

Remote Sensing-Based Aerosol Optical Thickness for Monitoring Particular Matter over the City [†]

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Abstract: Urban development contributing to air pollution is one of the factors seriously affecting public health. Besides the traditional ground observation methods, the current space technology has been added to the monitoring and managing environment. This research used Landsat satellite image to detect PM10 from by the Aerosol Optical Thickness (AOT) method for Ho Chi Minh City area. The regression analysis was used for establishing the relationship between the PM10 data obtained at ground stations and AOT values from processed images in 2003. The analysis showed a good correlation coefficient ($R = 0.95$) for the case of AOT calculated from spectral reflective green band. The relative radiation normalization was carried out for satellite imaging in 2015 in order to simulate the spatial distribution of PM10 with the same regression function. The distribution for PM10 aerosol pollution is focused on the urban area, traffic booth and industrial zones. The results of this study provided a picture of general distribution for current pollution status and also supported the determining of specified polluted areas. This has provided helpful and good support for zoning and urban environmental management in accordance with urban development.

Keywords: air pollution; AOT; PM10; reflective band; relative radiation normalization; urban development

1. Introduction

As urban development and industrialization increases, transportation activities become overloaded. The formation and development of export processing zones, and industrial parks makes the problem of pollution in general, and the problem of air pollution in particular, increasingly serious. Air pollutants in the aerosol form can be SO₂, NO₂, CO, or PM10 dust. The emission of air pollutants is often difficult to control because it is governed by many factors, such as wind direction, geomorphology of the area, and the presence of construction works. Therefore, air pollution is often especially variable in space, even over short distances.

At present, there is much research on the application of remote sensing to assess the air quality. The methods based on radiation data in the Earth's surface are stored in a digital image, which is then converted into surface reflectance values. It then estimates the concentration of PM10 dust by a number of direct or indirect methods and compares them with the data at the ground stations at the same time, in order to establish a relationship between them.

Currently, research related to the determination of aerosol optical sensitivities is being explored in order to find correlations between atmospheric pollution components. The spatial resolution of

Landsat and SPOT imagery allows for some researchers to develop a series of methods based on radiation equations, atmospheric models, and image-based methods. Aerosol Optical Thickness (AOT) is the degree to which aerosols prevent the transmission of light. The aerosol optical depth or optical thickness is defined as the integrated extinction coefficient over a vertical column of unit cross section. Extinction coefficient is the fractional depletion of radiance per unit path length (also called attenuation especially in reference to radar frequencies). The optical thickness along the vertical direction is also called normal optical thickness (compared to optical thickness along slant path length) [1].

Kaufman et al. (1990) have developed an algorithm that determines AOT (use of soil and water black objects) from differences in upward radiation received by satellites during a clear day in (zero pollution) and a misty day (with pollution). This method assumes that the surface reflectivity between a clear day and a misty day does not change [2].

Sifakis and Deschamps (1992) used SPOT images to estimate the distribution of air pollution in the city of Toulouse in France. They developed an equation for calculating the aerosol optical depth difference between a reference image (well-weathered) and a polluted image. Their method is based on the fact that after adjusting the observation angles and the sun, the remaining deviation of the apparent radiation is due to the pollutant [3].

In addition, Hadjimitsis and Clayton (2009) developed a method combining the Darkest Object Subtraction and radiated equations for calculating AOT values for bands 1 and 2 of Landsat TM. They used a new method to determine AOT through darkest atmosphere correction in the London Heathrow airport area and in the Pafos airport area in Cyprus [4].

There are many studies on the air environment in Vietnam, especially concerning the assessment of air pollution in big cities such as Hanoi, Ho Chi Minh City (HCMC), Da Nang, Can Tho. However, the majority of the research focuses on the analysis of statistics from measurements at ground monitoring stations, or on the basis of modeling for spatial simulation. Yet, the quantitative results are not detailed.

Luong Chinh Ke et al. (2010) studied the scientific basis of the ability to detect and monitor certain components of air pollution, based on a combination of satellite imagery and observation station data. At the same time, the group has proposed a technological process to establish an air pollution map for a specific area [5].

Tran Thi Van et al. (2011) carried out the project “Research on remote sensing of air quality (dust component) in urban areas, test for HCMC”. They demonstrated that the green wavelength spectrum of the Landsat satellite image correlated well with PM10 dust measurements from ground stations [6].

This paper presents the results of the research on the possibility of detecting PM10 dust from remote sensing technologies in urban areas, based on the correlation and regression between AOT values, calculated on satellite imagery and ground measurements from auto-observation stations, based on the built regression equation integrated with the relative radiometric normalization method. This study monitored the dust environment in two years, 2003 and 2015. The area of application is the middle of HCMC.

2. Methods

2.1. The Basis for Determining AOT

Techniques used to calculate AOT were developed by Sifakis and Paronis [7]. According to this method, AOT should be calculated from remote sensing to detect PM10. Then, by regression analysis, the relationship is established between PM10 data obtained at the stations on the ground, and the AOT values from the processed image. The two types of data must have the same date and time of acquisition. The method of determining the AOT is determined based on the standard deviation reflection on pollution days, and the reference date (day clean). In this study, two satellite images were compared according to the value of radiation. One image was captured in pollution and the other one, called the reference image, was obtained in clean air conditions. The origin of

calculations based on basic equations of reflection in satellite and AOT values are determined by the formula [3]:

$$\Delta\tau = \tau_2 - \tau_1 = \ln\left[\frac{\sigma_1(\rho)}{\sigma_2(\rho)}\right], \quad (1)$$

where, $\Delta\tau = \tau_2 - \tau_1$ is the optical thickness (not units) of clean days and days corresponding pollution; $\sigma_1(\rho)$ is the standard deviation of the reflectance of clean days; $\sigma_2(\rho)$ is the standard deviation of the reflectance of polluted days.

On the other hand, the optical thickness is approximately equal to 0 in the clean day, because there is no or very little pollution components, while $\tau_1 = 0$, formula (1) becomes:

$$\Delta\tau = \tau_2 = \ln\left[\frac{\sigma_1(\rho)}{\sigma_2(\rho)}\right], \quad (2)$$

Or, only the remaining component τ_2 which is the AOT on the image of pollution day.

2.2. Relative Radiometric Normalization to Multi-Temporal Images

The objects in the multi-temporal image are changed and almost impossible to perform the comparative automated methods. To accurately detect the change of the landscape according to the changes of surface reflectance from multi-temporal images, radiometric normalization needs to be implemented. There are two methods for standardizing radiation; in this case, it is the absolute and relative normalization. The absolute normalization method requires the use of ground measurements at the time of data acquisition. This cannot be done, because there is no measured data in parallel on the ground for the different images. The relative radiometric normalization method requires no ground measurements of the atmosphere at the image acquisition time. Accordingly, an image is used as a reference image, and the rest will be subject images. It means that the subject images will be adjusted according to the atmospheric, geometry, lighting and environment conditions by the reference image. The base premise of this approach is that the radiation reaching the satellite sensor can be represented as a linear function of the reflection [8]. For many sensors, the spectral radiance values in each band is a linear function of reflective radiation reaching the sensor. Thus, the difference in atmosphere and spectrum between the images is also linearly related. The linear expression is applied to the process of normalization as follows:

$$S_{\text{ref-}i} = a_i S_{\text{sub-}i} + b_i, \quad (3)$$

where $S_{\text{ref-}i}$ is the pixel value of the i th band in the reference image; $S_{\text{sub-}i}$ is the pixel value of the i th band in the subject image; a_i , b_i are the regression coefficients that will be calculated according to $S_{\text{ref-}i}$ and $S_{\text{sub-}i}$.

One of the important methods to be able to determine the coefficients a_i and b_i is the method of linear regression analysis according to the pair of unchanged points extracted from two images. The point does not change or is hardly changed over time, artificial objects such as roads, roofs, and parks are selected. According to Schott et al. (1998) [8] they are artificial objects with reflection independent of the season and the ecological cycle. The difference in the value of the object spectrum is assumed to be the linear function.

After determining the coefficients a_i and b_i , the subject image will be normalized according to the following formula:

$$S'_i = a_i S_i + b_i, \quad (4)$$

where S'_i is the pixel value normalized in the i th band; S_i is the pixel value in the original image in the i th band; a_i , b_i are the regression coefficients calculated from the above equation; RMSE (root mean square error) was evaluated for the case before and after the normalization to demonstrate the efficiency [9].

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum (S' - S)^2}, \quad (5)$$

where n is the number of pixels taken to calculate the RMSE; S' is the pixel value normalized; S is the value in the original image pixel, respectively. RMSE values have decreased after standardization, and are regarded as successful results.

3. Results and Discussion

Satellite images taken in this study were the Landsat ETM+ and Landsat/OLI and TIRS with acquisition time as follows: LANDSAT/ETM—16/2/2003; LANDSAT/OLI and TIRS—9/2/2015.

Data sets used to build regression were determined from the measured value of PM10 concentrations in ground auto-observation stations corresponding to the value of AOT in the image. AOT values were independent variable; the concentration of PM10 was the dependent one. Since then the empirical coefficients were determined. The best regression function will be selected in the process of statistical analysis to calculate the estimated value of PM10 on the entire image. It was based on the correlation coefficient. Regression function has been developed for Landsat dated 16/02/2003 under the best correlation to band AOT 2 (Table 1), and has form like formula 6.

$$PM10 = 15.639 \times AOT^2 + 87.147 \times AOT + 75.803 \quad (6)$$

Table 1. Correlation coefficient between spectral reflectance values of AOT images and PM10 dust concentration data at ground observation stations on 16 March 2003.

AOT Band	AOT-Band 1	AOT-Band 2	AOT-Band 3	AOT-Band 4
Correlation coefficient	$R^2 = 0.1981$	$R^2 = 0.9051$	$R^2 = 0.3995$	$R^2 = 0.342$

Currently, the auto-observation stations are mostly no longer active, so in the past (before 2003) and up to now (after 2009), there are no ground PM10 data to find correlations with for the images. To perform the PM10 distribution in 2015 in this study, the authors have used a relative radiometric normalization method to convert the environmental and atmospheric conditions on the images in 2015, according to the 2003 image conditions. Since then, we have calculated the AOT values for the appropriate band and applied the regression Equation (6) to determine PM10 values, finally mapped the simulation of PM10 spatial distribution in 2003 and 2015.

Checking the error of the results was done by absolute error, the difference between the PM10 concentrations at each observation station, and the corresponding PM10 concentration calculated on the Landsat image. From there, the root mean square error RMSE was determined with sample number $N = 6$ corresponding to 6 observation stations with a value of 11.07.

The map of PM10 dust concentration distribution according to satellite images was established for the middle of HCMC. The results from the LANDSAT image taken on 16 February 2003, and 9 February 2015 are shown in Figure 1. This is a snapshot of the PM10 dust environment at 10 a.m., not the average result of a measuring period. Therefore, the study has no comparison with the standards. The results will be the estimates of the spatial distribution of PM10 dust concentrations from satellite imagery, which demonstrate the ability to detect dust from satellite images in accordance with appropriate digital image processing.

Results on the map show that the contours of the PM10 values have localized shape, do not spread far, and distribute in many directions. This is explained by the process of dispersal of suspended matter in the air affected by the local wind. The urban area has quite a large surface roughness of terrain, and several high buildings close together. Therefore, seasonal prevailing wind and “vicious wind” do not impact much in the urban areas. Features of this wind are blowing in different directions under the effect of the flow of the vehicles as well as the anthropogenic heat waste. Comparison of the PM10 simulations between 2003 and 2015 reflects both a general picture, that is, in urban areas, concentrated urban areas, traffic points, and industrial parks, there was a high PM10 distribution, while they have a dispersed shape in the suburbs.

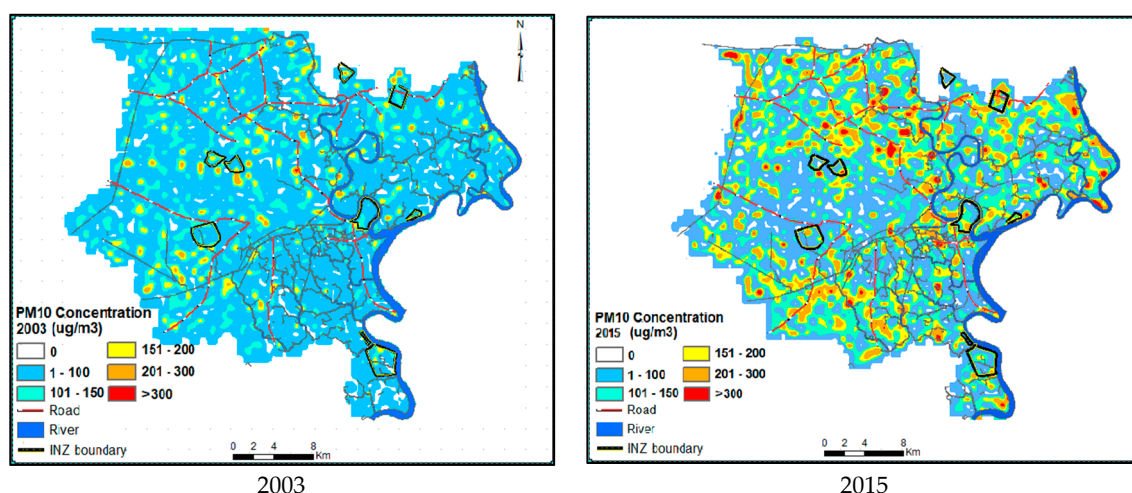


Figure 1. Spatial distribution of PM10 concentration on the time of image acquisition in the middle of HCMC. (INZ—Industrial zone).

The satellite image was taken at 10 am, which is the time of busy traffic when trucks are allowed to travel in the inner city, and production activities are also available and stable. The overall picture shows that in the whole area, low PM10 concentrations $< 100 \mu\text{g}/\text{m}^3$ were found in wetlands, in the north of Binh Chanh district, bordering with Long An, in the west of the district. Hoc Mon is bordered by Long An, Nha Be, south of District 9, Thanh Da Peninsula and along the Saigon River in District 12. Areas with high PM10 concentrations are concentrated in main roads, industrial parks with a value higher than $200 \mu\text{g}/\text{m}^3$, and even some places above $300 \mu\text{g}/\text{m}^3$. Generally, the expansion of high-value PM10 spatial distribution in 2015 as compared to 2003 is increasing, focusing on areas outside the urban core, where the new residential areas have been developing with new traffic routes. Today, the increasing traffic density in these areas, along with the immigration from other provinces into the HCMC, causes the air environment uncontrolled.

4. Conclusions

The paper presents a simulation study on PM10 concentration distribution, using the method of combining LANDSAT satellite image analysis with ground measurements through the aerosol optical thickness. The results of the study show the map of simulated PM10 dust for the years of 2003 and 2015. In the absence of ground measurements for calculation, the relative radiometric normalization method was used to standardize the 2015 image according to the 2003 image conditions, and then to simulate the distribution by the defined regression function. The results of this study provide an overview of the distribution of pollutants in a large area, as compared to previous methods. With the ground-based method, only the environmental situation at the location is measured, so it is not possible to measure the whole area. With the modeling approach, results are limited, due to the complexity of inputs (meteorology, emission sources, etc.). Therefore, the application of remote sensing technology to create a map of air quality for environmental management will bring about higher economic efficiency.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AOT	Aerosol Optical Thickness
PM	Particular Matter
RMSE	Root Mean Square Error
SPOT	(French) Satellite Pour l'Observation de la Terre, lit. "Satellite for observation of Earth"

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