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Remote Sensing of PM_{2.5} Over Penang Island from Satellite Measurements

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1. Introduction

Satellite remote sensing technique has provided new datasets for monitoring air quality at regional and urban area. Air pollution in Asian cities has grown with the progressing industrialization and urbanization. Air quality standards often refer to respirable suspended particulate matter (PM), being aerosols with a diameter smaller than 2.5 μm (PM_{2.5}). The generated algorithm was based on the aerosol optical depth. Remote sensed data provide comprehensive geospatial information on air quality with both qualitative imagery and quantitative data, such as particulate matters of size less than 2.5 micron (PM_{2.5}).

Remote sensing has been widely used for environmental application such as for air quality and water quality studies. But the atmosphere affects satellite images of the Earth's surface in the solar spectrum. So, the signal observed by the satellite sensor is the sum of the effects from the ground and atmosphere. Surface reflectance is a key to the retrieval of atmospheric components from remotely sensed data. The accuracy of aerosol remote sensing techniques heavily depends on the information on the ground reflectance (Kokhanovskya, et al., 2005).

Environmental pollution is coeval with the appearance of humans. When Homo sapiens first lighted fire, its smoke provided the first medium of environmental pollution. The burning of fuels for heating and cooking has contributed to the air pollution of inner spaces (Makra and Brimblecombe, 2004). Air pollution is one of the most important environmental problems, which concentrates mostly in cities. Generally, human activities induce monotonous accumulation of pollutants [Makra, et al., (2001a) and Makra, et al., (2001b)]. Sources of exposure to particulate air pollution are many, Indoor sources, including cooking, unvented heating appliances and pets often make important contributions to exposures. Road traffic, however, generally provides the major source of ambient particulate pollution (Gulliver and Briggs, 2004).

We used a DustTrak Aerosol Monitor 8520 to collect in situ data. The particulate matters of size less than 2.5 micron data were collected simultaneously during the satellite Landsat overpass the study area. An empirical relationship between PM_{2.5} derived from the SPOT using regression technique is explored. A new algorithm was developed base on the aerosol characteristics in the atmosphere. We were obtained the atmospheric reflectance values by subtracting surface reflectance from the amount of reflectance measured from the satellite. The satellite recorded reflectance is the sum of the surface reflectance and atmospheric reflectance. The surface refleatance values were retrieved using ATCOR3 in the PCI Geomatica 10.3 image

processing software. The atmospheric reflectance values were later used for PM_{2.5} mapping using the calibrated algorithm. The efficiency of the developed algorithm, in comparison to other forms of algorithm, will be investigated in this study. Based on the values of the correlation coefficient and root-mean-square deviation, the proposed algorithm is considered superior. It is found that a linear relationship reveal a good results with PM_{2.5} measurements where the R value exceeding 0.89. The calibrated algorithm will be used to generate the air quality maps over Penang Island, Malaysia. The finding obtained by this study indicates that the SPOT data can be used to retrieved air quality information for remotely sensed data.

2. Remote sensing

Remote sensing is a technique for collecting information about the earth without touching the surface using sensors placed on a platform at a distance from it. The major applications of remote sensing include environmental pollution, urban planning, and earth management. We have to understanding the basic concept of electromagnetic waves well enough to apply remote sensing techniques in our studies. We classify electromagnetic energy by its wavelength. This electromagnetic radiation give an energy source to illuminate the target except the sensed energy is being emitted by the target.

There are two types of remote sensors: active and passive. Passive remote sensors detect reflected energy from the sun back to the sensor; they do not emit energy itself. But active sensors can emit energy or provide its own source of energy and detect the reflected energy back from the target. There are two types of remotely sensed data: airborne and space-borne. Airborne images are captured using sensors placed on aircraft platform while space-borne images are captured using sensors placed on a satellite platform. Remotely sensed data began with the traditional black and white aerial photography and followed by colour photography. However hyperspectral airborne or space-borne images are readily available nowadays. We use both the multispectral airborne and space-borne digital images in our studies. The major advantage of using remote sensing data is that we can produce the final output as maps of the Earth's surface phenomena by studies.

3. Study area

The study area is the Penang Island, Malaysia, located within latitudes 5° 9' N to 5° 33' N and longitudes 100° 09' E to 100° 30' E. The map of the study area is shown in Figure 1. Penang Island is located in equatorial region and enjoys a warm equatorial weather the whole year. Therefore, it is impossible to get the 100 % cloud free satellite image over Penang Island. But, the satellite image chosen is less than 10 % of cloud coverage over the study area. Penang Island located on the northwest coast of Peninsular Malaysia.

Penang is one of the 13 states of the Malaysia and the second smallest state in Malaysia after Perlis. The state is geographically divided into two different entities - Penang Island (or "Pulau Pinang" in Malay Language) and a portion of mainland called "Seberang Perai" in Malay Language. Penang Island is an island of 293 square kilometres located in the Straits of Malacca and "Seberang Perai" is a narrow hinterland of 753 square kilometres (Tan, et al., 2010). The island and the mainland are linked by the 13.5 km long Penang Bridge and ferry. Penang Island is predominantly hilly terrain, the highest point being Western Hill (part of Penang Hill) at 830 metres above sea level. The terrain consists of coastal plains, hills and mountains. The coastal plains are narrow, the most extensive of which is in the northeast which forms a triangular promontory where George Town, the state capital, is situated. The

topography of “Seberang Perai” is mostly flat. Butterworth, the main town in “Seberang Perai”, lies along the “Perai” River estuary and faces George Town at a distance of 3 km (2 miles) across the channel to the east (Tan, et al., 2010).

The Penang Island climate is tropical, and it is hot and humid throughout the year. with the average mean daily temperature of about 27°C and mean daily maximum and minimum temperature ranging between 31.4°C and 23.5°C respectively. However, the individual extremes are 35.7°C and 23.5°C respectively. The mean daily humidity varies between 60.9% and 96.8%. The average annual rainfall is about 267 cm and can be as high as 624 cm (Tan, et al., 2010).

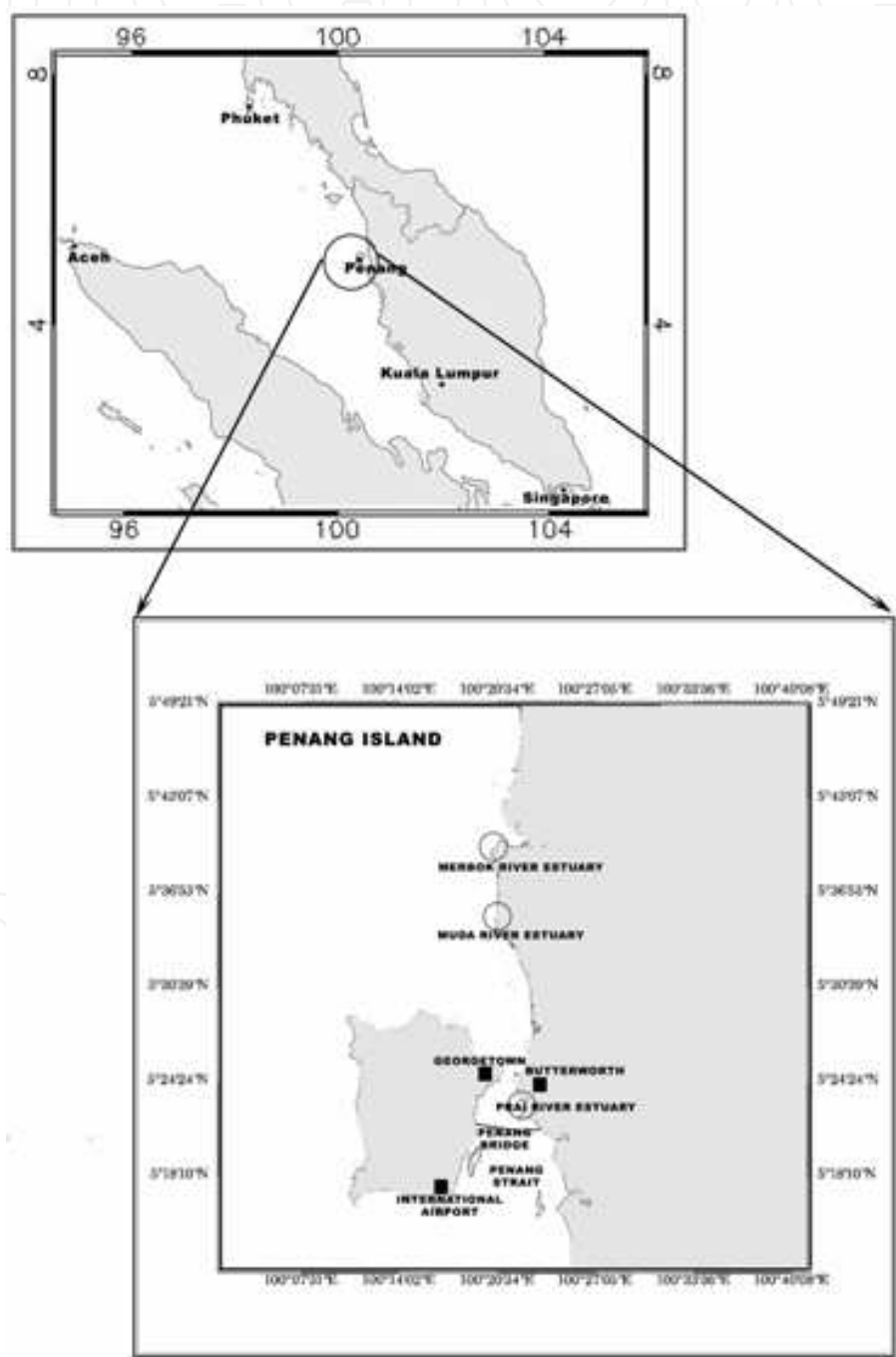


Fig. 1. The study area

4. Algorithm model

The atmospheric reflectance due to molecule, R_r , is given by (Liu, et al., 1996)

$$R_r = \frac{\tau_r P_r(\Theta)}{4\mu_s \mu_v} \quad (1)$$

where

τ_r = Rayleigh optical thickness

$P_r(\Theta)$ = Rayleigh scattering phase function

μ_v = Cosine of viewing angle

μ_s = Cosine of solar zenith angle

We assume that the atmospheric reflectance due to particle, R_a , is also linear with the τ_a [King, et al., (1999) and Fukushima, et al., (2000)]. This assumption is valid because Liu, et al., (1996) also found the linear relationship between both aerosol and molecule scattering.

$$R_a = \frac{\tau_a P_a(\Theta)}{4\mu_s \mu_v} \quad (2)$$

where

τ_a = Aerosol optical thickness

$P_a(\Theta)$ = Aerosol scattering phase function

Atmospheric reflectance is the sum of the particle reflectance and molecule reflectance, R_{atm} , (Vermote, et al., (1997).

$$R_{atm} = R_a + R_r \quad (3)$$

where

R_{atm} = atmospheric reflectance

R_a = particle reflectance

R_r = molecule reflectance

$$R_{atm} = \left[\frac{\tau_a P_a(\Theta)}{4\mu_s \mu_v} + \frac{\tau_r P_r(\Theta)}{4\mu_s \mu_v} \right] \quad (4)$$

$$R_{atm} = \frac{1}{4\mu_s \mu_v} [\tau_a P_a(\Theta) + \tau_r P_r(\Theta)]$$

The optical depth is given by Camagni and Sandroni, (1983), as in equation (5). From the equation, we rewrite the optical depth for particle and molecule as equation (6)

$$\tau = \sigma \rho s \quad (5)$$

where

τ = optical depth

σ = absorption

s = finite path

$$\tau = \tau_a + \tau_r \quad (\text{Camagni and Sandroni, 1983})$$

$$\tau_r = \sigma_r \rho_r s \quad (6a)$$

$$\tau_p = \sigma_p \rho_p s \quad (6b)$$

Equations (6) are substituted into equation (4). The result was extended to a three bands algorithm as equation (7). From the equation; we found that PM was linearly related to the reflectance for band 1 and band 2. This algorithm was generated based on the linear relationship between τ and reflectance. Retalis et al., (2003), also found that PM was linearly related to τ and the correlation coefficient for linear was better than exponential in their study (overall). This means that reflectance was linear with PM. In order to simplify the data processing, the air quality concentration was used in our analysis instead of using density, ρ , values.

$$R_{atm} = \frac{1}{4\mu_s\mu_v} [\sigma_a \rho_a s P_a(\Theta) + \sigma_r \rho_r s P_r(\Theta)]$$

$$R_{atm} = \frac{s}{4\mu_s\mu_v} [\sigma_a \rho_a P_a(\Theta) + \sigma_r \rho_r P_r(\Theta)]$$

$$R_{atm}(\lambda_1) = \frac{s}{4\mu_s\mu_v} [\sigma_a(\lambda_1) P P_a(\Theta, \lambda_1) + \sigma_r(\lambda_1) G P_r(\Theta, \lambda_1)]$$

$$R_{atm}(\lambda_2) = \frac{s}{4\mu_s\mu_v} [\sigma_a(\lambda_2) P P_a(\Theta, \lambda_2) + \sigma_r(\lambda_2) G P_r(\Theta, \lambda_2)]$$

$$P = a_0 R_{atm}(\lambda_1) + a_1 R_{atm}(\lambda_2) \quad (7)$$

where

P = Particle concentration (PM2.5)

G = Molecule concentration

R_{atm} = Atmospheric reflectance, $i = 1$ and 2 are the band number

a_j = algorithm coefficients, $j = 0, 1, 2, \dots$ are then empirically determined.

5. Data analysis and results

Remote sensing satellite detectors exhibit linear response to incoming radiance, whether from the Earth's surface radiance or internal calibration sources. This response is quantized into 8-bit values that represent brightness values commonly called Digital Numbers (DN). To convert the calibrated digital numbers to at-aperture radiance, rescaling gains and biases are created from the known dynamic range limits of the instrument.

The satellite image was rectified using the second order polynomial coordinated transformation using nearest neighbor method to relate ground control points (GCP) in the map to their equivalent row and column positions in the TM scene. Overall, both satellite images achieved the RMS errors less than 0.5 pixels in this study (Vicente-Serrano et al. 2008; Schroeder et al. 2006; Kabbara et al. 2008).

The digital numbers (DN values) corresponding to the ground truth sample locations were extracted from all the images. The DN for window size of 3 by 3 was used because the data set produced higher correlation coefficient and lower RMS value. The DN values were converted into radiance values and later reflectance values.

It should be noted that the reflectance values at the top of atmosphere is the sum of the surface reflectance and atmospheric reflectance. The signals measured in each of these visible bands represent a combination of surface and atmospheric effects, usually in different proportions depending on the condition of the atmosphere. Therefore, it is required to determine the surface contribution from the total reflectance received at the sensor. In this study, we extracted the surface reflectance from mid-infrared band because the surface reflectances at various bands across the solar spectrum are correlated to each other to some extent. The surface reflectances of dark targets in the blue and red bands were estimated using the measurements in the mid-infrared band (Quadrari and Vermote, 1999). Over a simple black target, the observed atmospheric reflectance, is the sum of reflectance of aerosols and Rayleigh contributions (Equation 8). This simplification, however, is not valid at short wavelengths (less than 0.45 μm) or large sun and view zenith angles (Vermote and Roger, 1996). In this study, a simple form of the equation was used in this study (Equation 9). This equation also used by other research in their study (Poop, 2004).

$$R_s - T R_r = R_{atm} \quad (8)$$

$$R_s - R_r = R_{atm} \quad (9)$$

where:

R_s = reflectance recorded by satellite sensor

R_r = reflectance from surface references

R_{atm} = reflectance from atmospheric components (aerosols and molecules)

T = transmittance

It should be noted that the reflectance values at the top of atmosphere was the sum of the surface reflectance and atmosphere reflectance. In this study, we used ATCOR3 image correction software in the PCI Geomatica 10.3 image processing software for creating a surface reflectance image. Usually, the absolute radiometric correction methods available only correct for atmospheric effects of satellite imagery (Janzen et al. 2006). Therefore, they may suitable in certain atmospheric correction in flat or terrain area. But, the algorithm proposed cannot reduce the topographic effects. Hence, in mountainous terrain, these methods may bring some errors while apply the algorithms to eliminate the atmospheric effects (Tan, et al., 2010).

In order to remove atmospheric and topographic effects efficiently, a method has been developed and implement in satellite imagery over mountainous area. The algorithm proposed is based on the Richter model (Richter 1990). The algorithm generates the three-dimensional atmosphere by considering the transmittance and radiance functions of different height, included atmospheric conditions alteration in horizontally. Consequently, it is able to solve the problem of haze through the statistical algorithm, which helps to manipulate the optical depths in different altitude.

ATCOR3 is a new approach implemented in PCI Geomatica 10.3 image processing software and the technique based on the ATCOR2 model. But ATCOR2 model restricted for a flat

terrain to calculate surface reflectance. Both of these models have the similarity, where the approaches apply the technique from dense dark vegetation approach (Liang et al. 1997) and the modified dense dark vegetation approach (Song et al. 2001).

A database contains radiative transfer code is acquired from the calculation of direct and diffuse solar flux, path radiance and atmospheric transmittance with the wide range of weather conditions, in terms of atmospheric conditions (Richter 1998). Beside, ATCOR3 requires the information, such as slope, orientation and surface elevation, to eliminate the topographic effects. The range cover the mountainous terrain should not greater than 3.5 km above the sea level. Furthermore, if ATCOR3 apply to the area involved rugged terrain, the algorithm need to calculate the specified atmospheric conditions based on Lambertian assumption. Overall, the method implemented here only restricted to high spatial resolution satellite sensors with small swath angle like Landsat and Systeme pour l'Observation de la Terre (SPOT).

The advantage of ATCOR3 is the module can generate a surface reflectance map using reference elevation data. In addition, retrieval of surface reflectance thematic map becomes more accurate, especially in high mountain terrain, because it considers the slope and aspect images. In this study, the reference DEM model known as ASTER Global Digital Elevation Map (GDEM) was used to retrieve the a surface reflectance values (Fig 2). And then the reflectance measured from the satellite [reflectance at the top of atmospheric, $\rho(\text{TOA})$] was subtracted by the amount given by the surface reflectance to obtain the atmospheric reflectance.

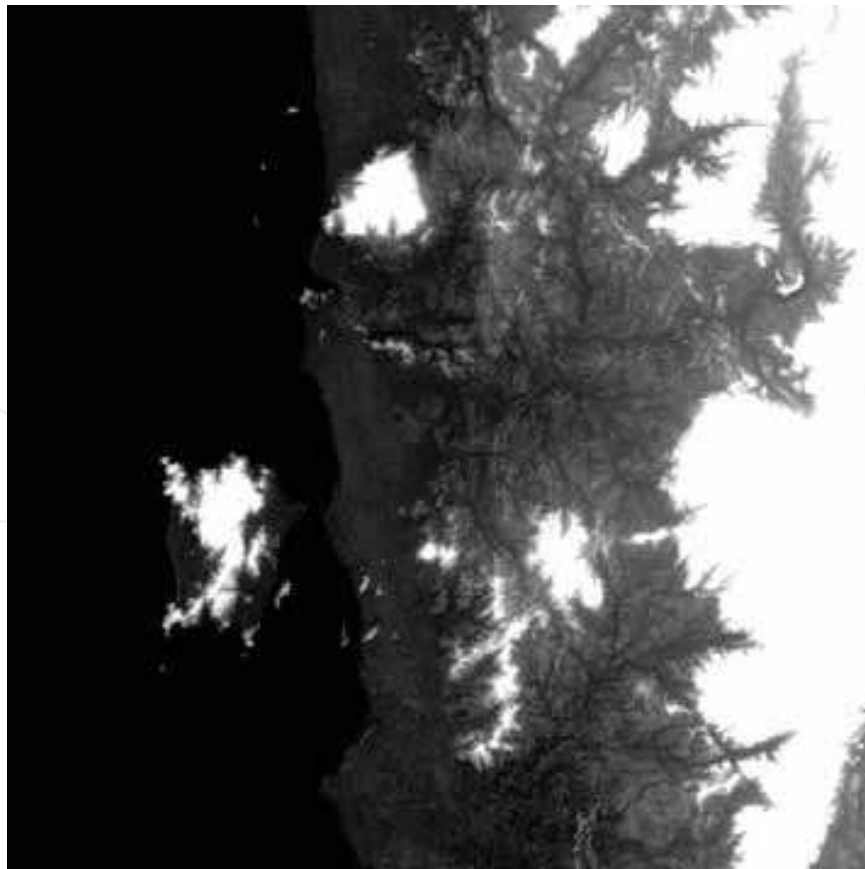


Fig. 2. GDEM data used in this study.

SPOT satellite data was selected corresponding to the ground truth measurements of the pollution levels (Fig. 3). The satellite image was acquired on 30 January 2005. The corresponding PM2.5 measurements were collected simultaneously during the satellite overpass. And then the atmospheric reflectance was related to the PM10 using the regression algorithm analysis.

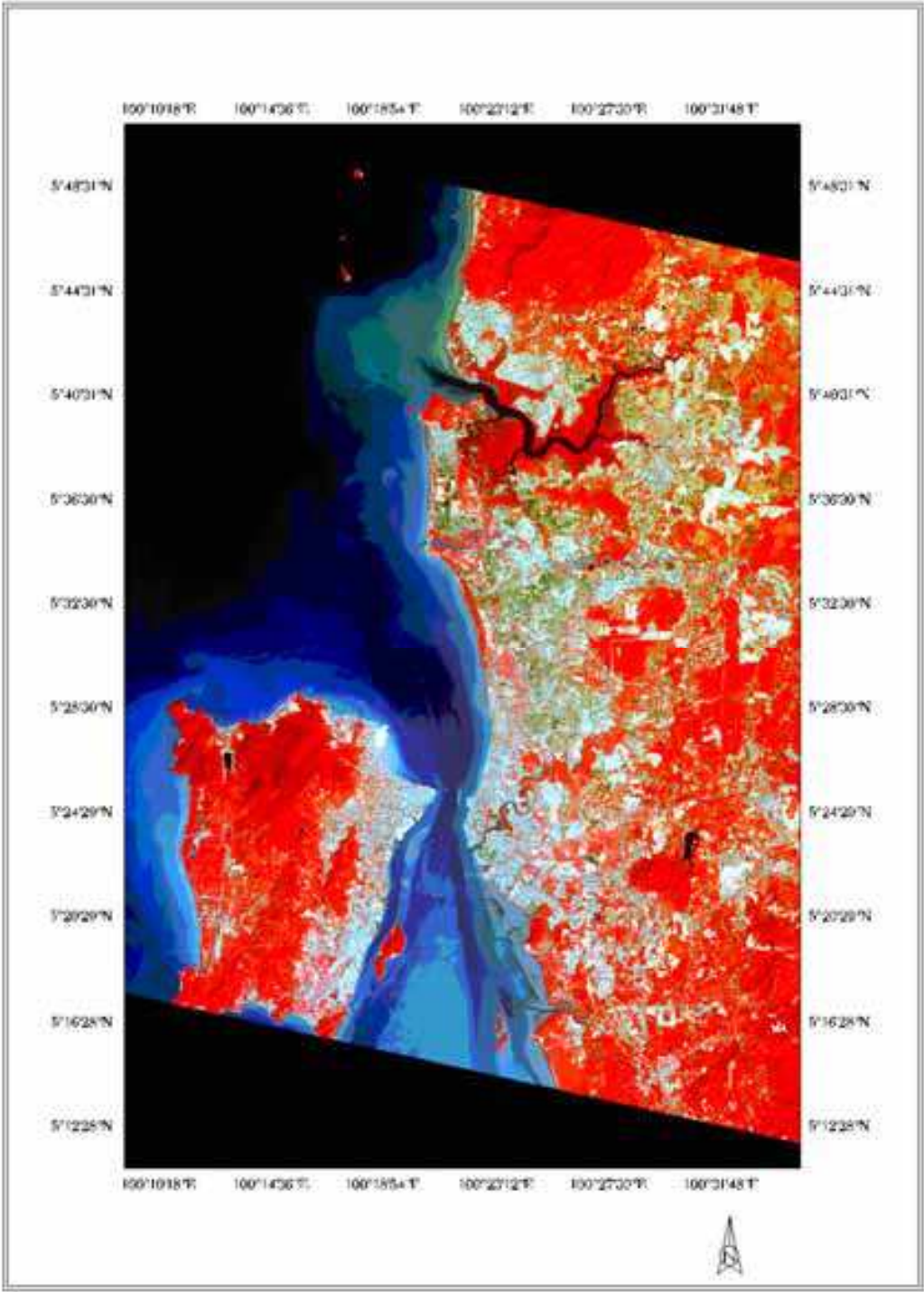


Fig. 3. Raw satellite image.

In this study, SPOT signals were used as independent variables in our calibration regression analysis. A good result was produced by the proposed model, which achieved the correlation coefficient of about 0.89. The PM10 map was generated using the proposed algorithm (Figure 4).

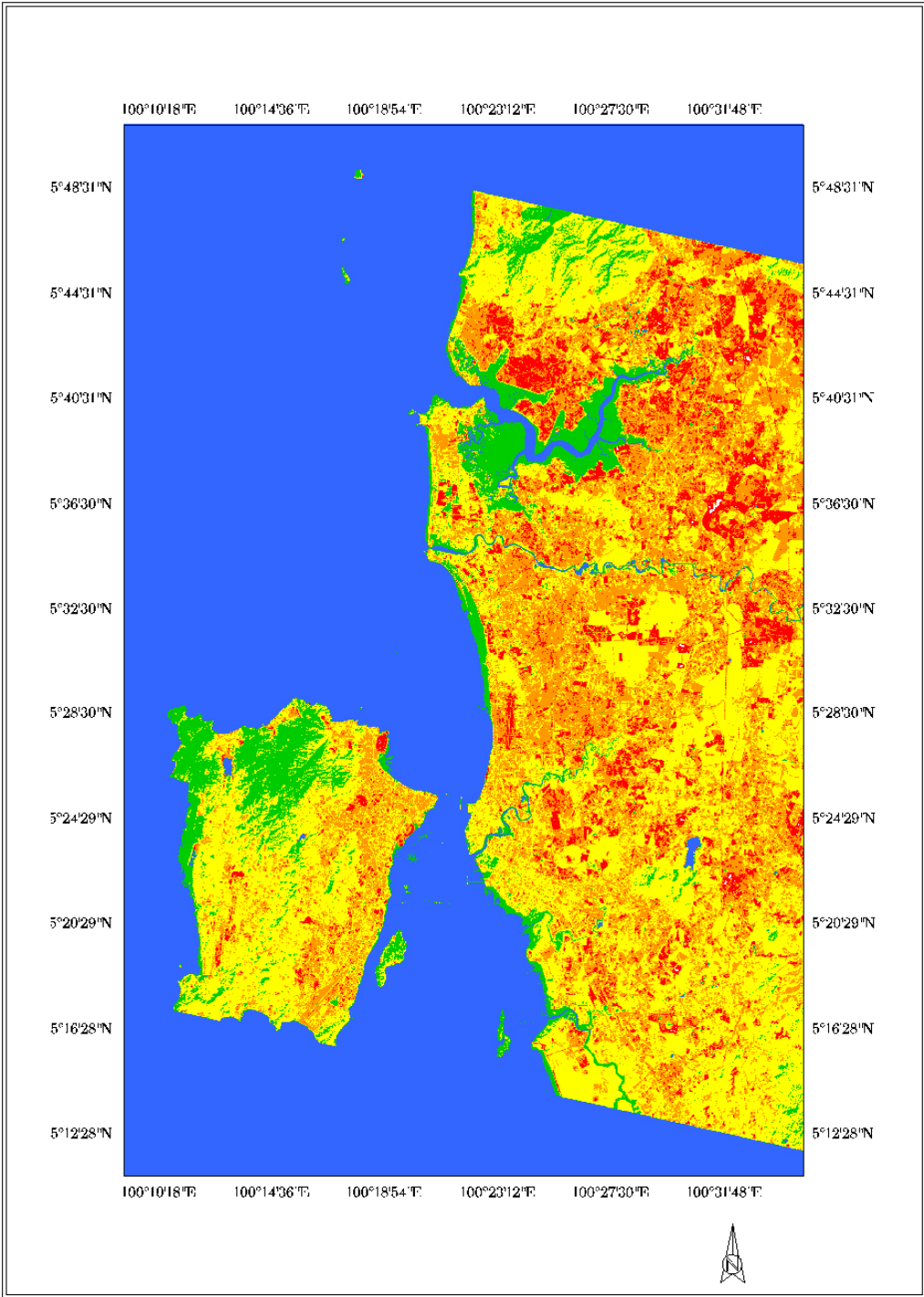


Fig. 4. Map of PM2.5 around Penang Island, Malaysia [Blue < 40 µg/m³, Green = (40-80) µg/m³, Yellow = (80-120) µg/m³, Orange = (120-160) µg/m³, Red = (>160) µg/m³ and Black = Land]

6. Conclusion

The result produce by this study indicated the used of SPOT satellite image for PM_{2.5} mapping over Penang Island. A good agreement was found in this study between PM_{2.5} measured by the DustTrak Aerosol Monitor 8520 and PM_{2.5} estimated using the newly proposed developed algorithm. The developed algorithm produced high R and low RMS values. This study indicates that satellite observation can be used for air quality mapping using SPOT data. The use of remotely sensed data produced better spatial resolution air quality map compared to the spacing between ground stations. Further study will be carried out to verify the results and a multi regression algorithm will be developed and used in the analysis.

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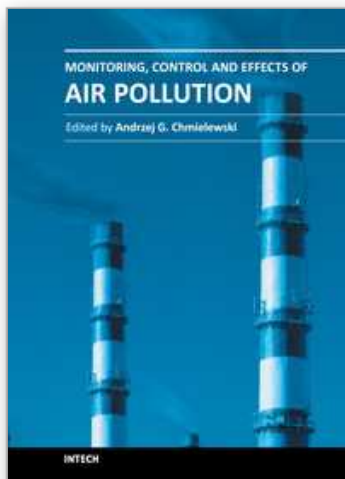
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Monitoring, Control and Effects of Air Pollution

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The book addresses the subjects related to the selected aspects of pollutants emission, monitoring and their effects. The most of recent publications concentrated on the review of the pollutants emissions from industry, especially power sector. In this one emissions from opencast mining and transport are addressed as well. Beside of SO_x and NO_x emissions, small particles and other pollutants (e.g. VOC, ammonia) have adverse effect on environment and human being. The natural emissions (e.g. from volcanoes) has contribution to the pollutants concentration and atmospheric chemistry governs speciation of pollutants, as in the case of secondary acidification. The methods of ambient air pollution monitoring based on modern instrumentation allow the verification of dispersion models and balancing of mass emissions. The comfort of everyday human's activity is influenced by indoor and public transport vehicles interior air contamination, which is effected even by the professional appliances operation. The outdoor pollution leads to cultural heritage objects deterioration, the mechanism are studied and the methods of rehabilitation developed. However to prevent emissions the new technologies are being developed, the new class of these technologies are plasma processes, which are briefly reviewed at the final part of the book.

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