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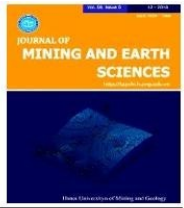

Combination of satellite and ground based observations in order to retrieve aerosol optical depth over urban and rural areas

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ABSTRACT

The aerosol optical depth (AOD) can be retrieved accurately with sequential ground - based measurements of the direct and diffuse solar radiance. However, spatial coverage and location frequency cause certain limitations. Hence, satellite image data are a proper tool for obtaining aerosol optical depth products with more spatial information and patterns of aerosol distribution. Currently, aerosol remote sensing may enhance our understanding of the optimal approach of AOD retrieval over urban and rural areas and could differ due to the characteristics of surface reflectivity. In this study, the concepts of contrast reduction and dark target approaches are examined with Landsat image and the observation of sun photometer (AERONET) for integrating AOD distribution over Taipei city in Taiwan. For the areas with bright surfaces such as urban area, the above concepts are applied by dispersion coefficient method together with sun photometer in order to considerably reduce errors in the product. In contrast, the dark target algorithm with the relationship of surface reflectance between blue (0.49 µm), red (0.66 µm), and infrared (2.1 µm) spectral bands, is suitable for moist soils and vegetation areas. The retrieval of AOD spatial distribution is compared with MODIS AOD products and AERONET for verifying the accuracy of the result. The RMSE ranged from 0.2 to 0.4, and about 50% amount of data were within expected error (EE=± (0.05+0.15 AOD sunphotometer).

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1. Introduction

Aerosols are known to be associated with pollution in the local atmosphere (Fenger, 1999). The small particle matter (PM), that are less than 10 micrometers (m) pose a risk to human health when inhaled into the lung (Harrison et al., 2000). Inhalation of aerosol particles lead to a variety of complications including irregular heartbeat, decreased lung function, non - fatal heart attacks and aggravated asthma (Pope et al., 2002). Therefore, crucial importance is placed on aerosol researches for PM concentrations to monitor the level of air pollution, thereby taking necessary steps to prevent further rise. Aerosols also play an integral role in a wide range of weather and climate phenomena on both small and large scales (Lenoble, 2013). The need for establishing aerosol optical depth distribution is therefore necessary for continuously monitoring the change over time and to predict their inference on climate.

Air pollution will be occur when gases or aerosol particles, which is emitted anthropogenic, and agglomerate high concentration sufficiently cause direct or indirect damage to humans, plant, animals, other life forms, ecosystems, structures, or works of art (Giese - Bogdan, 1995). Taipei is a rapidly developing city, where the high concentration of PM has a negative impact on health of its residents. Owing to the extreme weather conditions in recent years, Taipei city is selected as study area to better understand the PM's interaction. In aerosol retrieval algorithm, the key factor is estimated the surface reflectance of object. Two methods are utilized: a) using a dispersion coefficient, b) using dark target. The dispersion coefficient method is based on contrast reduction, assuming the ground reflectance is unchanged over time and the changes of aerosol properties are provided by variations in the apparent reflectance observed. This method is apt for urban regions. On contrary, the dark target approach identifies the darkest pixel in the image, assuming the surface reflectance of the pixel. This method is apt for rural areas with dark/dense vegetation. The primary objective of this study is to: (i) retrieval AOD by dispersion coefficient and dark target method over mixed surface in Taipei and (ii) verify the accuracy of these two methods applied in different regions compared with

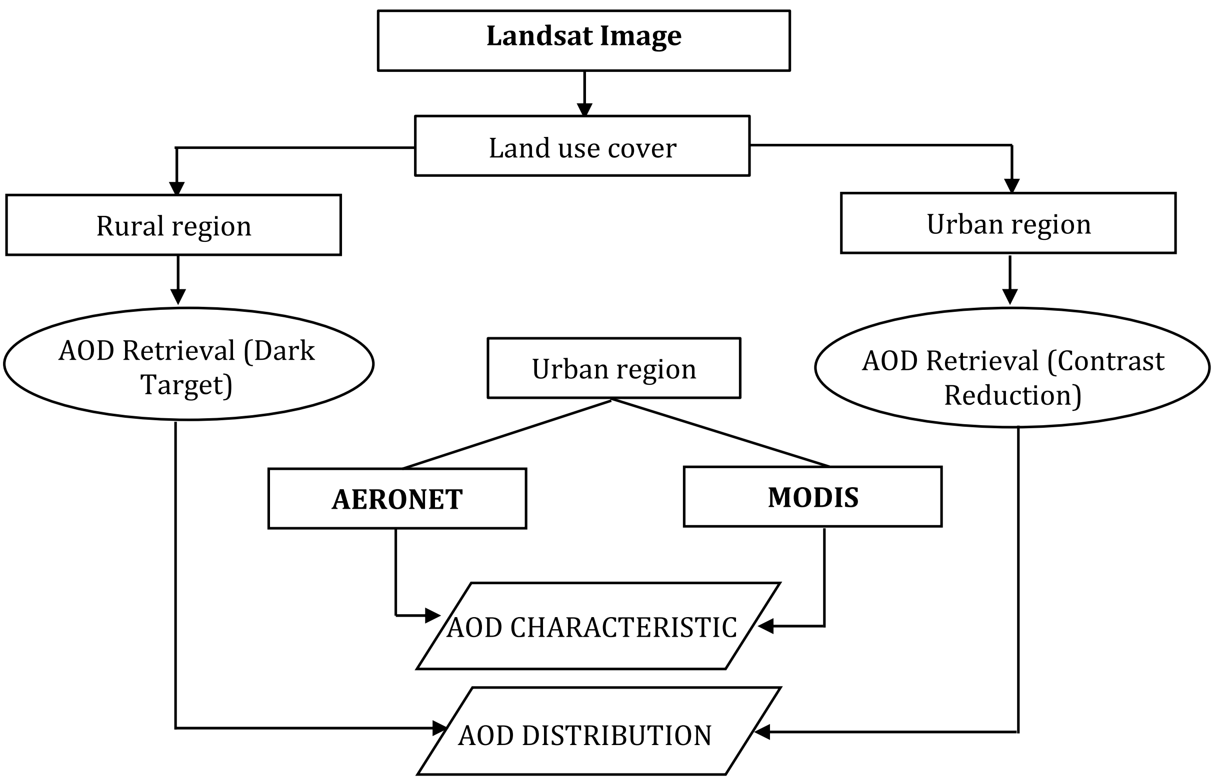

Figure 1. Overview of workflow methodology.

Aerosol Robotic Network (AERONET).

2. Methodology

The method involves in this study will be described. Dark Target and Dispersion Coefficient

In addition, it is also used to identify the characteristics of types of aerosol. The general workflow followed to achieve the objective is shown in Fig. 1 and equation (1).

$$\sigma(\rho^*) = \frac{T(\mu_s)\left[\sigma(\rho) exp\left[{}^{\tau}/_{\mu_v}\right]\right]}{1-\langle\rho\rangle s} \quad (1)$$

If neglect the variation of surface reflectance which means is constant, and the proportion of the standard derivation at time and can be obtained from the following equation (2):

$$\Delta_\tau = \tau(t_2)/\mu_{v2} - \tau(t_1)/\mu_{v1} = ln\left[\frac{\sigma(\rho^*/t_1)}{\rho^*_{t_1}} \Big/ \frac{\sigma(\rho^*/t_2)}{\rho^*_{t_2}}\right] \quad (2)$$

where ρ is the reflectance; τ is the optical thickness of the atmosphere; $T(\mu_s)$ is the total

(Contrast Reduction) method is applied to dark and bright surface for rural and urban area. The ground - based measurements and MODIS - AOD products are used to validate the AOD retrieval.

transmission function on the Sun ground path; Δ is the difference between the pixels' ground reflectance;

The equation (2) shows the AOD at the time can be calculated depending on the AOD at the reference time is known. This theory is supported by (Tanré et al., 1988).

2.2. The dark target method

As aerosol normally brighten a dark scene, the reflectance that satellites measured is larger than the surface reflected radiance (Lenoble et al., 2013). The dark target method is based on a technique proposed by (Kaufman et al., 1997), called the atmospheric correction technique. By this method, the darkest pixels in an image can be

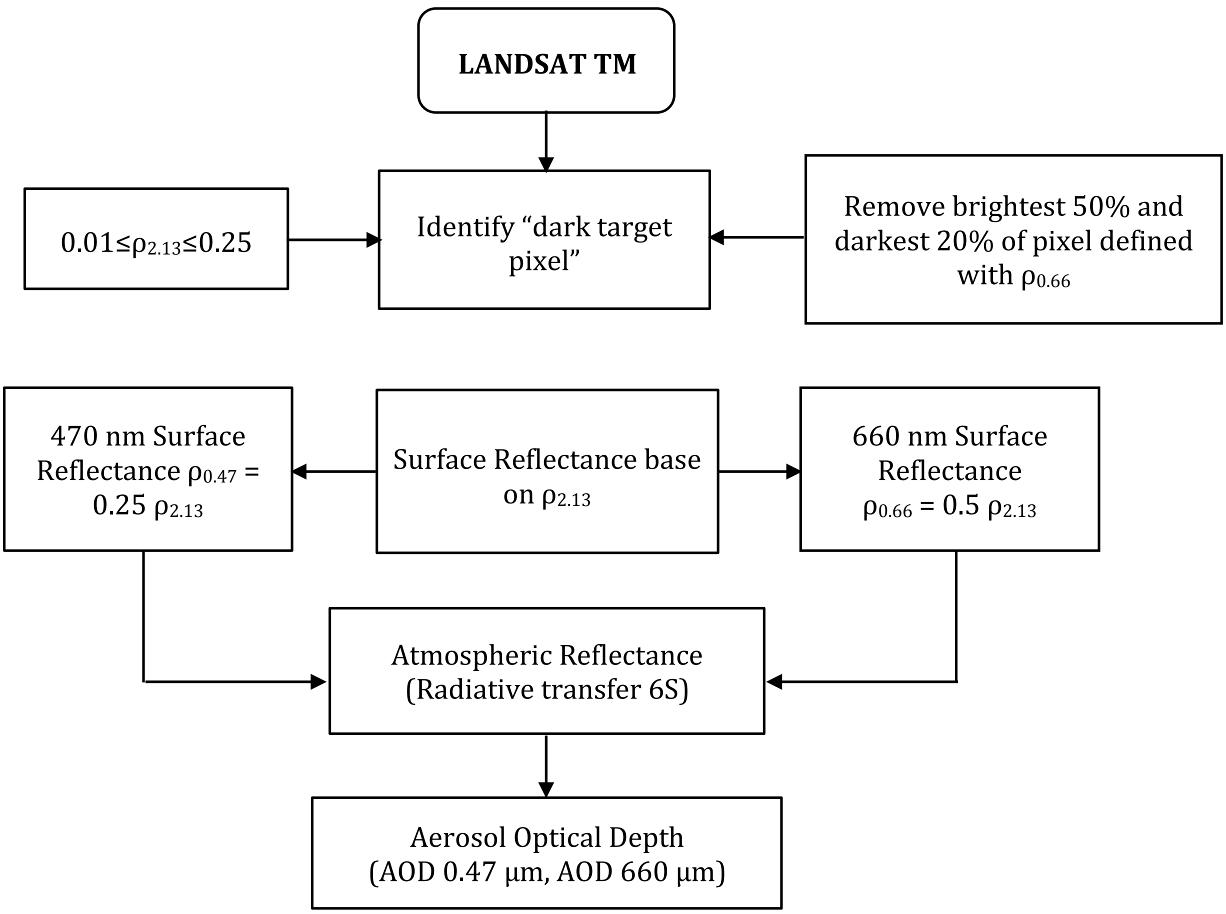

Figure 2. Flow chart of the dark target algorithm.

detected. If assume the surface reflectance of these pixels, one can extract the amount of aerosol.

In this study, whether the target is land or ocean, the criteria for method is excluded water, clouds, ice and snow pixels. After that, the dark target will choose on their reflectance 2.13μm must fall within the range 0.01≤ ρ_2.13≤ 0.25. The pixels remaining relative to term of their visible reflectance ρ_0.66. The 20 % darkest and 50% pixel brightest are removed in the reflectance ρ_0.66. The reason is discarded because of cloud shadows or odd surface at the dark end or residual cloud. The remaining 30% pixel is selective for calculation, the surface reflectance at 0.47 μm and 0.6μm are estimated from the average measured value in assumption empirical relationship the surface reflectance in the blue (0.49 μm), red (0.66 μm), and 2.1 μm follow the proportion (3):

$$\rho\ 0.49 = (\rho\ 0.66)/2 = (\rho\ 2.1)/4 \qquad (3)$$

(Remer et al., 2005)

where ρ is the reflectance. Both of Rayleigh correction and aerosol correction were estimated in each image by utilized the known altitude and the 6s radiate transfer code. There are two tricks for employing this method: finding the dark dense vegetation and assuming the surface reflectance at the wavelength of the retrieval in the image. The flowchart of the processing procedure is shown in Fig. 2.

3. Evaluation of aerosol retrieval

In order to assess the satellite aerosol retrieval, we used the aerosol obtained by the Sun photometer on the ground as the reference data. Several statistic indicators such as correlation coefficient (R), mean absolute error (MAE), root mean square error (RMSE), standard deviation (S), and expected error (EE) were employed. While the correlation coefficient (R) indicates well the agreement between AOD retrieved by the satellite and that by Sun photometers on the ground, the root mean square error is used to measure the different between them (Bilal et al., 2013). The larger R is, the better agreement between them, and the smaller RMSE is, the higher accuracy of the satellite AOD retrieval.

The RMSE is calculated as follow (4):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(AOD_{(satellite)} - AOD_{AERONET}\right)^2} \qquad (4)$$

The mean absolute error (MAE) is estimated as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |\, AOD_{(satellite)} - AOD_{AERONET} \qquad (5)$$

Where $AOD_{(satellite)}$ and $AOD_{(AERONET)}$ are satellite AOD retrieval and AOD measured by the Sun photometer (Bilal et al., 2013), respectively.

Standard deviation (STD) is calculated by the following formula:

$$STD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x - \bar{x})^2} \qquad (6)$$

Where x and $\bar{x}$ are $AOD_{(satellite)}$ and the average $AOD_{(satellite)}$, respectively.

Expected error (EE) is used here for the confidence envelopes of the retrieval algorithm over land to evaluate the quality of satellite retrieval (Bilal et al., 2013).

$$EE = \pm\,(0.05 + 0.15\, AOD_{sunphotometer}) \qquad (7)$$

Good matches (quality) of satellite - retrieved AOD are reported when the satellite - retrieved AOD falls within the following envelope (R. Levy et al., 2010):

$$AOD_{sunphotometer}|EE| \le AOD_{satellite} \le AOD_{sunphotometer} + |EE| \qquad (8)$$

4. Results and analyses

4.1. AOD retrieval by the dispersion coefficient method

4.1.1. Results of AOD retrieval

Dispersion coefficient method was conducted on the data of 29 May 2011, 25 August and 5 November 2011 for AOD retrieval over 8 locations (First Hotel Taipei, Banquiao Recreation Center, Luzhou, Sanchong, Taishan, Jieshou Park, Central Weather Bureau and National Taiwan

Museum). Six different window sizes were tested including 5×5, 10×10, 16×16, 20×20, 32×32, and 40×40. For example, for window size 5×5, results are outlined in Fig. 3.

Table 1 illustrates the AOD observed from the AERONET station in the CWB site at the wavelengths of 500, 675 and 870 nm. The AOD will be used in the next stage (Table 2). It consists of mean, maximum, minimum and standard deviation for each window size (5×5, 10×10, 16×16, 20×20, 32×32, 40×40). The accuracy of AOD retrieval is verified by two statistical parameters including root mean square error and mean absolute error.

Table 1. The AOD obtained from the AERONET station in the CWB site.

Date	870 nm	675 nm	500 nm
29/5/2011	0.157	0.214	0.325
25/0/2011*	0.064	0.017	0.128
5/11/2011	0.108	0.136	0.198

The retrieving aerosol optical depth evaluated by two factors including root mean square error and mean absolute error are given in Table 3. The dispersion coefficient method was tested on 29 May 2011 with different window sizes, and the result showed a fluctuation in the value of standard deviation. In addition, there was no significant difference between results. Furthermore, the result AOD retrieval errors did not show a linear relationship between window sizes.

Table 2. Descriptive statistics of the of AOD retrievals in each window size.

Size	40×40	32×32	20×20	16×16	10×10	5×5
Median	0.695	0.765	0.96	1.28	0.91	0.67
Min	0.28	0.28	0.05	0.02	0.062	0.02
Max	1.35	1.35	2.02	2.17	2.35	1.16
Mean	0.69	0.77	0.92	1.04	1.12	0.90
STD	0.23	0.26	0.57	0.64	0.61	0.97

Fig. 4 and Fig. 5 show the distribution of land cover types in the study area and the AOD distribution estimated from LANDSAT imagery acquired in 29 May 2011, respectively.

4.1.2 Comparison between AOD Satellite Retrieval and AERONET data

Table 3 presents a comparison between the AOD retrieval by using the dispersion coefficient

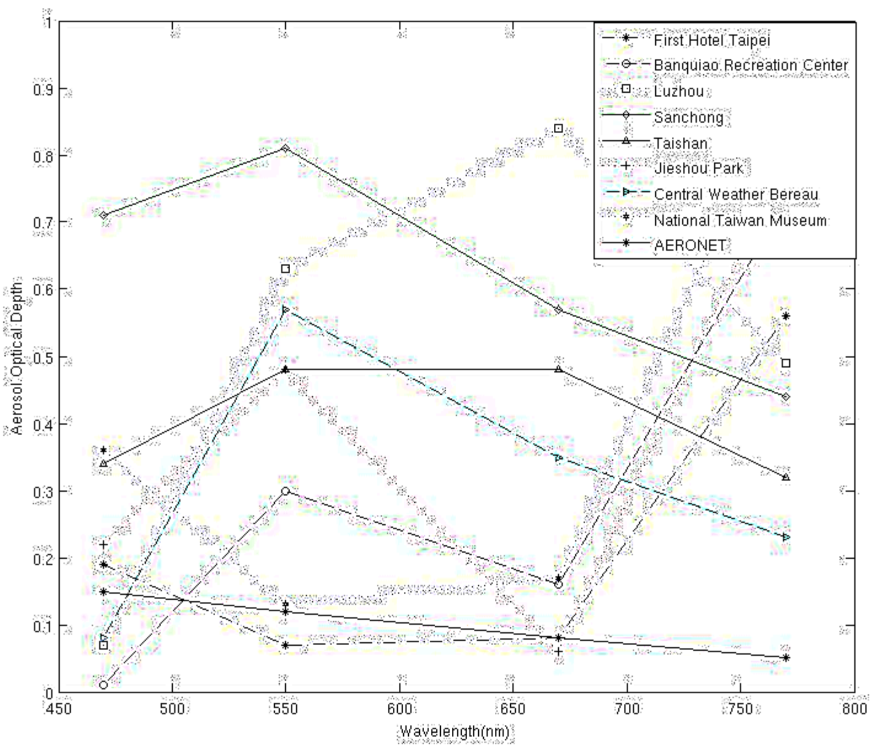

Figure 3. AOD retrieval in ground base station in 5 ×5window size.

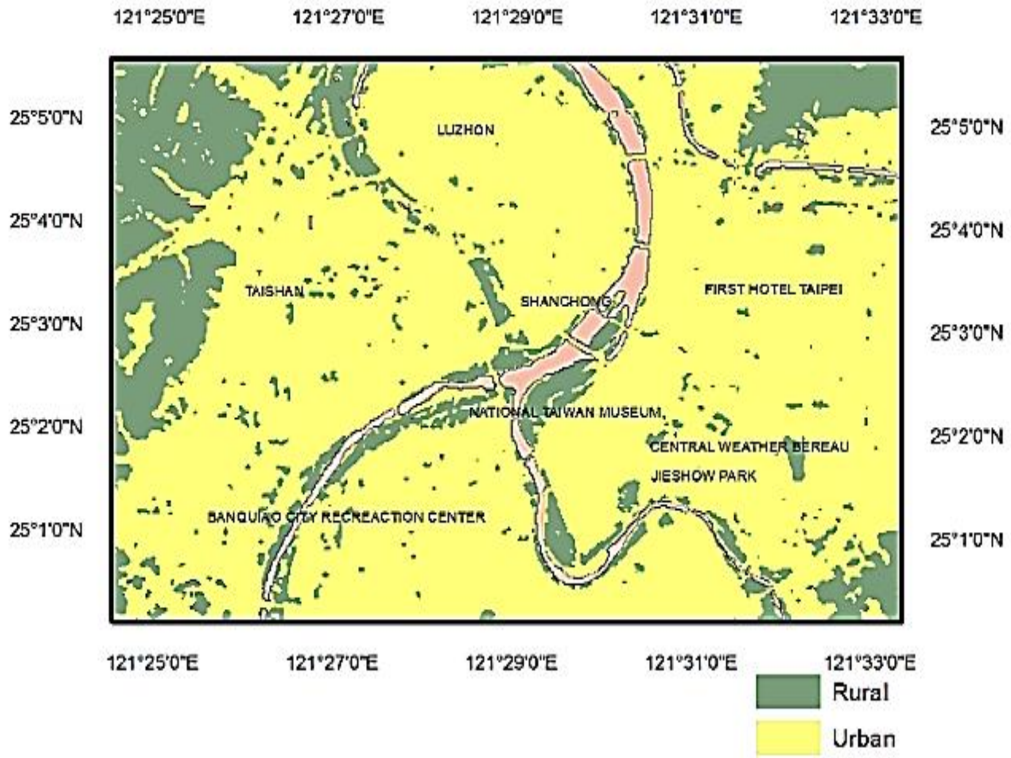

Figure 4. The study area in 29 May 2011.

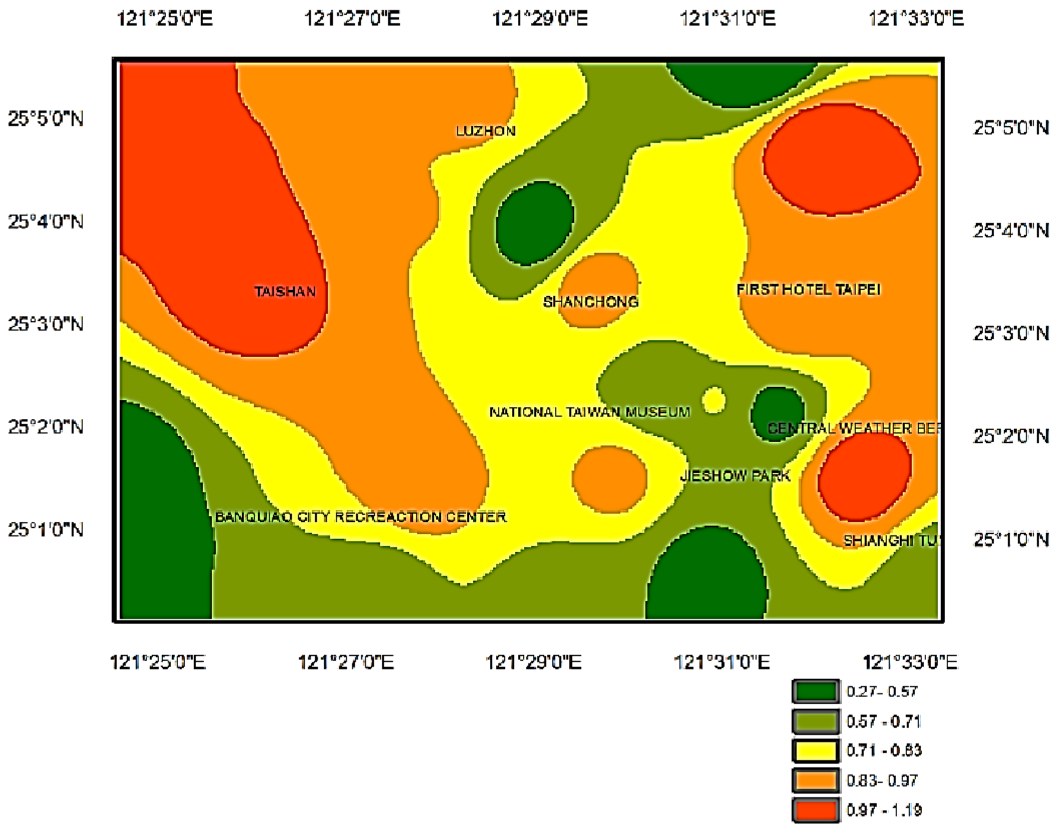

Figure 5. AOD distribution over urban areas by the dispersion coefficient method.

method and the AERONET data at the CWB in Taipei. The description statistics such as root mean square error (RMSE), mean absolute error (MAE), minimum, maximum and expected error (EE) were used for the comparison in 8 locations. These locations are First Hotel Taipei, Banquiao Recreation, Luzhou, Sanchong, Taishan, Jieshow Park, Central Weather Bereau and National Taiwan Museum. As is presented in the table 3, the AOD retrieval from the dispersion coefficient method achieved EE with nearly 50%. Specifically, Taishan has the best result with 60% in EE, followed by First Taipei Hotel and Sanchong with 50%. At the other stations, the value of EE fluctuated between 40 and 45%.

The AOD retrieved by the dispersion coefficient method was with the finer resolution in a comparison to the MODIS - AOD product provided for urban areas. The uncertainty may be explained by the surface reflectance is not invariable in each location of image. In this method, we assumed that the surface reflectance was unchanged from day to day. Therefore, the method required multiple images of the same scene and near real time. Also, the scene has to display contrasts at the scale consistent with the sensor resolution.

4.2 Retrieval AOD by the dark target method

4.2.1 Results of AOD retrieval by the dark target method

The relationship between the reflectance in the blue band (0.47 μm) and red band (0.66 μm) and the infrared (2.2 μm) channel were corrected in two images in two dates 29 May and November 5. Two locations in rural areas were chosen for aerosol retrieval including Fude Temple and Shangshi Tunnel. The apparent reflectance of LANDSAT TM 0.47μm and 0.66μm and the corresponding AOD retrieved by the dark target algorithm are shown in Fig. 6a, 6b and Fig. 7a,7b respectively.

4.2.2 Comparison Between AOD Retrieval and AERONET data

Table 4 shows a comparison between the AOD retrieved by the dark target method and AERONET on 5th Nov 2011. It can be clearly seen that the EE value was between 4 and 26%. In addition, the RMSE was from 0.04 to 0.74. These prove the better accuracy of the AOD retrieval by using this algorithm. Both atmospheric correction and sky radiometer data were used to calculate the Rayleigh correction. Analysis was carried out using the 6S mode for retrieving AOD. It was highly associated with the reduction of error.

Other five locations, namely Mochizuki, Yuan Tong temple, Xindan, Zizhu temple, and Niubu Path were conducted by the same method. The dark target method is proved to be extremely valuable as it helps to exclude discrepancies in results and makes it easier to compare results of all locations. The AOD retrieved by the dark target in rural areas are summarized in Table 5.

Table 3. Statistic of the AOD dispersion method and AERONET.

Location	RMSE	MAE	MIN	MAX	Data within EE
First Hotel Taipei	0.35	0.27252	0.07	0.96	50%
Banquiao City	0.41	0.36105	0.01	0.90	40%
Luzhou	0.44	0.38441	0.01	0.97	45%
Shanchong	0.37	0.39287	0.08	0.74	50%
Taishan	0.28	0.32075	0.06	0.88	60%
Jieshou Park	0.357	0.31174	0.06	0.82	45%
Central Weather Bereau	0.42	0.39258	0.06	0.81	45%
National Taiwan Museum	0.43	0.35881	0.04	0.96	40%

Table 4. Results of AOD retrieval from dark target on november 5, 2011.

λ	Location	Mean	RMSE	SD	Minimum	Median	Maximum	EE (%)
0.47	Fude Temple	0.16	0.04	0.03	0.07	0.17	0.21	19
0.47	Shanghi Tunnel	0.29	0.74	0.04	0.24	0.29	0.41	26
0.66	Fude Temple	0.48	0.36	0.09	0.27	0.51	0.65	4
0.66	Shanghi Tunnel	0.59	0.47	0.09	0.36	0.6	0.87	18

Table 5. The AOD retrieved by the dark target method in rural areas of Taipei.

Location	AOD (Retrieval)	AERONET
Mochizuki	0.228	0.214
Yuan Tong temple	0.261	0.214
Xindan	0.163	0.214
Zizhu temple	0.32	0.214
Niubu Path	0.163	0.214

A good agreement found between the AOD retrieved by the dark target method and AERONET data during the observation period for each location confirmed the robustness of this method. The average correlation coefficient, RMSE and MAE were 0.84, 0.06, and 0.05, respectively. Therefore, the results implied that the dark target method is better to retrieve accurately the AOD over rural areas.

4.2.2 Comparison between AOD Retrieval and MODIS data

In northwest border, the area next to the industrial city produced a high aerosol loading (AOD~0.8). In Taipei, despite large spatial differences, the AOD was observed across urban and rural areas. The aerosol optical depth ranges from 0.2 to 0.8. In this study, MODIS - AOD was obtained at the same AERONET locations. The AOD and Angstrom Exponent (AE) are tabulated in Table 6.

In order to compare the AOD retrieved by the dark target method with the MODIS - AOD retrieval, we used a 20×20 pixel slicing window. The result was shown in Table 7.

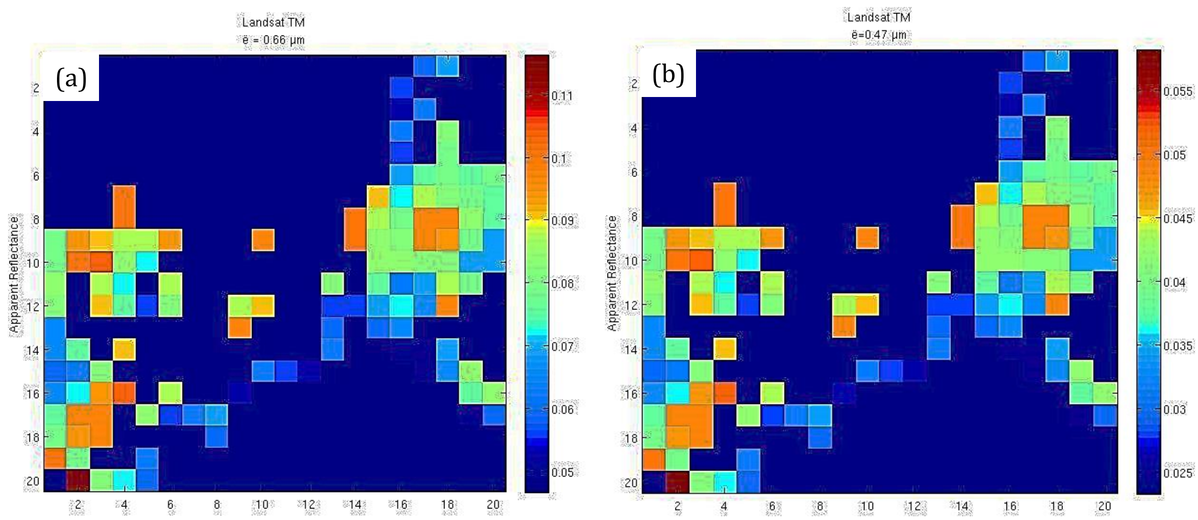

Figure 6. The apparent reflectance of red band (0.66 µm, (a)) and blue band (0.47 µm, (b)) from imagery on 5 November, 2011.

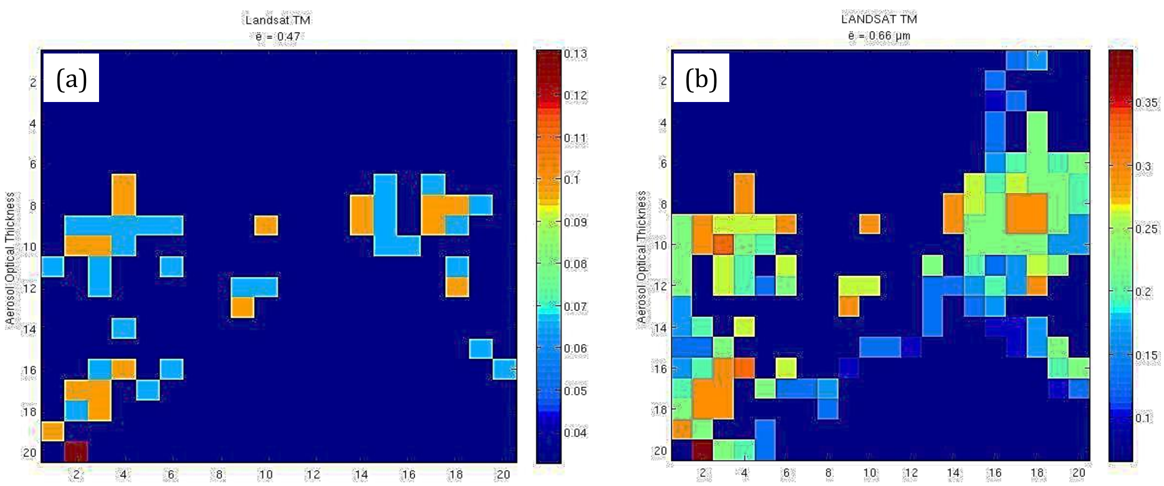

Figure 7. AOD retrieval at fude temple on 5 November, 2011.

Table 6. MODIS - AOD retrieval in this study.

Long	Lat	AOD 470	AOD 660	AOD 870	AOD 1020	AE
121.43	24.954	0.186	0.104	0.067853	0.053062	1.784
121.30	24.931	0.264	0.148	0.096379	0.075287	1.784

Table 7. Comparison between MODIS - AOD and the AOD retrieved by the dark target method.

Lat	Long	Mean AOD - MODIS
24.954	121.43	0.24

Although there was only a station for comparing aerosol retrieval in the study area, the result showed a remarkable agreement between MODIS - AOD and Dark Target - AOD from LANDSAT. This is because both have the similar algorithm. Over land surface, for the MODIS - AOD retrieval by the dark target algorithm, the value of surface reflectance in dark targets is low in parts of the visible and shortwave infrared spectrum. Generally, vegetable and dark soil areas are examples of such dark targets. The basic algorithm uses two visible wavelengths such as 0.47 and 0.65 µm and one shortwave infrared bands (2.1µm) (Kaufman et al., 1997; Levy et al., 2007). Thus, the degree of agreement between MODIS AOD and Dark Target - retrieved AOD from LANDSAT is considerable.

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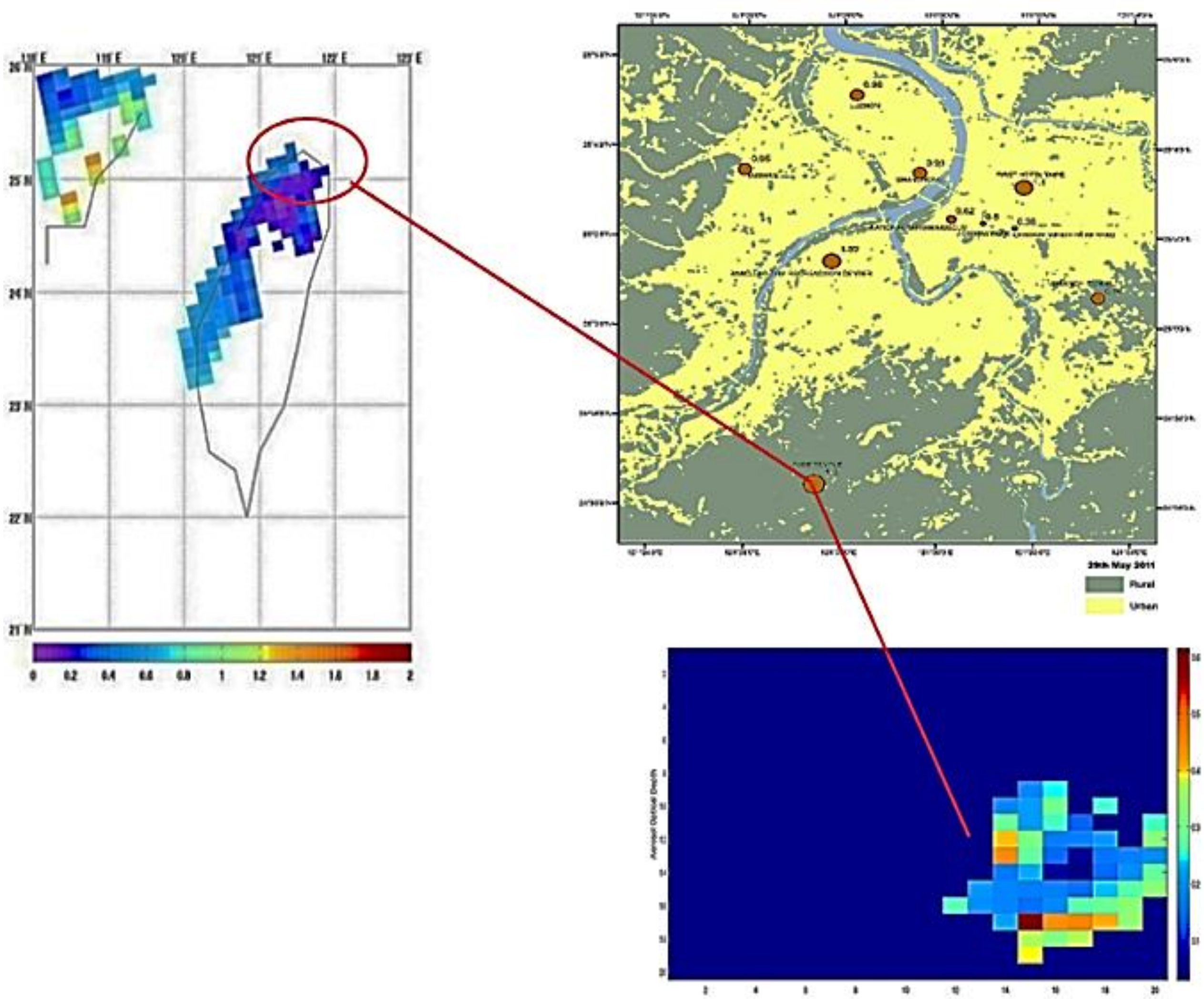

Figure 8. The spatial distribution of MODIS - AOD in Taipei on 29 May, 2011.

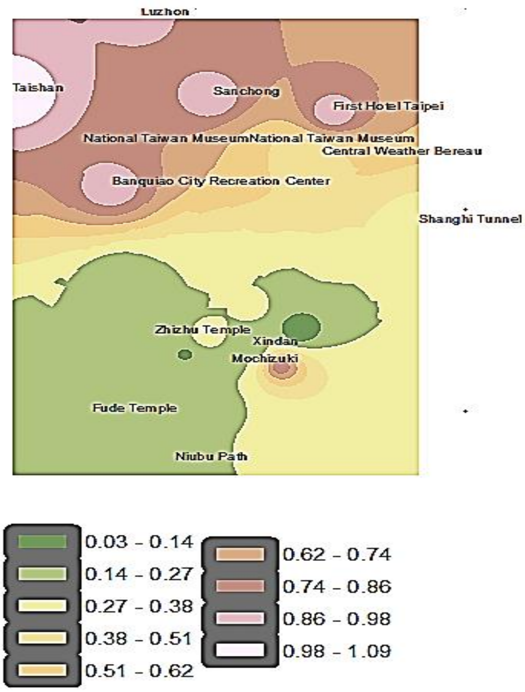

Figure 9. The spatial distribution AOD over study areas on and 29 May, 2011.

MODIS - AOD and Dark Target - AOD from LANDSAT. This is because both have the similar algorithm. Over land surface, for the MODIS - AOD retrieval by the dark target algorithm, the value of surface reflectance in dark targets is low in parts of the visible and shortwave infrared spectrum. Generally, vegetable and dark soil areas are examples of such dark targets. The basic algorithm uses two visible wavelengths such as 0.47 and 0.65 μm and one shortwave infrared bands (2.1μm) (Kaufman et al., 1997; Levy et al., 2007). Thus, the degree of agreement between MODIS AOD and Dark Target - retrieved AOD from LANDSAT is considerable.

Banquiao Recreation Center, Taishan, and First Hotel Taipei are the industrial regions, and have the high aerosol optical thickness. There was a fluctuation in the AOD value between 0.89 and 1 in these locations. Other stations such as National Taiwan Museum, Jieshow Park and Central Weather Bereau had a decrease in the aerosol loading from 0.6 to 0.8. In contrast, the of AOD was 0.16 in rural areas such as Fude Temple, Zhizhu Temple, and Niubu Path. It may be explained by these observations are located far from industrialized areas; the lower value of satellite AOD retrieval was depicted the less air pollution.

5. Conclusions

AOD retrieved by the dispersion coefficient method is associated with AERONET data. It is likely that contrast reduction methods were successfully demonstrated their improvement in obtaining a higher accuracy of atmospheric aerosol optical depth retrieval. The RMSE was from 0.2 to 0.4, and about 50% amount of data were within expected error (EE=±(0.05+0.15AODsunphotometer). The uncertainty of this method might be explained by simplification in variant surface reflectance, interaction between the surface and atmosphere, or atmospheric radiation assumption when estimating the AOD. In addition, the dispersion coefficient result shows a significant difference due to the difference of window sizes. AOD retrieval errors did not show linear relationship with window sizes. Urban areas have finer resolution of AOD as applying the dispersion coefficient method to Landsat data.

The dark target retrieval AOD was closely related to AERONET as well as MODIS - AOD. The result of comparison with that of the AERONET measurement revealed a high correlation between the remotely sensed values and the ground base measurements, with the correlation coefficient equals to 0.84. The uncertainty in the derivation is with errors of 4 - 26% of the optical aerosol thickness. The selective of dark pixel ensures 'strong pixels" as well as atmospheric correction process which improves the accuracy of this method.

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