THE INVESTIGATION OF AIR QUALITY OVER LANGKAWI ISLAND USING LANDSAT TM5

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ABSTRACT: The aim of this study is to investigate the air quality over Langkawi Island using Landsat TM5 images and ground truth data of PM10, which were obtained from Automatic Air Quality Monitoring System (AQMS). In this study, a map of particulate matter less than 10µm in diameter (PM_{10}) over Langkawi Island was generated in visible bands from Landsat TM5 image by using PCI Geomatica v10.1 Image Processing Software. The raw image of Landsat TM5 was converted from a Digital Number (DN) to radiance before converted again to two layers of reflectance, namely, (i) top of atmosphe (TOA) and (ii) ground surface reflectance. Then, atmospheric scattering values were generated by excluding TOA and ground surface reflectances. A linear regression between PM_{10} concentrations and atmospheric scattering was carried out to generate the PM_{10} concentrations map over Langkawi Island. This study shown that there is a good relationship between atmospheric scattering value from Landsat TM5 images and ground truth of PM_{10} concentrations from AQMS with correlation coefficient (R^2) of 0.82 and root-mean-squares error (RMS) of 0.05. This study therefore, has demonstrated the potential applications of digital Landsat TM5 satellite images for air quality studies.

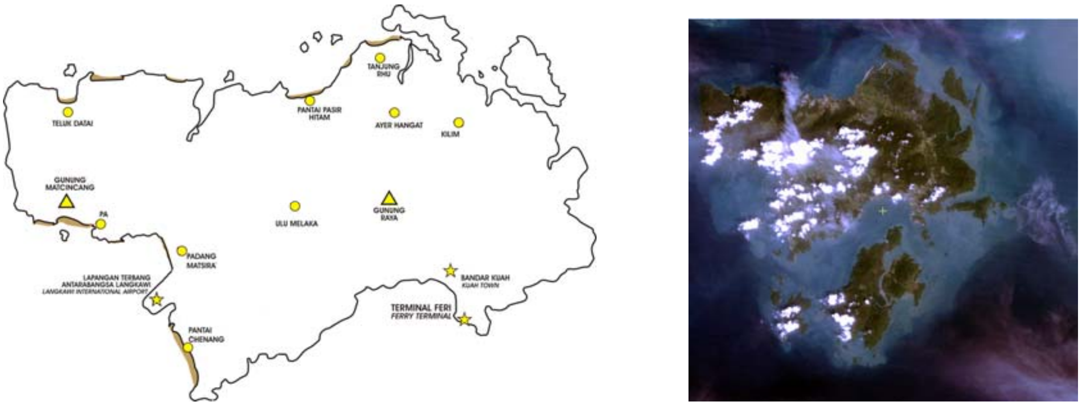
1. INTRODUCTION

Remote sensing of air quality studies usually requires simultaneous air quality measurements for calibration and assessment of algorithms accuracy. Correlation between ground measurements and multispectral scanner data for study sites were used to develop predictive equations for air quality parameters. The major effect of atmospheric aerosol on space observations can be analyzed by using spectral path radiance (Kaufman, 1993). The algorithm presented in this study is based on the relationship between the spectral path radiance (radiance that contaminates satellite observations of the Earth) using analytical derivations based on single-scattering radiation transfer theory. Many forms of aerosol optical thickness and particulate matter algorithms have been developed (Sifakis and Deschamps, 1992; Kaufman, et al., 1993; Ahmad and Hashim, 2000; Remer, 2005; and Zhang et al., 2011). Coefficient values of each algorithm were determined empirically and many studies presented different values. Hence, it is essential to calibrate these algorithms to suit a particular air environment. This study presents the potential of Landsat TM5 satellite image to determine the concentrations of particles less than 10µm in diameter (PM_{10}) in the atmosphere over Langkawi Island, Malaysia.

TM data was chosen because of its higher spatial resolution, relatively cheaper and availability of suitable bands for the current applications. TM data have been used widely in air quality studies over land area (Tanre et al., 1988; and Lim et al., 2006) and over ocean area (Tanre et al., 1997). However, most of the studies focused only one type of area. Conversely, studies covering both areas are still lacking to date. To study air quality in an area with land and water combination, an algorithm model is required to relate the TM signals with multispectral radiance responses as a mean of air quality monitoring. This requires air quality samples to be collected simultaneously as the satellite passes. The objectives of this study are (i) to develop remote sensing retrieval algorithms for PM_{10} concentration in land and coastal waters based on air optical model through regression with coincident ground-truth data and (ii) to perform data correction for multi-date analysis in order to establish calibrated algorithms for local application using TM data.

2. STUDY AREA AND DATA ACQUISITIONS

The study area is Langkawi Island which located within latitudes $99^0$56’33”E to $100^0$00’54”E and longitudes $6^0$09’43”N to $6^0$29’01”N (Figure 1). Langkawi Island is one of the most attractive tourist destinations in Malaysia, which located to the north-west of Peninsular Malaysia. Topography of Langkawi Island is mountainous covered by forests reserve areas of 26,266 ha. The corresponding satellite track for the Landsat TM5 scenes is 128/56. Due to high cloud cover, only four TM scenes were available were captured on 21st February 2006, 9thMarch 2006, 4th November 2006 and 20th September 2007.



(a) (b)

Figure 1. The study area – Langkawi Island. (a) map of Langkawi Island; (b) True color of Landsat 5 TM satellite image 4th November 2006.

The ground truth data of PM_{10} were obtained from Automatic Air Quality Monitoring System (AQMS), which installed by the Department of Enviroment Malaysia at three strategic places, namely; (i)Sport Complex Langkawi; (ii)Sekolah Menengah Agama Mergong, Alor Setar, and; (iii) Sekolah Kebangsaan Bakar Arang, Sungai Petani. All air quality data were collected from February 2006 to September 2007 simultaneously during the satellite passing over the study area at 11:00AM. Figure 2 showed the air quality (PM_{10}) data from Air Quality Monitoring System at Sport Complex Langkawi on November 2006. The ground truth data of PM_{10} were used for calibration of algorithm and the other half for accuracy analysis. All meteorological data used in this study were taken from Weather Underground webpage, which also used by Cogliani (2001) and Rodr'iguez et al (2009). A Landsat TM5 satellite image, which were captured on 4th November 2006 were chosen to perform data correction for multi-date analysis in order to establish calibrated algorithms for local application using TM data with PM_{10} color coded based on Air Pollution Index scale.

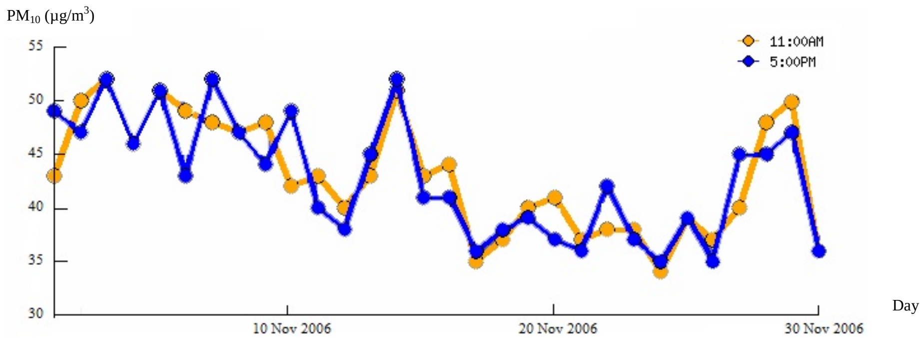


Figure 2. Air quality (PM_{10}) data from AQMS at Sport Complex Langkawi on November 2006.

3. AIR OPTICAL MODEL

3.1 Radiometric and Atmospheric Correction

A physical model relating radiance from the ground and the concentrations of air quality constituents provides the most effective way to analyze air quality by remote sensing. Radiometric correction was applied to transform the Digital Number (DN) values to radiance (L_λ) or reflectance (ρ_λ) values. There are two stages of radiometric calibration, which are; (i)conversion of the DN sensor to at-sensor radiances, which requires sensor calibration information (Mather, 2004) and; (ii)transformation of the at-sensor radiances to radiances at the earth's surface. Radiometric correction was applied to transform the DN values to radiance or reflectance values by using an algorithm given by Chander et al. (2009)

$$L_\lambda = Grescale * QCAL + Brescale \tag{1}$$

The value of *Grescale*, *QCAL* and *Brescale* for Landsat 5 TM used in this study were based on Chander et al. (2009). Ground surface reflectance, ρ_{ground}, over land and sea areas was carried out by using atmospheric correction (ATCOR2) algorithm developed by Dr. Rudolf Richter (Richter, 1997, 2005; Richter et al., 2009) in PCI Geomatica image processing software v10.1. ATCOR2 calculates corrections for flat terrain areas by applying constant or varying atmosphere accounting for adjacent effect. For relatively clear Landsat scenes, a reduction in between-scene variability can be achieved through normalization of solar irradiance by converting spectral radiance to planetary reflectance or albedo. This combined surface and atmospheric reflectance of the Earth is also known as top of atmosphere reflectance (ρ_{TOA}) and computed with the following formula (Mather, 2004)

$$\rho_{TOA}(\lambda,\theta_S,\theta_V,\phi) = \frac{\pi L(\lambda,\theta_S,\theta_V,\phi)d^2}{ESUN_\lambda \cos\theta_S} \tag{2}$$

where, d is Earth-Sun distance in astronomical units, $ESUN_\lambda$ is mean solar exo-atmospheric irradiances and, θ_S is solar zenith angle in degrees. Both values of d and $ESUN_\lambda$ were based on values given by Chander et al. (2009)

3.2 Atmospheric Scattering

This study assumed that both the land and water surface areas were lambertian and homogeneous. A lambertian surface condition assumption is usually used in a remote sensing image analysis, to simplify methods for reflectance retrieval. This assumption means that the surface reflective property will not vary by different observation geometry or terrain effects. If gas absorption is neglected, the total reflectance at the top of the atmosphere can be written as a function of surface reflectance. For dark target approximation method (Kaufman et al., 1997), the contribution of atmospheric scattering ρ_{atm} into the sensors field of view over dark surfaces basically can be expressed as

$$\rho_{atm}(\lambda,\theta_S,\theta_V,\phi) = \rho_{TOA}(\lambda,\theta_S,\theta_V,\phi) - \rho_{ground}(\lambda,\theta_S,\theta_V,\phi) \tag{3}$$

3.3 Aerosol Optical Thickness

The Mie scattering theory was applied to compute the aerosol phase function, $P_a(\theta_S,\theta_V,\phi)$ and spectral optical thickness, based on size distribution, real and imaginary index (Fukushima et al., 2000). Paronis and Hatzopoulos (1997), was neglecting Rayleigh scattering, therefore, Hahn (2009), was used the Mie theory for describing most spherical particle scattering systems, including Rayleigh scattering by following formula

$$\tau_a(\lambda) = \left(\frac{4\mu\mu_o}{\omega_o P_a(\theta_S,\theta_V,\phi)}\right)\rho_{atm}(\lambda,\theta_S,\theta_V,\phi) \tag{4}$$

where $\tau_a(\lambda)$ is aerosol optical thickness, μ is cosines of the view directions, and μ_o is cosines of the illumination directions. $\tau_a(\lambda)$ of the layer with height H is given by equation (5).

$$\tau_a(\lambda) = \pi f(RH)\int_0^H\int_0^5 Q_{ext,amb}(r)n(r)r^2 drdz \tag{5}$$

where $f(RH)$ is the ratio between size distribution integrated extinction efficiencies, $Q_{\tau ext,amb}$ is the extinction efficiency under ambient conditions and $n(r)$ describes the aerosol size distribution under dry conditions.

3.4 PM10 Mass Concentration of Air

It is possible to correlate satellite measured AOT to ground PM_{10} concentrations via a single homogeneous atmospheric layer containing spherical aerosol properties. The mass concentration at the surface is obtained after drying the sampled air and correlates with aerosol mass density, M is given by Koelemeijir et al. (2006)

$$PM_{10} = \frac{4}{3}\pi M_{atm}\int_0^5 r^3 n(r)dr \tag{6}$$

4. REGRESSION ALGORITHM

Hence, it can be expected that the parameter PM_{10} correlates better with atmospheric scattering directly by substituting the relations of equation (4), (5) and (6), PM_{10} can be rewrite in term of atmospheric scattering as

$$PM_{10} = \frac{16\mu\mu_o Mr_{eff\ (PM_{10})}}{3Hf(RH)Q_{ext(PM_{10})}\,\omega_o P_a} * \rho_{atm} \tag{7}$$

Solving the above simultaneous equations for PM_{10} concentrations, the series consisting of the atmospheric scattering value recorded on visible bands from Landsat TM5 images is simplified as

$$PM_{10} = \alpha_1 \rho_{atm}(\lambda_3) + \alpha_2 \rho_{atm}(\lambda_3) + \alpha_3 \rho_{atm}(\lambda_3) \tag{8}$$

Where $\alpha_i = \frac{16\mu\mu_o Mr_{eff\ (PM_{10})}}{3Hf(RH)Q_{ext(PM_{10})}\,\omega_o P_a}$, *i=1,2* and *3* are the functions of the coefficients in equation (7) which to be determined empirically by using multiple regression analysis.

5. ANALYSIS OF TM DATA

All of TM satellite image processing analyses were used by PCI Geomatica v10.1 Image Processing Software. A sub-scene of satellite for each date was extracted for analysis. The images were then rectified to the corresponding map to determine their geographical coordinates by using the second order polynomial coordinate transformation. The raw image in the visible channel of Landsat TM5 was converted from a Digital Number to radiance before converted again to two layers of reflectance, namely, (i) top of atmosphe (TOA) and (ii) ground surface reflectance. Then, atmospheric scattering values were generated by excluding TOA and ground surface reflectances.

The relationship between the ground truth reference data (PM_{10}) and the atmospheric scattering recorded by TM signals was carried out by examining the images for multi-date analysis. Figure 3 shows the relationship between PM_{10} concentrations and atmospheric scattering from TM signals. In this figure, atmospheric scattering at blue band, (λ_1) gave the highest value than others. Similar result was also recorded by Othman (2011).

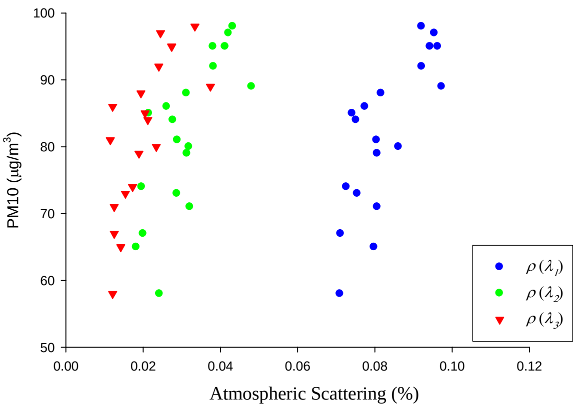


Figure 3. The relationship between PM_{10} concentrations and atmospheric scattering from TM signals.

A linear regression between ground truth of PM_{10} concentrations and atmospheric scattering recorded by TM signals were choose for calibration of PM_{10} algorithm. A total of eight forms of regression algorithms were tested with these data sets and their accuracies were compared (Table 1). The model of algorithm were selected based on the highest of correlation coefficient (R) and the lowest of root-mean-square error (RMSE).

The single band method was found to be less accurate. The calibration results showed that when a single independent variable was used the polynomial from gave better accuracy than the simple linear model. The accuracy was observed to improve when higher order series were used. Generally the accuracy increased when more spectral bands and higher order series was included in the regression analysis. The proposed model used these criteria and therefore produced superior results using different sets of data transformations.

Table 1. Regression results using different forms of algorithms for PM_{10}.

Regression Algorithm	PM_{10}	
	R	RMSE
$PM_{10} = \alpha_1 \rho_{atm}(\lambda_1)$	0.74	1.20
$PM_{10} = \alpha_1 \rho_{atm}(\lambda_2)$	0.61	1.48
$PM_{10} = \alpha_1 \rho_{atm}(\lambda_3)$	0.64	1.17
$PM_{10} = \alpha_1 \rho_{atm}(\lambda_1) + \alpha_2 \rho_{atm}(\lambda_2)$	0.69	0.98
$PM_{10} = \alpha_1 \rho_{atm}(\lambda_1) + \alpha_2 \rho_{atm}(\lambda_3)$	0.75	0.54
$PM_{10} = \alpha_1 \rho_{atm}(\lambda_2) + \alpha_2 \rho_{atm}(\lambda_3)$	0.35	4.5
$PM_{10} = \alpha_1 \rho_{atm}(\lambda_1)^2 + \alpha_2 \rho_{atm}(\lambda_3)^2$	0.78	0.28
$PM_{10} = \alpha_1 \rho_{atm}(\lambda_3) + \alpha_2 \rho_{atm}(\lambda_3) + \alpha_3 \rho_{atm}(\lambda_3)$	0.82	0.05

6. RESULTS AND DISCUSSIONS

For those multi-date analyses, the uses of combined raw data have produced satisfactory results. Maps of these air quality parameters were then generated by using the coefficients obtained from the regression analysis of the proposed algorithm. Land and cloud areas were masked out by using threshold values of band 4 and thermal band data. The air quality images were corrected geometrically through resampling process by using the nearest neighbor method. Image smoothing was performed to each map by using the Gamma filter to remove random noise while preserving high frequency features (edges). The generated map was color-coded for visual interpretation based on Air Pollution Index by Department of Environment, Malaysia.

The spatial distribution of PM10 over Langkawi Island was generated from Landsat TM5 satellite image on 4th November 2006 using developed multispectral algorithm (Figure 4). A PM_{10} map consisting a regions in colour of green (good), yellow (moderate), orange (unhealthy for sensitive groups), red (unhealthy) and black (cloud area). A map shown, the computed values of PM10 concentrations in the Langkawi Island on 4th November 2006 are in the range of 0 to 100µg/m^3 which consist of 75.67% of good area, 15.77% of moderate area and 8.58% of cloud cover area. In the validation analysis, a compute of PM10 concentrations was performing with ground truth data of PM10 concentrations which the proposed algorithm gave a high of accuracy (R^2=0.78).

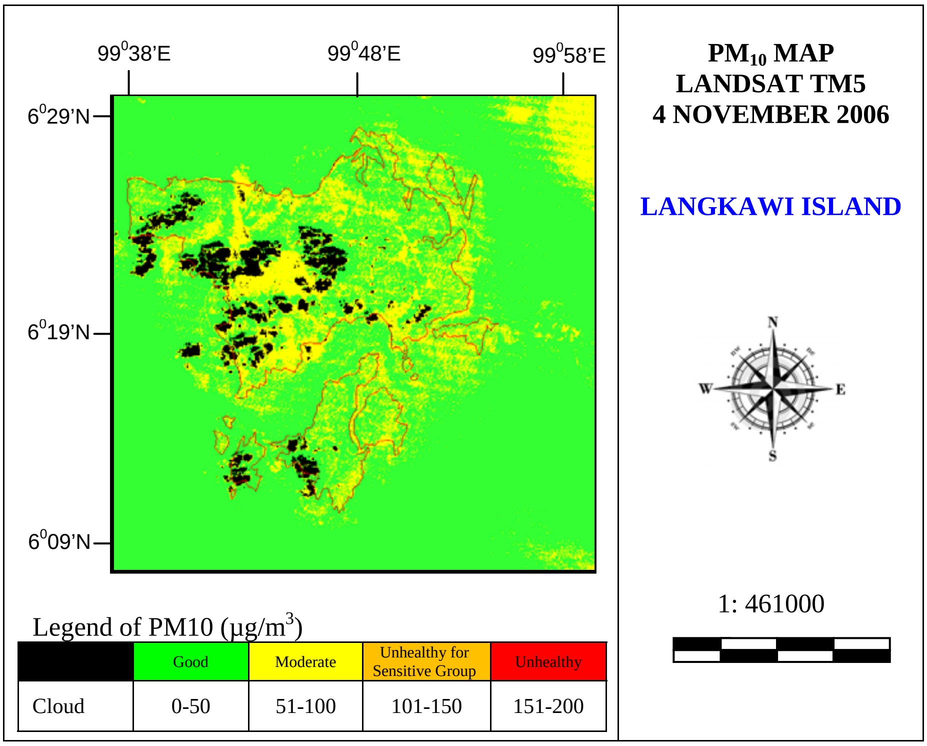


Figure 4. PM_{10} concentrations map over Langkawi Island on 4th November 2006.

7. CONCLUSION

The study shows that remote sensing technique using Landsat TM5 is capable of determining PM_{10} concentrations spatially and continuously with minimum cost and time over land and ocean area in Langkawi Island. Current progress of using this integration technique has showed a promising outcome. Despite of having only four satellite images, the proposed model can still provides a useful multi-date TM air quality calibration algorithm for Langkawi Island. The accuracy of the ground truth data played a very important role in determining the reliability of the calibrated algorithm and the quality of the generated air quality maps. The feasibility of applying the present techniques for operational use has to be validated and gave a high of accuracy. For a further application, a proposed algorithm can be used for other area in tropical region.

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