these criteria fall ideally in ideal clear sky condition which is free from cloudy and overcast data. Therefore, only intensity data of D_n with NI and ε more than or equal to 0.96 and 1.51 respectively, are used for the calibration purpose.

The result after filtration step is implemented to the Langley plot to find k is shown in Figure 1. Figure 1(a) shows the Langley plot of unfiltered data for 470 nm that consist 740 points. After Langley plot is filtered by using PDM model, the data point reduced to 417 and the corresponding Langley plot is shown in Figure 1(b). The Langley plot in Figure 1(b) is then used to determine the calibration constant for wavelength 470, k_{470} by dividing its extrapolated values with with extraterrestrial constant at TOA obtained from ASTM G173-03 Reference Spectra. These processes were repeated for wavelength 500 nm and 550 nm. Figure 2 show the Langley plot for completely filtered data for the wavelength of 500 nm and 550 nm and Table 2 provide all the corresponding information about Langley plot for each wavelength. The total initial data for each wavelength is 740 where, n represent remaining data point after filtration, and R^2 is correlation coefficient.



(a)Before Filtration

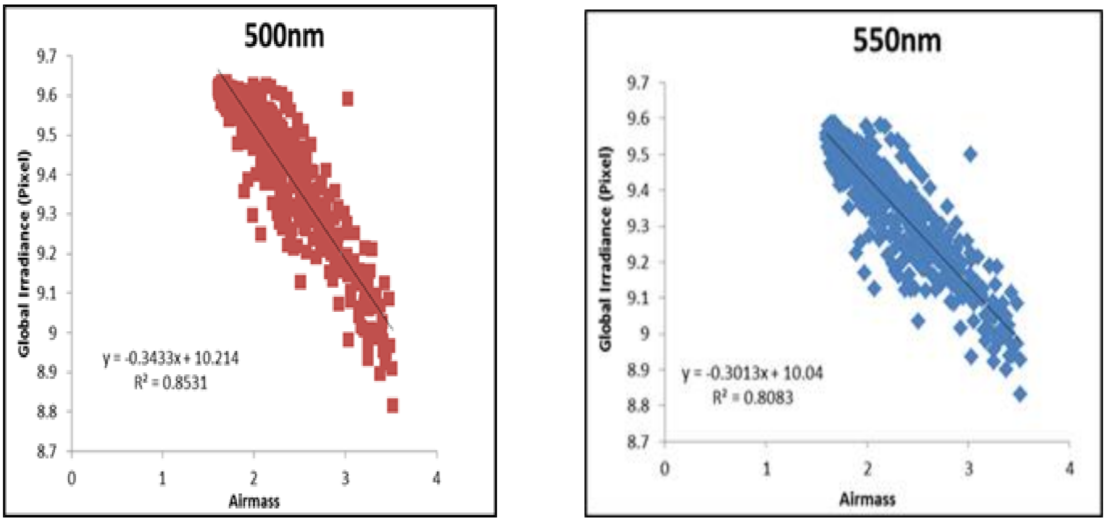


(b) After filtration

Fig. 1: Langley plot at 470 nm (a) before filtration, (b) After filtration using PDM model ($NI \geq 0.96$ and $\varepsilon \geq 1.51$).

Table 2: Summary of Langley plot after filtration using PDM model.

Wavelength	Filtration criteria	Number of data,	Regression line	R^2	Extraterrestrial constant (W/m^2 /nm)	Calibration factor, k
470 nm	NI ≥0.96 and $\varepsilon \geq 1.51$	417	$y = -0.3159x + 10.203$	0.8414	1.939	7.1857E-05
500 nm	NI ≥0.96 and $\varepsilon \geq 1.51$	417	$y = -0.3433x + 10.214$	0.8531	1.916	7.0228E-05
550 nm	NI ≥0.96 and $\varepsilon \geq 1.51$	417	$y = -0.3013x + 10.04$	0.8083	1.863	8.1264E-05



(a) 500 nm (b) 550 nm

Fig. 2: Langley plot at (a) 500 nm, (b) 550 nm after filtration using PDM model ($NI \geq 0.96$ and $\varepsilon \geq 1.51$).

2) Retrieval of Calibrated Spectra Cloud Optical Depth:

Corresponding air mass for each global irradiance T_{470}, is calculated by using Sun Calculator. Next, by using regression line formed in Figure 1(b) value of C_{470} is determined and the next step to obtained calibrated cloud optical depth values for λ_1 from 0900 to 1400 is by multiply T_{470} and C_{470} with k_{470} and substituted the calibrated value of global irradiance T_{470} and corresponding clear sky irradiance C_{470}, into parameter *r* inside the Eq. (6). Steps were repeated for 500 nm and 550 nm. Figure 3 show a graph which represents calibrated spectra cloud optical depth for 3 wavelengths in 5 days.

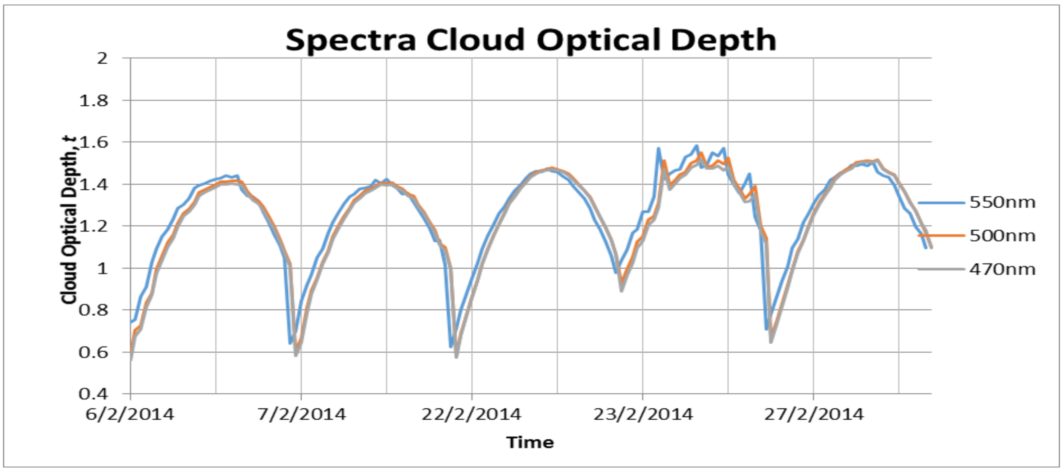


Fig. 3: Spectra Cloud Optical Depth for wavelength 470 nm, 500 nm, and 550 nm in 5 days.

Based on Figure 3, it can be seen that there were no significant difference in pattern and reading for spectra cloud optical depth for wavelength 470 nm, 500 nm, and 550 nm in 5 days. The graph patterns slowly increase from 0900 until about 1200, and then slowly decrease until 1400 and minimum reading is fall at 0.56 which occur during the morning and maximum reading is 1.70 which occurs at noon.

This pattern was formed due to the changes of air mass in atmosphere as cloud optical depth will increase when air mass decrease and this result fall ideally in cloud optical range for thin ice cloud which is below than 2 and this result is supported by research conducted by Meyer *et. al.* [11]. These researches have stated that, cloud optical depth for tropical area has average reading between 0 until 2 for thin ice cloud.

Conclusion:

Instrument calibration procedure is an important step before COD measurement take place. This step is taken in order to increase instrument accuracy of COD value. Langley method have been widely used over long time to calibrate ground based instrument. But this method may impractical for long term monitoring purpose since this method need to be done at high altitude. With this limitation, PDM method was developed by combining clear sky detection model to produce clear data set which is close to high altitude condition. Calibration constant obtained after used PDM method show a good performance when measuring COD for thin cirrus cloud. COD reading fall ideally in cloud optical range for thin ice cloud which is below than 2. Based on the positive result in this study, it is expected that near sea level monitoring network can do frequent calibration for COD measurement without travelling to high altitude and at the same time can increase the accuracy of COD monitoring worldwide.

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