EFFECTIVE AEROSOL OPTICAL THICKNESS RETRIEVAL ALGORITHM USING MODIS 500 METRE DATA

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DEDICATION

Specially dedicated to

my beloved parents, wife, siblings

and all my fellows friends

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ABSTRACT

Aerosol estimation from satellite data is crucial for the air quality assessment, visibility estimation, and climate modelling. Numerous retrieval algorithms have been developed for aerosol optical thickness estimation but there are still uncertainties in estimation due to several factors that need to be addressed for the development of an effective retrieval algorithm. Therefore, the main goal of this study is to develop an effective aerosol retrieval algorithm using Moderate Resolution Imaging Spectroradiometer 500 metre data considering the effects of different Radiative Transfer codes, surface reflectance estimation techniques, local aerosol models, and atmospheric transmission contributions. The aerosol estimation algorithm has been developed using several processing steps include i) estimation of aerosol reflectance from satellite data, ii) local aerosol models characterization using aerosol inversion product, iii) estimation of aerosol reflectance as function of aerosol optical thickness using different Radiative Transfer codes and direct method, iv) retrieval of aerosol optical thickness by comparing the residual of aerosol reflectance between satellite data and Radiative Transfer codes using Look-up Tables based on optimal spectral shape fitting function, and v) validation of retrieved aerosol optical thickness with in-situ ground measurement. Results indicate that aerosol optical thickness can be successfully retrieved from the satellite data using Second Simulation of a Satellite Signal in the Solar Spectrum vector code, 2-channel of Moderate Resolution Imaging Spectroradiometer data, and surface reflectance derived from the Radiative Transfer code based atmospheric correction using continental and desert aerosol model together. The proposed algorithm is very effective and retrieved aerosol optical thickness from Moderate Resolution Imaging Spectroradiometer 500 metre data with the accuracy of 96% and low uncertainty for the both study sites. This finding highlights the potential of this algorithm to retrieve aerosol optical thickness from satellite data with high accuracy and good spatial information compared to the 10 kilometres satellite aerosol product.

ABSTRAK

Anggaran aerosol daripada data satelit adalah penting untuk penilaian kualiti udara, anggaran kebolehlihatan, dan pemodelan iklim. Pelbagai algoritma penerbitan telah dibangunkan untuk anggaran ketebalan optik aerosol tetapi masih terdapat keraguan dalam anggaran yang disebabkan oleh beberapa faktor yang perlu diberi perhatian untuk pembangunan algoritma penerbitan aerosol yang efektif. Oleh itu, tujuan utama bagi kajian ini adalah untuk membangunkan algoritma penerbitan aerosol menggunakan data Pengimejan Spektroradiometer Resolusi Sederhana 500 meter dengan mempertimbangkan kesan-kesan bagi kod Pemindahan Sinaran yang berbeza, teknik anggaran kepantulan permukaan, model aerosol tempatan, dan penyumbangan penghantaran atmosfera. Algoritma anggaran aerosol telah dibangunkan menggunakan beberapa langkah pemprosesan termasuk i) anggaran bagi kepantulan aerosol daripada data satelit, ii) pencirian model aerosol tempatan menggunakan produk penterbalikkan aerosol, iii) anggaran bagi kepantulan aerosol sebagai fungsi ketebalan optik aerosol menggunakan kod Pemindahan Sinaran yang berbeza dan kaedah secara langsung, iv) penerbitan ketebalan optik aerosol dengan membandingkan nilai perbezaan kepantulan aerosol di antara data satelit dan kod Pemindahan Sinaran yang menggunakan Jadual Carian berdasarkan fungsi penyesuaian bentuk spektral yang optimal, dan v) pengesahan ketebalan optik aerosol yang diterbitkan dengan pengukuran di tanah lapangan. Hasil kajian menunjukkan bahawa ketebalan optik aerosol dapat diterbitkan dengan jayanya daripada data satelit menggunakan kod vektor Simulasi Kedua bagi Isyarat Satelit di dalam Spektrum Suria, 2-saluran data Pengimejan Spektroradiometer Resolusi Sederhana, dan kepantulan permukan diterbitkan daripada kod Pemindahan Sinaran berdasarkan pembetulan atmosfera menggunakan model aerosol benua dan padang pasir bersama-sama. Algoritma yang dicadangkan adalah sangat efektif dan ketebalan optik aerosol yang diterbitkan daripada data Pengimejan Spektroradiometer Resolusi Sederhana 500 meter dengan ketepatan sebanyak 96% dan ketidakpastian yang rendah bagi kedua-dua kawasan kajian. Penemuan ini menekankan keupayaan algoritma ini untuk menerbitkan ketebalan optik aerosol daripada data satelit dengan ketepatan yang tinggi dan maklumat ruang yang bagus berbanding dengan produk satelit aerosol 10 kilometer.

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LIST OF ABBREVIATIONS

6S	-	Second Simulation of a Satellite Signal in the Solar Spectrum
AATSR	-	Advanced Along-Track Scanning Radiometer
AOT	-	Aerosol optical thickness
AOD	-	Aerosol optical depth
AI	-	Aerosol Index
AERONET	-	Aerosol Robotic Network
ANOVA	-	Analysis of Variance
ATCOR	-	Atmospheric correction
ACE-Asia	-	Asian Pacific Regional Aerosol Characterization Experiment
AVHRR	-	Advanced High Resolution Radiometer
BAER	-	Bremen AErosol Retrieval
BRDF	-	Bidirectional Reflectance Distribution Functions
CALIOP	-	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	-	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CCN	-	Cloud Condensation Nuclei
CNES	-	Centre for Space Studies
CO_2	-	Carbon dioxide
CPC	-	Climate Prediction Centre
DAE	-	Direct Analytical Equation
DDV	-	Dark Dense Vegetation
DISORT	-	Discrete Ordinate Radiative Transfer
DOY	-	Day of Year
EOS	-	Earth Observation Satellite

ERTS	-	Earth Resources Technology Satellite
GCP	-	Ground Control Point
GDAS	-	Global Data Assimilation System
GLAS	-	Geoscience Laser Altimeter System
HK	-	Hong Kong
HKIA	-	Hong Kong International Airport
H_2O	-	Water vapour
ICESat	-	Ice Cloud and Elevation Satellite
IDL	-	Interactive Data Language
ILAS	-	Improved Limb Atmospheric Spectrometer
IR	-	Infrared
Lidar	-	Light detection and ranging
LITE	-	Lidar In-Space Technology Experiment
LOWTRAN	-	Low Resolution Transmittance
LUT	-	Look-up table
LSR SCF	-	Land Surface Reflectance Science Computing Facility
MERIS	-	Medium Resolution Imaging Spectrometer on the Environmental Satellite
MFRSR	-	Multifilter Rotating Shadow Band Radiometer
MISR	-	Multiangle Imaging SpectroRadiometer
MRT	-	Minimum reflectance technique
MODIS	-	Moderate Resolution Imaging Spectroradiometer
MOD02HKM	-	MODIS Calibrate Radiances L1B Swath 500 m
MOD021KM	-	MODIS Calibrate Radiances L1B Swath 1 km
MOD03	-	MODIS geolocation data
MOD04 L2 C005	-	MODIS aerosol product level 2 collection 005
MOD05	-	MODIS precipitable water product
MOD07	-	MODIS atmospheric product
MOD09GA	-	MODIS land surface reflectance product
MODTRAN	-	Moderate Resolution Transmittance
MRT	-	Minimum Reflectivity Technique
MSS	-	Multi Spectral Scanner

NASA	-	National Aeronautics and Space Administration
NASDA	-	National Space Development Agency of Japan
NCAR	-	National Centre for Atmospheric Research
NCEP	-	National Centres for Environmental
NDVI	-	Normalized Difference Vegetation Index
NOAA	-	National Ocean and Atmosphere Administration
NO_2	-	Nitrogen dioxide
O_3	-	Ozone
PM	-	Particulate matter
POAM	-	Polar Ozone and Aerosol Measurement
POLDER	-	Polarization and Directionality of the Earth’s Reflectance
Poly-U	-	Polytechnic University
Qext	-	Extinction coefficient
REFI	-	Imaginary refractive index
REFR	-	Real refractive index
ROI	-	Region of Interest
RSR	-	Relative Spectral Response
RTM	-	Radiative Transfer Model
SAGE	-	Stratospheric Aerosol and Gas Experiment
SAM	-	Stratospheric Aerosol Measurement
SARA	-	Simplified Aerosol Retrieval Algorithm
SBDART	-	Santa Barbara DISORT Atmospheric Radiative Transfer
SBUV	-	Solar Backscatter Ultraviolet Radiometer
SCIAMACHY	-	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SeaWiFS	-	Sea-Viewing Wide Field-of-View Sensor
SHARM	-	Spherical Harmonic
SOS	-	Successive Orders of Scattering
SSA	-	Single scattering albedo
TIROS	-	Television and Infrared Observation Satellite
TOA	-	Top of Atmosphere
TOMS	-	Total Ozone Mapping Spectrometer

TOVS	-	TIROS Operational Vertical Sounder
UTM	-	Universal Transverse Mercator
UV	-	Ultraviolet
VIIRS	-	Visible Infrared Imaging Radiometer Suite
VRC	-	Variance Ratio Criteria
WGS	-	World Geodetic System
WHO	-	World Health Organization

LIST OF SYMBOLS

α	-	Angstrom exponent coefficient
θ_s	-	Solar zenith angle
θ_v	-	Sensor zenith angle
μ	-	Cosine zenith angle
ϕ	-	Relative azimuth angle
ρ_{TOA}	-	Top of Atmosphere reflectance
L_{TOA}	-	Top of Atmosphere spectral radiance
ρ_{Aer}	-	Aerosol reflectance
ρ_{Ray}	-	Rayleigh reflectance
T_{atm}	-	Total atmospheric transmission
$T_{(\theta_s)}$	-	Total transmission from Sun to Earth's surface
$T_{(\theta_v)}$	-	total transmission from Earth's surface to sensor
T_g	-	Total transmission of other gases
T_{H_2O}	-	Total transmission of water vapour
T_{O_3}	-	Total transmission of ozone gas
U_{H_2O}		Total water vapour content
U_{O_3}	-	Total ozone content
M	-	Air mass factor
ρ_s	-	Surface reflectance
ρ_{Hem}	-	Hemispheric reflectance
τ_{aer}	-	Aerosol optical thickness
τ_{Ray}	-	Rayleigh optical thickness
$P_{Ray}(\theta)$	-	Rayleigh phase function
ω_o	-	single scattering albedo
g	-	asymmetry parameters

σ_e	-	Volume extinction coefficient
σ_{aer}	-	Aerosol extinction coefficient
λ	-	Wavelength
n	-	Complex refractive index
m	-	Real refractive index
T	-	Temperature
P	-	Pressure
z	-	Elevation
θ	-	Scattering angle
$p(\theta)$	-	Phase function
µm	-	Micrometre
nm	-	Nanometre
I	-	Spectral radiance
$Esun_{\lambda}$	-	Mean solar exoatmospheric irradiance
δ	-	Depolarization factor
k	-	Number of cluster

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Atmospheric aerosol, suspension of liquid and solid particles with radii varying from a few nanometre (nm) to larger than 100 micrometre (µm), plays an important role in solar radiation budget, climate change, hydrology process, air quality and visibility through the scattering and absorption of incoming solar energy (Levy *et al.*, 2009). Natural aerosol (such as dust, volcanic, sea-salt) and anthropogenic aerosol (such as industrial activity, fossil fuel burning) are the two main sources of aerosols (Lee and Kim, 2010), however, based on the size distribution aerosols can also be classified into two groups i.e. particulate matter 2.5 (PM 2.5) and particulate matter 10 (PM 10). PM 2.5 is also known as fine mode that refers to the particles of aerosol with the diameter of size less than 2.5 µm, while PM 10 is known as coarse mode which describes particles with the diameter less than 10 µm. The particulate matters can be measured as the amount of particles contained in a cubic meter of air, expressed as micrograms per cubic meters (µg/m^3).

Both the PM 2.5 and PM 10 aerosol particles have been known for causing harm to human health especially PM 2.5 because of its small particles size that can penetrate through respiratory system and affect the lungs and heart (Brook *et al.*, 2004). Concentration of aerosol in atmosphere can influence climate directly as well as indirectly. Direct effects can be seen as greenhouse effect that producing the phenomena of global warming due to the fact that aerosol particles absorb the solar radiation from the sun and trap the heat into the atmosphere layer. On the other hand, aerosol concentration indirectly altering cloud properties by providing more cloud condensation nuclei (CCN) that affect rainfall pattern, radiation balance and hydrological balance (De Leeuw *et al.*, 2011).

Two main properties of aerosol are optical properties and microphysical properties (e.g. aerosol size distribution and refractive index). Aerosol optical property consists of several parameters such as aerosol optical thickness (AOT), extinction coefficient (Q_{ext}), aerosol phase function ($p(\theta)$), single scattering albedo (ω_o), and asymmetry parameters (g) (Levoni *et al.*, 1997). Extinction coefficient (Q_{ext}), aerosol phase function ($p(\theta)$), single scattering albedo (ω_o), and asymmetry parameters (g) can be derived from microphysical properties using Mie scattering calculation (Wiscombe, 1978). Meanwhile, AOT can be retrieved from direct solar radiation measurement by using sun-photometer instrument. However, two key parameters for retrieving aerosol from satellite measurement are aerosol optical thickness (AOT) and Angstrom exponent coefficient (α). AOT can be described as an integral of the aerosol light extinction over vertical path through the atmosphere and it is a function of wavelength (Kokhanovsky and de Leeuw, 2009). Whereas, Angstrom exponent is related to the spectral dependence of the extinction at two different wavelengths. AOT tells us how much direct sunlight is prevented from reaching the ground by these aerosol particles. It is a dimensionless number that is related to the amount of aerosol in the vertical column of atmosphere over the observation location. A value of 0.01 corresponds to an extremely clean atmosphere, and a value of 0.4 would correspond to a very hazy condition.

Retrieval of AOT is a complex process and can be carried out from ground measurement and airborne measurement. Ground measurement has been used over 100 years for measuring air pollution in the atmosphere (Brimblecombe, 1987) using hand held, ship-based, and ground based network measurement based on sun photometer instrument. The most widely used ground based measurement instrument for aerosol retrieval over land with high spatial and temporal resolution is AERONET (Aerosol Robotic Network) which provides direct Sun algorithm measurement (e.g. AOT value and precipitable water) and inversion of sky radiance measurement (e.g. microphysical properties) from visible to near infrared spectrum (Aube *et al.*, 2000). On the other hand, airborne measurement such as air balloon, aircraft, and remote sensing satellite can be used to retrieve aerosol in directly or indirectly with high spatial and wide areas coverage of aerosol information (Aube *et al.*, 2000). Moreover, remote sensing satellites are increasingly being used for retrieving information on aerosol properties includes optical properties and microphysical properties because remote sensing satellite has capability to retrieve AOT information at good spatial resolution, high temporal resolution, and wide coverage (Kokhanovsky and de Leeuw, 2009). However, it is important to note that AOT retrieval requires satellite data with high spatial and temporal resolution because of the short life span of aerosol (7 to 10 days) (Zubko *et al.*, 2007).

The first operational aerosol product was retrieved from satellite measurement using Advance High Resolution Radiometer (AVHRR) sensor on-board the Television and Infrared Observation Satellite (TIROS) platform launched in 19 October 1978 (Stowe *et al.*, 2002). However, there are many satellite sensors available now a days with different capabilities to retrieve AOT such as i) Multiangle Imaging SpectroRadiometer (MISR), ii) Polarization and Directionality of the Earth’s Reflectance (POLDER), iii) Lidar In-Space Technology Experiment (LITE), iv) Geoscience Laser Altimeter System (GLAS) and v) Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). Apart from these sensors, Moderate Resolution Imaging Spectroradiometer (MODIS) sensor has showed excellent capabilities for measuring aerosol due to high spatial resolution (compare to others of aerosol remote sensing sensors), wide spectral range and high temporal resolution (Levy *et al.*, 2003).

Although many satellite sensors can be used for the estimation of AOT, retrieval of AOT directly from satellite estimation is rarely possible without an effective algorithm. Numerous aerosol retrieval approaches are available based on the characteristics of satellite data as retrieval algorithms are varied due to different properties of sensors such as spectral, spatial, view angles, polarizations, and so on. Aerosol retrieval algorithm over land using remote sensing techniques is more complicated compared to the aerosol retrieval over ocean because of the heterogeneous land features (Kokhanovsky and de Leeuw, 2009). However, aerosol retrieval over land can be simplified by decomposing the Top of Atmosphere (TOA) reflectance from surface reflectance and the Rayleigh reflectance in order to retrieve aerosol reflectance. The key factor on the aerosol retrieval algorithm is to estimate surface reflectance which attempts to differentiate the aerosol signal from surface (Kaufman *et al.*, 1997b).

The most common estimation of surface reflectance over land uses dark surface assumption techniques by retrieving surface reflectance at dark pixels using shorter wavelength (near ultraviolet and UV) (von Hoyningen-Huene *et al.*, 2003; Hsu *et al.*, 2004, 2006; von Hoyningen-Huene *et al.*, 2006). Over vegetation areas, Kaufman et al. (1997) was firstly proposed the dark dense vegetation (DDV) technique for estimating surface reflectance using the multi-wavelength algorithm on the MODIS images. Thus, Levy et al. (2009) has developed an algorithm for estimating surface reflectance over dark target based on empirical surface reflectance relationship using Normalized Difference Vegetation Index (NDVI). However, apart from the DDV algorithm, many other techniques can also be used to estimate surface reflectance over land such as empirical relationship between short-wave infrared and visible channel (Levy *et al.*, 2007; Vermote and Saleous, 2006) and Minimum Reflectance Technique (MRT) (Wong *et al.*, 2011).

Another important part of aerosol retrieval process is that a Radiative Transfer Model (RTM) is required in the aerosol retrieval method for accounting molecular effects (molecular scattering and absorption) by constructing look-up tables (LUTs) for a set of geometries, wavelengths, and aerosol models in order to obtain aerosol reflectance as a function of AOT values (Kokhanovsky and de Leeuw, 2009). Several radiative transfer (RT) codes are available that can be used to construct LUTs such as Low Resolution Transmittance (LOWTRAN) code, Moderate Resolution Transmittance (MODTRAN) code, Second Simulation of a Satellite Signal in the Solar Spectrum (6S) code, Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) code, and so on although all RT codes are equally effective for aerosol retrieval. For aerosol retrieval, all RT codes require an accurate estimation of the optical aerosol properties such as extinction efficiency, single scattering albedo, asymmetry parameter, etc. (von Hoyningen-Huene *et al.*, 2003). Although in past the RT code was difficult to use because of the generation of the code in operation environment, recently lots of improvement for RTM have been done to make user-friendly interfaces for RTM code (Ricchiazzi *et al.*, 1998).

Development of AOT model from satellite data over high population density areas such as in Hong Kong region is important because of intensive economic activities that produce aerosol which can affect air quality, local climate as well as human health. Several studies have already been conducted for the retrieval of AOT in Hong Kong region using MODIS data at 500 m to 1 km spatial resolution with different approaches and techniques (Li *et al.*, 2005; Wong *et al.*, 2008, 2010; Bilal *et al.*, 2013). The outcome of their results showed that a good agreement ($R>0.9$) can be achieved between AOT derived from MODIS (500 m or 1 km) and AOT from AERONET measurement. However, there are several shortcoming of the existing MODIS aerosol retrieval algorithms which can be seen in context of spatial resolution of data, retrieval/use of land surface reflectance, correction technique of atmospheric transmission, selection of aerosol model, and the selection of RT code for the aerosol retrieval. Therefore, there is still plenty of scope to improve the AOT retrieval procedure by incorporating robust RT code, accurate land surface reflectance, appropriate aerosol model, and gasses correction method.

1.2 Problem Statement

The increasing amount of tropospheric aerosol in the atmosphere due to anthropogenic activities can cause harm to human health as well as premature deaths. World Health Organization (WHO) has recorded 3.7 million of premature deaths due to air pollution that occurs in the cities and rural areas for worldwide in 2012. The greatest number of premature deaths (88%) caused by air pollution occurs in the low and medium income countries such as Western Pacific and South-East Asia. Effect of premature deaths from air pollution (fine particles) contributes to chronic diseases such as heart disease and stroke (80% of premature deaths), chronic obstructive pulmonary disease (14% of premature deaths) and lung cancer (6% of premature deaths). Exposure to fine particle more risky to elderly, patients with pre-existing heart and lung disease, children, and asthmatic (U.S EPA, 1997). Indeed, a detailed measurement of aerosol over urban region is required in order to prevent these problems from become worse.

Aerosol measurement from ground-based sun-photometer instruments (e.g. AERONET and shipboard measurement) have provides high accuracy of AOT retrieval over land and ocean (Porter *et al.*, 2001; Mishchenko *et al.*, 2007). However, ground-based measurements have disadvantage on spatial information (narrow coverage) due to point based measurement technique. Moreover, it's impossible to obtain aerosol information over whole region (global coverage) especially in remote areas. Therefore, to overcome these limitations, remote sensing satellite has become powerful scientific tools to retrieve aerosol information in the Earth's atmosphere from space. Besides, it can provide AOT distribution at local and global scale, good spatial resolution, and high temporal resolution.

Numerous aerosol products at global scale have been generated from different types of satellite data such as AVHRR, Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), MODIS, MISR and Total Ozone Mapping Spectrometer (TOMS) (Li *et al.*, 2009). The global aerosol product can be used to understand global aerosol distributions for long-term effects in climate studies, but, the problems of global aerosol product are;

(i) Aerosol product derived from satellite data has offers aerosol information at low spatial resolution. For example, MOD04 L2 C005 has provides aerosol product at 10 km spatial resolution in order to monitor aerosol distribution at global scale. However at local scale, low spatial resolution could not be able to give good spatial information to monitor aerosol sources from anthropogenic activities. With the low spatial resolution of MODIS aerosol product, only few pixels can be covered for urban, industrial, and rural areas. Therefore, it is insufficient to show aerosol variation due to inherent aerosol variability over heterogeneous land surface (Li *et al.*, 2005).

(ii) It uses global aerosol model for retrieving aerosol product at global scale. Global aerosol model has provides aerosol model based on aerosol properties at global scale. However, aerosol properties are varied depending on local area circumstances such as sources, emission rate, and removal mechanism (Omar *et al.*, 2005). Therefore, by using global aerosol model to estimate aerosol at local scale can cause uncertainty to the radiative forcing (Li *et al.*, 2005). Zhao *et al.*, 2008 have performed sensitivity study about the influence of aerosol model selection on the AOT retrieved from AVHRR with fixed aerosol model and found that wrong selection of aerosol model can give false result to AOT long-term trend on the regional scale. Furthermore, investigation from the studies (Mishchenko *et al.*, 1999; Jeong, 2005) also indicated that there is an impact of the differences in size distribution function and the refractive index on the AOT retrieval, and improper of size distribution can produce large AOT discrepancies which normally can be occurred in case of global aerosol model. Therefore, monitoring of local aerosol characterization is not suitable with global aerosol product because monitoring of AOT at local scale requires several local aerosol models to be investigated.

Many studies actually have been carried out using data from different satellite sensors and diverse aerosol retrieval algorithms based on Look-up tables (LUTs) from Radiative Transfer Model (RTM) (Lee *et al.*, 2007; Levy *et al.*, 2009; Kokhanovsky *et al.*, 2010). AOT retrieved from satellite data by constructing LUTs using Radiative Transfer (RT) code shows a good agreement against AOT from AERONET measurement (von Hoyningen-Huene *et al.*, 2003; Lee *et al.*, 2007; Wong *et al.*, 2010). But, the construction of LUTs for set of geometry angles, aerosol models, and so on using RT code are complex and difficult. The LUTs construction process require lots of parameters in order to do computation and simulation which is not easy to carry out within a short period because LUTs is based on huge bulk of pre-computed data which needs to be recomputed every time as the atmospheric model changes (Katsev *et al.*, 2010). Instead of constructing LUTs, AOT can also be retrieved using direct computation without RT codes (Bilal *et al.*, 2013) but this technique has several limitations i.e. i) computation is too simple without accounting properly molecular effects, ii) require to make several of assumptions and iii) can only be operated under condition of atmospheric optical thickness value is less and equal than 0.01 (Kokhanovsky, 2008).

However, apart from the complexity of LUTs construction, selection of RT code, selection of appropriate local aerosol model and selection of suitable satellite data, the most challenging part of aerosol estimation over bright surfaces is to retrieve surface reflectance information due to bidirectional effect and adjacency effect from heterogeneous surface though the estimation of surface reflectance over ocean (homogeneous surface) can be retrieved easily using dark ratio technique. Although estimation of surface reflectance is challenging part for aerosol retrieval over land, the measurement of accurate surface reflectance over land is necessary in order to monitor the sources of aerosol over land, and an error of 0.01 for surface reflectance estimation results in an uncertainty of 10% in AOT estimation (Kaufman *et al.*, 1997).

Previously, the dark surface approach was applied using near-UV and UV channels in order to estimate surface reflectance over bright surface but this assumption is not effective at longer wavelengths (Kokhanovsky and de Leeuw, 2009). Therefore, the Dark Dense Vegetation (DDV) techniques was introduced to estimate surface reflectance based on empirical relationship between surface reflectance at shortwave infrared channel and surface reflectance at visible channel, and the DDV technique has been used for retrieving MODIS aerosol product (MOD04 L2 C004) over land region (Kaufman *et al.*, 1997c). However, this algorithm works only on vegetation areas with coverage larger than 60% where the surface reflectance are very low, and because of this assumption DDV algorithm can't be used effectively for aerosol estimation over bright surface such as deserts and urban. Thus, in the MODIS collection 005, the improvement has been made by developing algorithm from empirical relationship between shortwave infrared and visible channel based on NDVI values. Although, this algorithm is more reliable compared to previous algorithm, however, AOT value over urban region (bright surfaces) show bias (<2 %) (Levy *et al.*, 2010).

However, it is worthwhile to state again that accurate estimation of AOT is essential for many purposes such as air quality, human health, climate modelling and so on but the estimation process of AOT is not straightforward especially AOT retrieval over land surface due to several factors stated above. Despite the difficulties, several studies have been conducted for the development of AOT retrieval algorithm using different types of data and processing techniques but there are still research gaps which can be identified in context of use of RT codes, selection of local aerosol model, selection of suitable satellite data, correction of gasses effect, and retrieval of land surface reflectance. A comprehensive AOT retrieval model is still absent in the literature, therefore, this study is going to develop an effective aerosol retrieval algorithm using MODIS 500 m data by exploring the potential of several RT codes, land surface retrieval techniques and gasses effect correction method, and expected that this study would make a significant contribution in the field of AOT retrieval process not only for Hong Kong but also for other urban areas. Moreover, the high resolution of MODIS data (500 m) planned to be used in this study would provide spatial distribution of AOT value in detail at urban region compared to spatial distribution of AOT from MODIS aerosol product (10 km).

1.3 Objectives of the Study

The main objective of this study is to develop an effective aerosol optical thickness (AOT) retrieval algorithm over land using 500 m spatial resolution MODIS data. There are several specific objectives that need to be addressed in order to achieve the main objective:

(i) to evaluate the potential of MODIS 500 m data for the retrieval of AOT using different retrieval algorithms,

(ii) to investigate the effect of surface reflectance estimated/obtained using different techniques,

(iii) to validate AOT retrieved from MODIS 500 m with the AOT from AERONET data and AOT from MODIS aerosol product (10 km), and

(iv) to propose an effective AOT retrieval algorithm using MODIS 500 m data considering accuracy and errors with respect to ground based AERONET data and MODIS aerosol product.

1.4 Scope of the Study

The study focused on the aerosol estimation in Hong Kong (HK) region by using MODIS 500 m data. Hong Kong region was selected in this study due to several reasons, which are; i) Hong Kong is one of the most populated urban areas in the world where air pollution is a very frequent incident due to different anthropogenic activities in and around the city, ii) the availability of long-term ground data measurement (AERONET data) from the two AERONET stations (one is located in city center and the other is located in rural area) which is very important in order to develop an effective aerosol retrieval algorithm, iii) the availability of MODIS data due to less cloud cover in several months in a year, and iv) several studies were carried out in this study area which is crucial to understand the effectiveness of the proposed algorithm.

In this study, data from MODIS Terra satellite was used to retrieve aerosol reflectance at 0.466 µm, 0.553 µm, 0.646 µm and 2.119 µm wavelength by categorizing it into three primary data, which include i) MOD02HKM (MODIS calibrated radiance at 500 m), ii) MOD03 (MODIS geolocation data) and iii) MOD09GA (MODIS land surface reflectance product). Besides that, total ozone content (MODIS atmospheric product, MOD07), total water vapour content (MODIS precipitable water product, MOD05) and cirrus cloud data (MODIS calibrated radiance at 1 km, MOD021KM) were used in retrieval computation to reduce uncertainty due to the cloud and gas effect. However, for the ground measurement, AERONET data from HK Poly-U site (2006-2011) and HK Hok Tsui (2007-2009) site were used to validate AOT retrieved from MODIS 500 m data. Moreover, a set of parameter from AERONET inversion product level 2 data were taken in order to classify local aerosol model into several types. Additionally, MOD04 L2 C005 (MODIS aerosol product level 2 collection 005) was used to make a comparison with AOT retrieved from MODIS 500 m data.

Several RT codes are available for AOT retrieval and previous studies used these RT codes different ways. However, considering the potential of these RT codes and the outcome of the previous studies, this study has focused on aerosol estimation using three different techniques, which included i) AOT retrieval using LUTs generated from SBDART code, ii) AOT retrieval using LUTs generated from 6SV code and, iii) AOT retrieval using direct analytical equation (no LUTs was required). It is worthwhile to mention that land surface reflectance is an important part of the

AOT retrieval algorithm, therefore, surface reflectance from three techniques were used to investigate the effect of surface reflectance on AOT retrieval process that are i) taking directly from MOD09GA, ii) extracting from Dark Dense Vegetation (DDV) technique and iii) deriving using atmospheric correction based on 6SV code (ATCOR-6SV).

In this study, aerosol optical and microphysical properties obtained from AERONET inversion product level-2 data were used to develop local aerosol models using K-mean clustering analysis. All the developed aerosol models were tested in the RT code and an effective aerosol retrieval model was chosen based on the high accuracy obtained through validation with AERONET measurement. There are several software i.e. remote sensing (such as ENVI) and programming (Matlab, IDL, Python) were used for the overall processing of AOT retrieval.

1.5 Study Area

The study area of this research is Hong Kong (Figure 1.1a), which is located on China's south coast that close to the Pearl River Delta and South China Sea. It has been recognized as one of the densely populated areas of over seven million people living in 1104 km^2 of land areas. The topography of Hong Kong is covered by natural terrain (60%) and the developed areas (40%). The natural terrain is quite rigorous in the New Territories where highest peak of 957 m and 12 other peaks over 500 m height makes the terrain very complex (Li *et al.*, 2005). However, most of the developed areas is located over flat terrain and extends as far as sloped that are too steep to develop. The climate of Hong Kong is sub-tropical with distinct seasons and influenced by Asian monsoons. There are four seasons in Hong Kong such as a cool and dry winter, unstable and wet spring, hot and humid summer, and warm and pleasant autumn. Commonly, wind comes from the north and northeast in winter, east in spring and autumn, and south and southwest during the summer (Guo *et al.*, 2007). The mostly cloudy weather occurs in January and February with prevailed by dry northerly winds. Then, high humidity with fog and drizzle happens in March and April and most of the rainfall occurs between May and September. While in November and December, the weather is sunny with pleasant breezes and comfortable temperatures (HKO, 2003).

The major economic activity in Hong Kong is service sector such as trade, financial services, tourism, retail, and real estate. The industrial activity in Hong Kong is very minimal as most of the industrial plants were relocated to the neighbour by region. However, since Hong Kong is close to the Pearl River Delta region (big industrial activities); it has given big impact in worsening air quality of Hong Kong due to the high emission of aerosols from industrial activities at Pearl River Delta region. Furthermore, Hong Kong city is densely populated and its massive urban infrastructures contribute to increase aerosol emission from the various anthropogenic activities (e.g. transportation and construction activity).

There are two AERONET sites in Hong Kong region that located in two different areas i.e. Hong Kong Polytechnic-University (Poly-U) located at center of the Kowloon city (22° 18’ 10” N, 114° 10’ 48” E) (Figure 1.1b) and Hok Tsui (22° 12’ 36” N, 114° 15’ 28” E) located at rural areas (Figure 1.1c). The ground data measurement (AERONET station) is available in the long term since 2003 for HK Poly-U site and 2007-2009 for HK Hok Tsui.

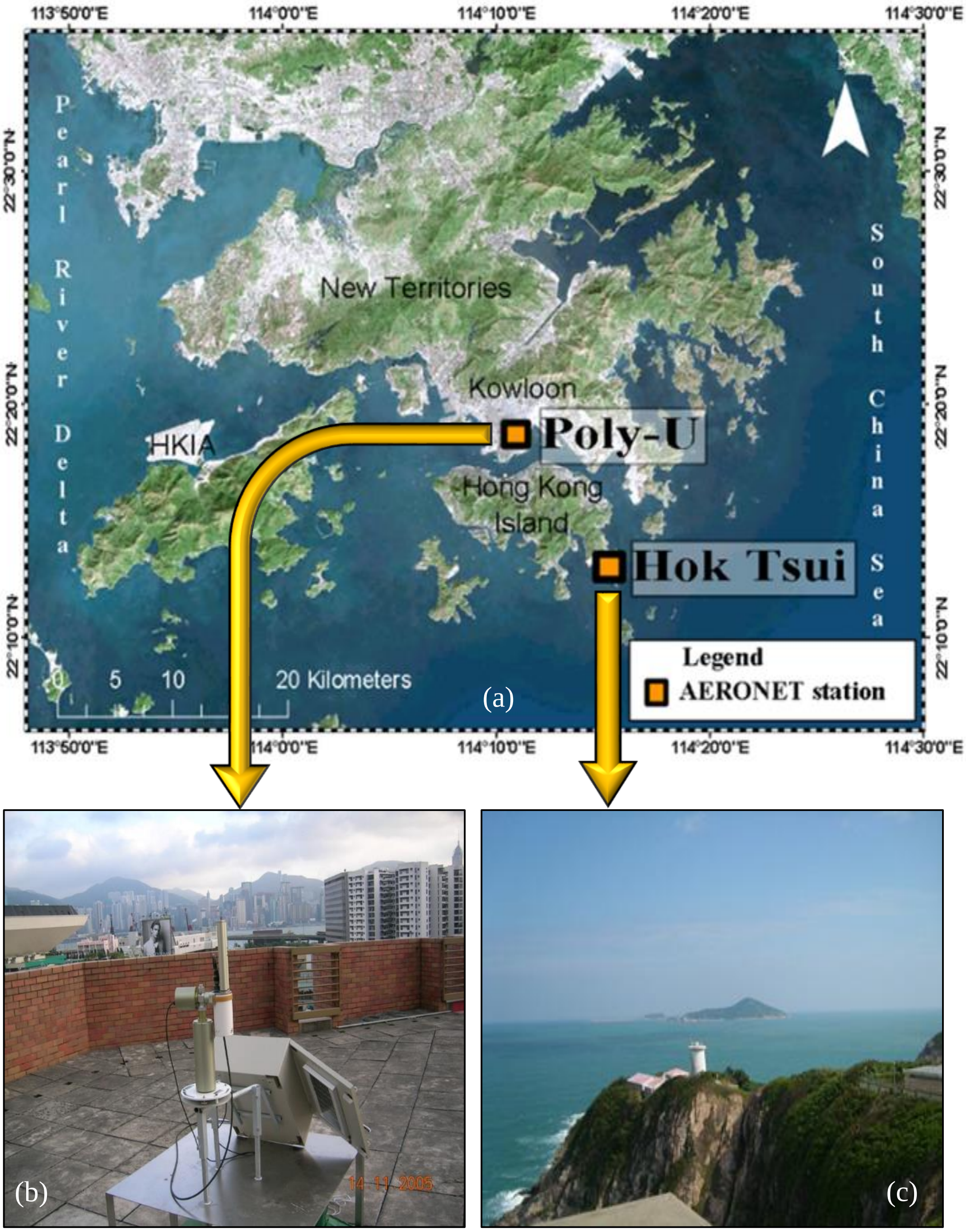

Figure 1.1 (a) Study area of Hong Kong, (b) AERONET station at Hong Kong Polytechnic-University site and (c) AERONET station at Hong Kong Hok Tsui site

1.6 Significance of the Study

The importance of air quality estimation is well-known since air quality has obviously an impact on human health, economic activities, the environment, and climate change. However, although the accurate estimation of air quality can be obtained from the point-based ground measurement, the lacking of such information over a larger area or a remote area is created a demand to use satellite data for estimating air quality over larger area though the process of air quality estimation is very complex.

However, the main problem to obtain high accuracy aerosol information from satellite data is that which algorithms/techniques are going to be used to estimate AOT over land by minimum retrieval error since several complex processing steps are involved, thus, not so much studies have been carried out to estimate AOT over land from the satellite data. Therefore, the proposed AOT retrieval algorithm using MODIS 500 m data has an immense significant in the field of air quality estimation as it has a potential to obtain aerosol information with good accuracy and minimum retrieval error. Nevertheless, the specific contributions of this study can be described as follows:

(i) It determines which RT codes that can be used to obtained high accuracy against AOT from AERONET measurement.

(ii) Investigate whether AOT retrieved using direct analytical equation can produce better accuracy than AOT retrieved using LUTs generated from RT code.

(iii) Able to show the influence of channel selection from MODIS data on the AOT value.

(iv) Promote new accurate surface reflectance estimation technique that can solve significant bias over bright surface.

(v) It can show how far the accuracy of AOT retrieved from MODIS 500 m can be achieved against AOT retrieved from AERONET data.

Indeed, the high resolution of MODIS data (500 m) planned to be used in this study would provide spatial distribution of AOT value in detailed in urban region compared to spatial distribution of AOT from MODIS aerosol product (10 km). The necessaries of high spatial resolution to estimate aerosol over urban region due to this region are the sources of anthropogenic aerosol. Therefore, AOT value at 500 m spatial resolution could provide good spatial distribution with high accuracies level that could be used over urban region. Furthermore, the local aerosol model used instead of global aerosol model could increase the accuracies level due to the characteristic of aerosol model, based on its usage on local areas. The research would also be significant for obtaining AOT value at near real time acquisition due to MODIS aerosol product that does not provide data at near real time. Thus, with the achieved AOT data at near real time, the spatial distribution and concentration of aerosol could be monitored quickly.

1.7 Outline of the Thesis

This thesis comprises of six chapters. Chapter 1 is the introduction and consists of six sections that are; background of the study, problem statement, objectives, scope of the study, study area, and significant of the study. The background of the study briefly describes about the atmospheric aerosol, aerosol retrieval techniques from satellite data and overview of previous research. The problem statement highlights several problems of the research approach. The main objective was provided and the specific objectives to achieve the main objective were stated. The scope, study areas, and significant of the study were discussed in details in this chapter.

In Chapter 2, the overview of aerosol background including types, sources, parameters and properties, effects, measurement techniques, and algorithm were described in detailed. In this chapter, previous studies of aerosol retrieval techniques using satellite data were analysed in order to develop an effective technique/approach to retrieve aerosol information. A detail clarification of Radiative Transfer Model (RTM) were described and several radiative transfer (RT) codes were listed and discussed.

Chapter 3 provides a comprehensive methodology for retrieving aerosol optical thickness (AOT) from MODIS 500 m data using different techniques. It consists of data preparation, data pre-processing, aerosol reflectance estimation, local aerosol model characterization, AOT retrieval, and validation and comparison of AOT retrieved.

Chapter 4 presents and analyses results which obtained from different processing algorithms. A detail description of the outcome of the local aerosol model characterization, surface reflectance estimation, validation of MODIS AOT 500 m using AOT from AERONET, comparison of accuracy of different AOT retrieval models, comparison between AOT from MODIS 500 m and AOT from MODIS product, and spatial distribution of MODIS 500 m AOT were presented.

In Chapter 5, research findings were discussed with supporting arguments from the other studies. At last, the final chapter, Chapter 6 presents the research achievements and conclusive remarks which include recommendations for further research.

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