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# Retrieval of Aerosol Optical Thickness using MODIS 500 x 500m$^2$, a study in Hong Kong and Pearl River Delta region

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***Abstract*—Aerosol detection and monitoring by satellite observations has been substantially developed over past decades. While several state-of-art aerosol retrieval techniques provide aerosol properties in global scale, the more detail characteristics remain unknown because most of the satellite sensors are limited to 1km resolution observations. However, a new aerosol retrieval algorithm for the Moderate Resolution Imaging Spectroradiometer (MODIS) 500m resolution data is developed to retrieve aerosol properties over land, which helps on addressing the aerosol climatic issues in local/urban scale. The rationale of our technique is to first estimate the aerosol reflectances by decomposing the top-of-atmosphere (TOA) reflectance from surface reflectance and Rayleigh path radiance. The modified Minimum Reflectance Technique (MRT) is adopted for the determination of the seasonal surface reflectances. A good agreement is revealed between the surface reflectances of MRT images and MODIS land surface reflectance products (MOD09), with a strong correlation of 0.9. Moreover, comprehensive look up tables (LUT) are constructed with the considerations of various aerosol optical properties and sun-viewing geometry in the radiative transfer calculations. The resulting 500m aerosol optical thickness (AOT) data are highly correlated (r=0.94) with the AERONET sunphotometer observations in Hong Kong. This study demonstrates the applicability of aerosol retrieval at fine resolution in urban areas, which can assist the study of aerosol loading distribution and the impact of transient pollution on urban air quality. In addition, the MODIS 500m AOT images can also be used to study the cross-boundary aerosols and feasible on locating the pollutant sources in the Pearl River Delta (PRD) region.**

## I. INTRODUCTION

Aerosol retrieval from satellite remote sensed images has been developed for decades and it basically aims to retrieve the attenuated radiation by aerosols from the reflection of atmosphere and surface. It is always complex to retrieve aerosol from satellite remote sensing where the surface reflectances on ground are always undistinguishable. The estimation of surface reflectances is then the key factor on the aerosol retrieval which attempts to differentiate the aerosol signal from surface.

Kaufman and Tanré first proposed the dense dark vegetation (DDV) method using the multi-wavelength algorithm on the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images [1]. The DDV (called as collection 4) algorithm works only on vegetation areas with coverage larger than 60% where the surface reflectances are very low. It prohibits the widespread use of aerosol estimation on the areas of bright surface, such as deserts and urban. Chu et al. revealed that the MODIS collection 4 algorithm has a positive bias in comparison to the AErosol Robotic NETwork (AERONET [3]) sunphotometer data [2]. Remer et al. [4] and Levy et al. [5] reported certain inherent problems in determining surface reflectance using the DDV algorithm. These results imply that inaccurate surface properties can lead to errors in aerosol retrieval. Recently, Levy et al. [6] modified the surface reflectance determination in MODIS aerosol retrieval algorithm (called as collection 5) by considering the band correlation based on vegetation index ($NDVI_{SWIR}$) and the scattering angle. Although significant improvements of MOD04 collection 5 algorithm was shown both on the accuracy and continuity of aerosol retrieval [7][8], the southern China especially in Hong Kong and the PRD region has been identified as having a large error of AOT [1]. In spite of the stated accuracy on aerosol retrieval over land, there are two major limitations of MOD04 data for local/urban scale study, which are bright surfaces and spatial resolution. To overcome these limitations, new techniques are developed in this study.

It is a challenging task for aerosol retrieval over bright surfaces, where the land surfaces and aerosol contents are not ease for differentiating due to their high reflectance values. Hsu et al. recently developed a deep blue algorithm for aerosol retrieval over desert, arid, semiarid and urban areas using MODIS images [9][10]. This algorithm made use of the blue wavelengths where the surface reflectances are bright in red region and darker in blue region. In order to infer the aerosol information, a surface reflectance database was developed based on the minimum reflectance technique (MRT) [11][12]. The accuracy of resulting AOT was validated with a good

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agreement (within 30%) with AERONET ground measurements. Lee et al. [13] used similar technique on the estimation of the surface reflectance for the aerosol retrieval in Korea. This technique indicates the advantageous on aerosol observation over bright surface areas.

The coarse spatial resolution of the MODIS products (10 km) only provide meaningful depictions on a broad regional scale, whereas aerosol monitoring over complex regions, such as urban areas in Hong Kong (1,095 $km^2$) (Figure 1) requires more spatial and spectral details. Li et al. [14] have developed a 1km AOT algorithm based on the MODIS collection 4 algorithm for a study in Hong Kong, but it was limited on dense vegetated areas and the validation was made use with the handheld sunphotometers during limited period. In order to retrieve the inherent aerosol and map the aerosol loading distribution with a high detailed level, a new MODIS 500m resolution aerosol retrieval algorithm coupled with the modified MRT is proposed in this study.

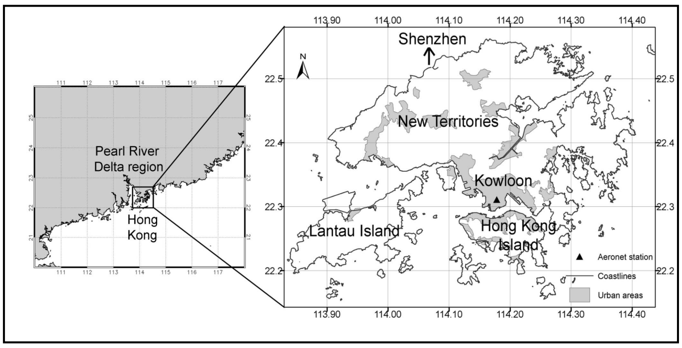


Figure 1. Map of Hong Kong and AERONET station

## II. DATA USED

In this study, the 500m resolution TERRA/MODIS level 1b calibrated reflectance (MOD02Hkm) and MODIS level 2 aerosol products (MOD04) of year 2007 were collected. Validation of retrieved AOT was carried out by comparing with the AERONET data in Hong Kong. AERONET is a federated network of ground sunphotometers, which consists of Cimel sunphotometer for measuring the aerosol extinction every fifteen minutes using multiple wavelengths radiometer. In order to validate the surface reflectance estimated from the modified MRT, the MODIS surface reflectance products (MOD09 8-days composite surface reflectance images) were also acquired from NASA Goddard Earth Science Distributed Active Archive Center (DAAC) for year 2007. The MOD09 images are corrected for the aerosol, gaseous and water vapour using the inputs of MODIS atmospheric data. The surface reflectances are validated with 150 AERONET stations and it is theoretically considered as good if the data has error ± 0.005 + 5% [15].

## III. METHODOLOGY

The rationale of the proposed aerosol retrieval algorithm is the determination of the aerosol reflectances by decomposing the Top-of-Atmosphere (TOA) reflectances from surface reflectance and the Rayleigh path radiance. The TOA reflectance $\rho_{TOA}(\theta_0, \theta_s, \phi)$ is expressed as:

$$\rho_{TOA}(\theta_0, \theta_s, \phi) = \rho_{ATM}(\theta_0, \theta_s, \phi, \tau_{Aer}, \tau_{Ray}, p(\theta), \omega_0) + \frac{T_{Tot}(\theta_0) \cdot T_{Tot}(\theta_s) \cdot \rho_{Surf}(\theta_0, \theta_s)}{1 - \rho_{Surf}(\theta_0, \theta_s) \cdot r_{Hem}(\tau_{Tot}, g)} \quad (1)$$

where $\theta_0$ is the solar zenith angle, $\theta_s$ is the satellite zenith angle, $\phi$ is the azimuth angle, $\tau_{Aer}$, $\tau_{Ray}$ and $\tau_{Tot}$ are aerosol optical thickness, Rayleigh optical thickness, and total optical thickness respectively. $p(\theta)$ is the phase function, $\omega_0$ is a single-scattering albedo, g is the asymmetry parameter, $\rho_{ATM}$ is the atmospheric path reflectance, $T_{Tot}(m_0)$ is the total transmittance, $\rho_{Surf}(\theta_0, \theta_s)$ is the surface reflectance, and $r_{Hem}(\tau_{Tot}, g)$ is the hemispheric reflectance. Figure 2 illustrates the work flows of aerosol retrieval in this study. The discussion of Rayleigh path radiance, surface reflectances and Look Up Table (LUT) are illustrated in following sections.

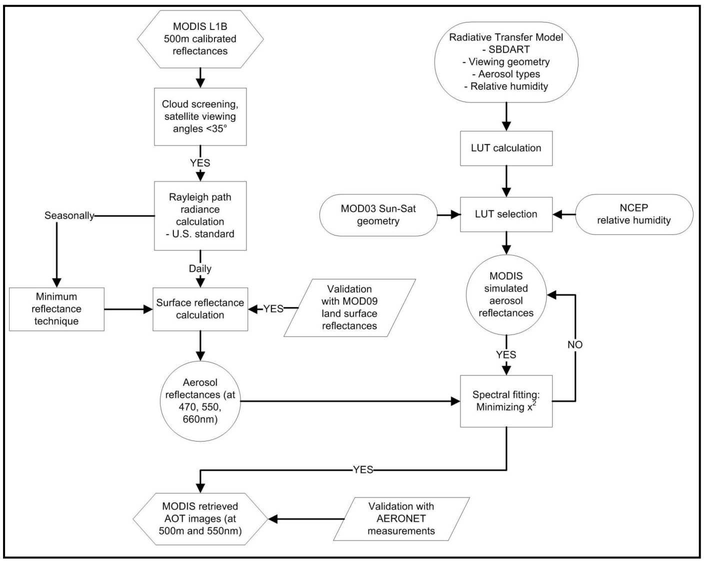


Figure 2. Schematic diagram for aerosol retrieval in the study

### A. Rayleigh and surface reflectances

The determination of the Rayleigh path radiance is based on the computation of spectral dependence of the Rayleigh optical depth and phase function. The equation 2 is adopted for calculating the Rayleigh scattering optical thickness [16].

$$\tau_{Ray}(\lambda) = A \cdot \lambda^{-(B + C\lambda + D/\lambda)} \times \frac{p(z)}{p_0} \quad (2)$$

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where A, B, C, D are the constants of the total Rayleigh scattering cross-section and the total Rayleigh volume scattering coefficient at standard atmospheric. P(z) is the pressure relevant to the height and it is determined by parameterized barometric equation.

$$p(z) = p_0 \cdot \exp\left[\frac{-29.87 \cdot g \cdot 0.75 \cdot z}{8.315 \cdot (T_{SURF} - g \cdot 0.75 \cdot z)}\right] \quad (3)$$

A fine resolution Digital Elevation Model (DEM) is used for estimating the height z and for calculating the pressure p(z) for each pixel. g is the gravity acceleration ($9.807 ms^{-2}$) and Tsurf is the surface temperature.

The basic scheme of the modified MRT is to extract the minimum reflectance values of land surfaces over a time period. To overcome the seasonal land cover changes, seasonal minimum reflectance images were derived based on at least thirty clear-sky images on each season. Then, the second minimum reflectance values were retrieved to prevent abnormal low reflectance such as noise or shadow. It is noted that the second minimum reflectance values have the stronger agreement with the surface reflectances. In addition, the cloud screening method was used for determining the cloud contamination and it is important for cloud removal particularly in cloud-prone area like Hong Kong. The nadir images with satellite viewing angle <35$^o$ have only been considered in this study which can minimize the angular effects caused by bidirectional reflectivity in the heterogeneous areas.

*B. Aerosol retrieval*

This study used the Santa Babara DISORT Radiative Transfer (SBDART [17]) code for constructing the LUT, which is used to calculate the aerosol reflectance as a function of AOT under various sun-viewing geometries and relative humidity (RH). Input data for SBDART consists of three main types, they are atmosphere, aerosol, and surface data. A few aerosol models from the Optical Properties of Aerosols and clouds (OPAC [18]) database were used in this study. Each aerosol model are characterized by their own microphysical and optical properties, such as particle size distribution, complex refractive indices, RH, etc. They are classified as i. continental clean (CC), ii. continental average (CA), iii. continental pollutant (CP), iv. desert dust (DD), v. martime clean (MC), vi. marine pollutant (MP) models.

For the LUT construction, above 6 aerosol models with 9 solar zenith angles (0°~80°, Δ=10°), 17 view zenith angles (0°~80°, Δ=5°), 18 relative sun/satellite azimuth angles (0°~170°, Δ=10°), 8 RH values (RH=0%, 50%, 70%, 80%, 90%, 95%, 98%, and 99%) are considered. The SBDART code uses the aerosol properties associated with a given model, plus the combinations of values for the 5 parameters listed above (amounting to 132,192 combinations at 3 bands (470, 550, 660 nm)), to compute hypothetical AOT. Figure 3 represents one of the numerous LUTs from the SBDART results.

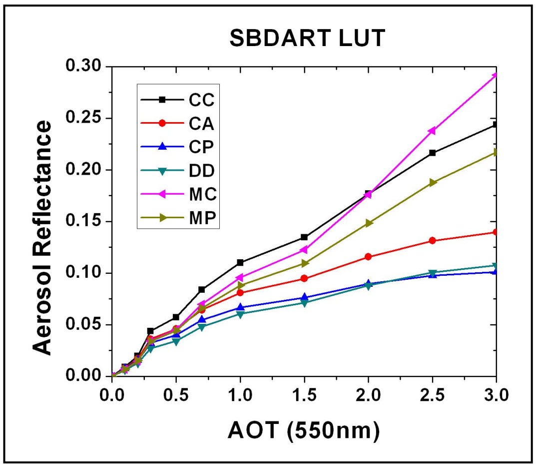


Figure 3. Aerosol reflectance as a function of AOT. The SBDART calculations were performed with solar zenith angle=30$^o$, satellite zenith angle=10$^o$, azimuth angle=150$^o$, and RH=50%

The first step in this retrieval starts from reading of the LUTs with specific RH. RH values are acquired from the National Centers for Environmental Prediction (NCEP) model [19]. The second step is the interpolation of the LUT geometry to the measured (satellite) geometry. These two steps can reduce the number of LUT to being read in the computer memory. In the third step, hypothetical aerosol reflectances are determined based on the satellite estimated aerosol reflectance at 470nm band. Finally, the satellite observed aerosol reflectances are compared to the set of hypothetical aerosol reflectances for each geometrical-corrected LUT. For these comparisons, an optimal spectral shape-fitting technique was executed for selecting the appropriate aerosol model with the smallest systematic errors ([1][20][21][22]). The optimal spectral shape-fitting algorithm is expressed as:

$$x^2 = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\rho^m_{Aer}(\lambda_i) - \rho^a_{Aer}(\lambda_i)}{\rho^m_{Aer}(\lambda_i)}\right)^2 \quad (4)$$

where the error term of $x^2$ is described as the residual of the measured aerosol reflectances $\rho^m_{Aer}(\lambda_i)$ from MODIS and modeled aerosol reflectances $\rho^c_{Aer}(\lambda_i)$ from aerosol models. The minimum residual of $x^2$ is selected among six aerosol types on each pixel. Thus, the appropriate aerosol type is selected and the corresponding AOT values are then derived on each pixel.

## IV. RESULTS

### *A. Validation with surface reflectance*

The minimum reflectance images have been derived seasonally for the estimation of surface reflectances. The validation of the MRT images was undertaken by comparing with the MOD09 images. The direct comparisons between seasonally averaged MOD09 images and MRT images are shown in Figure 4. Due to the present of broken clouds cover on MOD09 images, the higher surface reflectances always observed in the northwest of the PRD region especially on Figure 4a. However, the MRT images on the longer wavelengths (e.g. 550 and 660nm) show their highly similarity with the MOD09 images (Figure 4c, d). The correlation analysis results reveals that strong correlations were observed in the fall and winter seasons (r>0.9), while moderate correlation were noted in the spring season (r>0.8). It is found that the differences in surface reflectances between MOD09 and MRT were less than or equal to 0.01 at 550 and 660nm wavelengths while the differences are higher at 470nm wavelength (~0.02-0.03). These overestimated surface reflectances in MRT may lead to AOT values of 0.2-0.3. However, this estimation is presumably assumed the MOD09 images are ground surface reflectances whereas it does consist errors [15]. Thus, the uncertainty of AOT values induced by the MRT surface reflectances may be in a range from 0 to 0.2 where it is significant in the shorter wavelength (470 nm) and minor in the longer wavelengths (550, 660 nm).

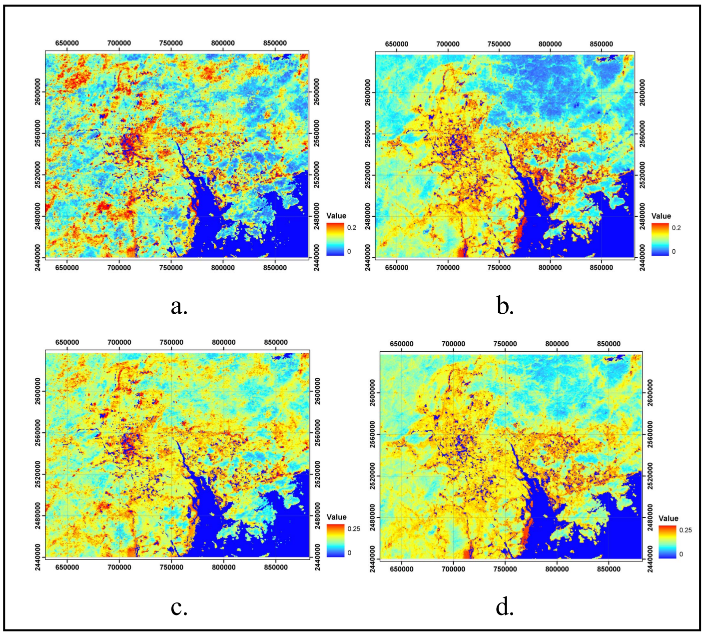


Figure 4. Surface reflectance maps in fall season (in UTM grid coordinate system); a. MOD09 at 470nm, b. MRT at 470nm, c. MOD09 at 550nm, d. MRT at 550nm

### *B. Validation with AERONET measurements*

Due to the coarse resolution but large areal coverage, MODIS images are only be considered for the air pollution mapping in a regional context. This would be a prominent improvement of the aerosol retrieval in a higher resolution (500m). To evaluate the performance of our methodology, the MODIS 500m retrieved AOT was validated with the AERONET measurements in year 2007 (Figure 5a). The MOD04 collection 4 and 5 AOT data were also compared with the AERONET which are shown in Figure 5b. Good agreements are shown between the MODIS 500m AOT and the AERONET, with a linear-fitting correlation coefficient (r) of 0.937, which is higher than those from MOD04 collection 5 (r=0.913) and MOD04 collection 4 (r=0.877) data. In addition, the slope of the linear-fitting equation on MODIS 500m plot (Figure 5a) is closer to the unity which performs superior than those on Figure 5b. Although a strong correlation is revealed between MODIS 500m AOT and AERONET data, it tends to underestimate the AOT with a value of ~0.055. Similar values are also shown on the collection 5 and collection 4 data. Most importantly, our methodology can retrieve AOT images in a highly detailed context which can depict the AOT in both urban and vegetated areas. This certainly can help on the improvements of AOT retrieval in complex topography areas like Hong Kong.

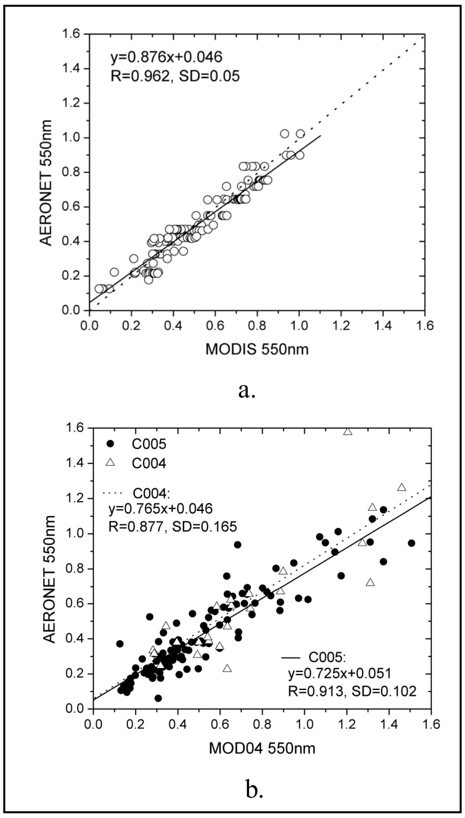


Figure 5. Comparison plot, a. between MODIS 500m AOT with AERONET measurements; b. between MOD04 collection 4 and 5 AOT with AERONET measurements. Note that there is insufficient of MOD04 collection 4 data in the NASA GSFC database since the collection 4 data is replaced with collection 5 data in schedule, only twenty-four measurements were temporarily matched with AERONET data

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The AOT distribution over Hong Kong and the PRD region on 20 October 2007 retrieved using MODIS 500m data is shown in Figure 6c, with a resolution of 500 x 500m$^2$. The AOT is relatively high from a range of ~0.6 on rural areas to ~2 on urban areas. It is noted that the AOT values are high in urban areas due to the anthropogenic pollutions and the AOT values are comparative small in countryside (see RGB image in Figure 6a). The northern part of Hong Kong especially nearly the border of Shenzhen has suffered the cross-boundary pollutants which are emitted from the industries in the PRD region, AOT value of 1.2 is observed. In Figure 6c, severe air pollution was observed in the Guangzhou areas, which was caused by the emission of industries and power plants. The pollutants are often trapped in the PRD areas due to the low wind speed (~2ms$^{-1}$) in the fall. In contrast, results from the MODIS collection 5 algorithm (Figure 6b) compares less favorably, which has coarser resolution (10 x 10km$^2$) and is ineffectual for aerosol mapping especially in urban areas.

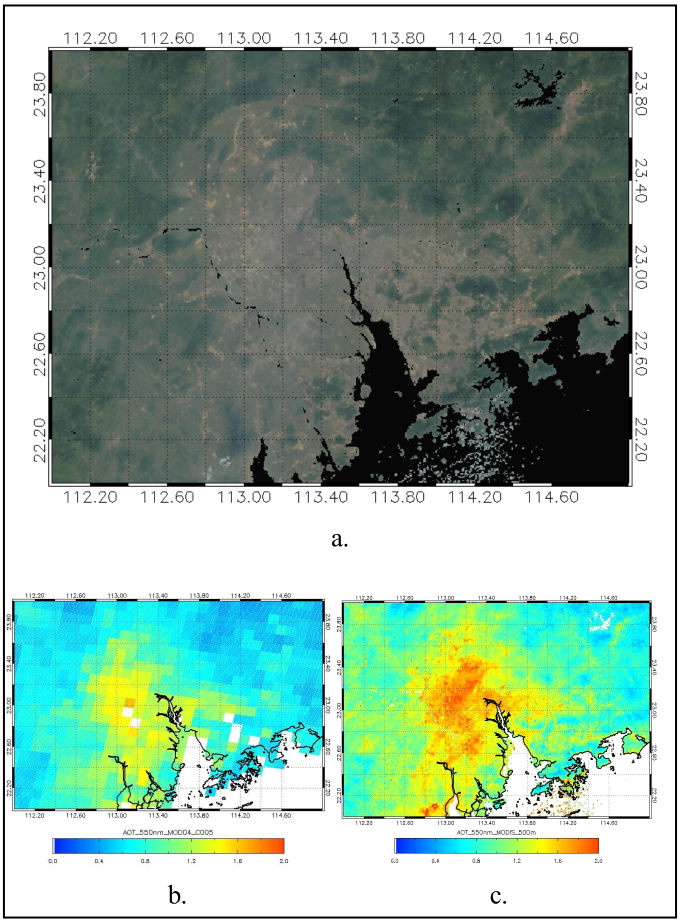


Figure 6. a. Color composite RGB image on 20th October, 2007, b. AOT at 550nm derived from MODIS MOD04 collection 5 algorithm and c. from this study with 500 x 500m$^2$ over Hong Kong over the Pearl river Delta (PRD) region

## V. CONCLUSION

New aerosol retrieval algorithm for MODIS 500m data was proposed in this study. This method is coupled with the modified MRT which is used to derive the surface reflectance images and comprehensive LUTs which consider the various aerosol models, sun-satellite geometries and RH conditions in the radiative transfer modeling. The MODIS 500m AOT was able to estimate the aerosol over both urban and vegetated areas in a high detailed context. Good correlation in the comparison of land surface reflectance was found between the MRT images and MOD09 products which suggest the MRT images are useful for the surface reflectance estimation. The derived MODIS 500m AOT showed good accuracy (r=0.962) compared with ground-based AERONET measurement, where lower correlations were found using MODIS collection 5 (r=0.913) and collection 4 (r=0.877) data. Given with the higher accuracy and higher spatial resolution of derived MODIS 500m AOT images, they can be used to study the cross-boundary transient aerosol and local anthropogenic aerosol loading distribution.

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