# MODIFICATION OF RADIATIVE TRANSFER MODEL FOR ESTIMATING SOLAR IRRADIANCE OVER PENINSULAR MALAYSIA

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# DEDICATION

**To my beloved FAMILY**

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# ABSTRACT

The availability of atmospheric parameters is important in estimating solar irradiance using Radiative Transfer Model. Atmospheric data such as temperature, relative humidity, pressure and atmospheric trace constituent in the function of altitude are the basic requirement for estimating solar irradiance and it is very limited. Static atmospheric model such as Air Force Geophysics Laboratory Atmospheric Constituent Profiles does provide the required parameter however it is outdated and does not reflect the local atmospheric condition. A Local Static Atmospheric Model for Malaysia was built in this study to provide the needed atmospheric parameters. The model was built based on monthly data from Atmospheric InfraRed Sounder in a period of ten years at peninsular Malaysia and validated with local meteorological data. Along with the atmospheric model, simple model of the atmospheric radiative transfer of sunshine was rewritten in MATLAB environment with some minor modification that allows the local atmospheric model to be integrated into the radiative transfer model. The modified radiative transfer model takes five parameters for the calculation of the solar irradiance which are, date, time, longitude, latitude and altitude. It reduces the parameter needed by the conventional radiative transfer model such as the inputs of atmospheric parameter, pressure, zenith angle, path length, and earth-sun distance. The modified the radiative transfer model was design to include the local atmospheric model as the main atmospheric input which improve its accuracy and suitable to be used locally. The results of the study were compared with the solar flux data from Aerosol Robotic Network which return an overall correlation of 97% with 4.8% root mean square error for zenith angle below 60°.

# ABSTRAK

Ketersediaan parameter-parameter atmosfera adalah penting bagi penganggaran sinaran suria dengan menggunakan model pemindahan sinaran. Maklumat atmosfera seperti suhu, kelembapan relatif, tekanan dan unsur surih atmosfera dalam fungsi ketinggian adalah keperluan asas bagi penganggaran sinaran suria dan ia adalah amat terhad. Model atmosfera statik seperti Profil Atmosfera Makmal Tentera Udara Geofizik ada meyediakan parameter-parameter yang diperlukan tetapi ia telah ketinggalan zaman dan tidak mencerminkan keadaan atmosfera tempatan. Model atmosfera statik tempatan untuk Malaysia dibina dalam kajian ini bagi menyediakan parameter-parameter atmosfera yang diperlukan untuk anggaran sinaran suria. Model ini dibina dengan menggunakan data bulanan daripada pengukuran inframerah atmosfera di Semenanjung Malaysia selama sepuluh tahun dan telah disahkan dengan data cuaca tempatan. Selain daripada model atmosfera, model mudah pemindahan atmosfera sinaran suria telah diprogramkan dalam persekitaran MATLAB dengan pengubahsuaian bagi membolehkan model atmosfera tempatan diintegrasikan dalam model pemindahan sinaran. Model pemindahan sinaran yang telah diubahsuai memerlukan lima parameter untuk membuat pengiraan sinaran suria iaitu tarikh, masa, longitud, latitud dan altitud. Ia mengurangkan parameter yang diperlukan oleh model pemindahan sinaran konvensional seperti parameter atmosfera, tekanan udara, sudut kemuncak matahari, jarak suria dalam atmosfera dan jarak bumi dengan matahari. Model pemindahan sinaran yang telah diubahsuai ini direka untuk menggunakan model atmosfera tempatan sebagai permasukan atmosfera utama yang meningkatkan ketepatan penganggaran dan sesuai digunakan untuk penganggaran tempatan. Keputusan kajian ini dibandingkan dengan data fluks suria daripada Rangkaian Robot Aerosol dengan korelasi sebanyak 97% dengan 4.8% punca min ralat kuasa dua bagi sudut kemuncak kurang daripada 60°.

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| | | |
|---|---|---|
| *gph* | - | Geopotential height. |
| *p* | - | Pressure at the point of measurement |
| *rho* | - | Air density at the point of measurement |
| $g_o$ | - | Gravity at mean sea level |
| *Z* | - | Geometric height. |
| *G* | - | Gravity ratio |
| $R_e$ | - | Radius of the earth at latitude |
| $twc_h$ | - | Total cumulative water column at height h. |
| $wmr_h$ | - | $H_2O$ mixing ratio as a function of height |
| $\rho_h$ | - | Air density as a function of height |
| $P_h$ | - | Pressure as a function of height |
| $R_d$ | - | Gas constant (287.058 J $kg^{-1}$ $K^{-1}$) |
| $T_h$ | - | Temperature as a function of height |
| $\mathrm{I}_{total}$ | - | Total irradiance reaches the earth surface |
| *z* | - | Solar zenith angle, |
| $\mathrm{I}_{f\lambda}$ | - | Diffuse irradiance |
| $\mathrm{I}_{d\lambda}$ | - | Direct irradiance as a function of wavelength. |
| $\mathrm{I}_{on\lambda}$ | - | Corrected extraterrestrial irradiance for actual earth-sun distance |
| $\mathrm{T}_{r\lambda}$ | - | Transmission of Rayleigh component |
| $\mathrm{T}_{a\lambda}$ | - | Transmission of aerosol component |
| $\mathrm{T}_{w\lambda}$ | - | Transmission of water vapour as the function of wavelength |
| $\mathrm{T}_{o\lambda}$ | - | Transmission of ozone as the function of wavelength |
| $\mathrm{T}_{u\lambda}$ | - | Transmission of Uniformly mixed gas as the function of wavelength. |

| | | |
|---|---|---|
| M’ | - | Pressure corrected air mass |
| $\lambda$ | - | Wavelength |
| $P_o$ | - | Ptandard pressure, 1013.3mB |
| M | - | Geometrical air mass (path length) |
| $\beta$ | - | Aerosol optical depth. |
| $\alpha$ | - | Wavelength exponent |
| $a_{w\lambda}$ | - | Water vapour absorption coefficient as a function of wavelength |
| $a_{o\lambda}$ | - | Ozone absorption coefficient as a function of wavelength |
| $M_o$ | - | Ozone air mass |
| $h_o$ | - | Height of maximum ozone concentration |
| $a_{u\lambda}$ | - | Uniformly mixed gas absorption coefficient as a function of Wavelength |
| $m_g$ | - | Gas optical mass |
| $u_g$ | - | Altitude-dependent scale path length |
| $a_{no2\lambda}$ | - | Nitrogen absorption coefficient as a function of wavelength |
| $m_{no2\lambda}$ | - | Nitrogen dioxide optical mass |
| $I_{r\lambda}$ | - | Rayleigh scattering component |
| $I_{a\lambda}$ | - | Aerosol scattering component |
| $I_{g\lambda}$ | - | Multiple reflection component |
| $H_{a\lambda}$ | - | Extraterrestrial irradiance at the mean earth-sun distance |
| D | - | Earth-sun distance correction factor |
| $T_{aa\lambda}$ | - | Transmittance of aerosol absorption |
| $H_{a\lambda}$ | - | Extraterrestrial irradiance at the mean earth-sun distance |
| fs | - | Aerosol forward scattering fraction |
| $r_s$ | - | Sky reflectivity |
| $r_g$ | - | Ground Albedo |

# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| 6S | - | Second Simulation of a Satellite Signal in the Solar Spectrum |
| AERONET | - | Aerosol Robotic Network |
| AFGL | - | Air Force Geophysics Laboratory |
| AIRS | - | Atmospheric Infrared Sounding |
| AVHRR | - | Advanced Very High Resolution Radiometer |
| COESA | - | Committee on Extension to the Stanadard Atmosphere |
| DISC | - | Data and Information Services Center |
| ETR | - | Extraterrestrial Irradiance |
| FORTRAN | - | Formula Translation |
| GES | - | Goddard Earth Sciences |
| GPH | - | Ground Potential Height |
| GRAM | - | Global Reference Atmosphere Model |
| GUACA | - | Global Upper Air Climatic Atlas |
| HITRAN | - | High resolution Transmission Model |
| ICAO | - | International Civil Aviation Organization |
| IRS | - | Indian Remote Sensing |
| LOWTRAN | - | Low resolution Transmission Model |
| LSAMM | - | Local Static Atmospheric Model for Malaysia |
| MAP | - | Middle Atmosphere Program |
| MATLAB | - | Matrix Laboratory |
| MET | - | Marshall Engineering Thermosphere |

| | | |
|---|---|---|
| MMD | - | Malaysia Meteorology Department |
| MODIS | - | Moderate Resolution Imaging Spectrometer |
| MODTRAN | - | Moderate Resolution Atmospheric Transmission Model |
| MSFC | - | Marshall Space Flight Center |
| NASA | - | National Aeronautic and Space Administration |
| NDVI | - | Normalized Difference Vegetation Index |
| NIR | - | Near Infrared |
| NOAA | - | National Oceanic and Atmospheric Administration |
| RH | - | Relative Humidity |
| RTF | - | Radiative Transfer Function |
| RTM | - | Radiative Transfer Model |
| SMARTS | - | Simple Model of Atmospheric Radiative Transfer of Sunshine |
| SNO | - | Simultaneous Nadir Overpass |
| SPCTRAL | - | Simple Spectral Transmission Model |
| UMG | - | Uniformly Mixed Gas |
| USSA76 | - | United State Standard Atmospheric |
| USSR | - | Union of Soviet Socialist Republics |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

The Earth receives 174 petawatts (pw) of incoming solar radiation at the upper atmosphere. Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans and land masses (Jensen, 2006). The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared range with a small part in the near ultraviolet.

Earth's land surfaces, oceans and atmosphere absorb solar radiation, and this raises their temperature. Sunlight absorbed by oceans and land masses keep the surface at an average temperature of 14°C (Someville, 2007). By photosynthesis green plants convert solar energy particularly in Photosynthesis Active Radiation (PAR) into chemical energy, which produces food, wood and the biomass from which fossil fuels are derived. With the advancement of science and technology, people now are able to store the solar radiation and convert it into all kind of energy via solar conversion products.

Interest has been increasingly focused on the study of solar irradiance across the globe. Scientific interest has expanded from the total amount of solar energy to its spectral distribution (Kaskaoutis and Kambezidis, 2009). For appropriate and accurate calculation of solar irradiance, a proper knowledge of the radiative transfer function of the solar radiation is necessary.

Studies of solar radiation and the atmosphere are essential for the prediction of incoming solar irradiance. The solar irradiance is needed in fields such as remote sensing, energy analysts, designers of thermal devices, photovoltaic engineers, architects and engineers, agronomists, hydrologists and meteorologist (Iqbal, 1983). The basic of irradiance estimation requires the knowledge of almanac and atmospheric physics. This knowledge is fundamental in calculating the intensity of incoming irradiance as well as the absorption and scattering process in the atmosphere.

The incoming solar irradiance is absorbed and scattered by the atmosphere based on the atmospheric condition and the zenith angle. To accurately calculate the solar irradiance, the atmosphere and radiative transfer of the solar irradiance need to be modelled.

This study modelled the atmosphere using the data provided by Atmospheric Infrared Sounding (AIRS). The atmospheric model in this study namely Local Static Atmospheric Model for Malaysia (LSAMM) is a static atmospheric model that is localized without the atmospheric motion that is suitable to be used by radiative transfer model. The atmospheric model provides the parameter needed by a radiative transfer model to simulate the propagation of the solar irradiance. Radiative transfer model used in this study was the modified version of Simple Model of Atmospheric Radiative Transfer of Sunshine (SMARTS2). This model allows the adaptation of LSAMM in its calculation of the solar irradiance.

The background of this study includes a brief introduction on solar irradiance, importance of solar irradiance, attenuation of surface level solar irradiance, standard static atmospheric model for solar irradiance estimation, and basic concepts on estimating the solar irradiance.

## 1.2 Background

The sun emits a spectrum of solar radiation that is close to a black body at the temperature about 5800K (Vasarevicius and Martavicius, 2011). The incoming solar radiation covers the entire electromagnetic spectrum from gamma and X-rays, through ultraviolet, visible, and infrared radiation to microwaves and radio waves. According to Houghton (1985), a total of 99 percent of solar energy reaching the earth is between 150nm and 4000nm accumulated of 9 percent from the ultraviolet radiation (150 nm to 400 nm), 49 percent in the visible light (400 nm to 700 nm), and 42 percent from the infrared radiation (more than 700 nm).

On earth, solar radiation is measured by irradiance (power per unit area on Earth's surface) (Bird and Riordan, 1986). Solar irradiance continuously generated by the sun in waveform dispersed into the space and it is assume that no energy is lost in space.

On the top of atmosphere, the solar constant on a mean Earth-Sun distance (149,597,887.5km) during solar minima is 1360.8 $Wm^{-2}$ and increment of 0.12% during solar maxima (Kopp and Lean, 2011). The irradiance decreased up to 90% due to the absorption and scattering by atmosphere depend on the hour of the day.

Solar irradiance was selectively absorbed and scattered by the atmosphere during the propagation from the top of the atmosphere to the ground. Primary particles that are responsible for the absorption are ozone, carbon dioxide, oxygen, nitrogen dioxide, water and methane. The amount of scattered and absorption are depends on the availability of the particle in the atmosphere. These properties changes according to season, location and altitude (Keeling *et al.*, 1976). The intensity of the solar irradiance or solar irradiance data is recorded by many meteorology stations around the globe.

Solar irradiance data is important and needed by variety of applications from different disciplines of three main groups which are remote sensing, solar energy studies and primary sources of energy for vegetation.

In the application of remote sensing, solar irradiance illuminates the earth surface where the reflected radiance is sensed by the passive remote sensing sensor. Solar irradiance data provide useful information in the remote sensing sensor design (Gascon *et al*., 2001) and the correction of the remotely sensed data (Mahiny *et at*., 2007, Yamazaki *et al*., 1997). Studies of solar irradiance enable the prediction of number of photon that can be received by the sensor where this information is useful for the sensor calibration before the launch.

One of the popular aims in solar energy studies is the direct conversions of solar irradiance into other useful forms of energy such as electricity and heat. Detailed knowledge on the transmission of solar irradiance of different wavelength is essential for the study and design of solar energy conversion devices. This knowledge is considerable important in application to high efficiency solar cell, spectrally selective surface for heating, heat absorbing and reflective glasses used in building and photosynthetic process of plant growth.

Conversion of solar irradiance into electric energy using silicon currently has the efficiency of 12% to 18% (Todorov *et al.*, 2002). This conversion efficiency is relatively higher compared to the conversion efficiency by photosynthesis which is 3.5% to 7% (Blankenship *et al*., 2011). Researches show that the rate of photosynthesis is affected by the amount of illumination of the solar irradiance on the vegetation (Gorton *et al*., 2010). Series of studies had been conducted in quantifying the relationship between photosynthesis rate and amount of radiation and the effect of solar radiation on photosynthesis (Zheng and Gao, 2009). Eventually, a good estimation of solar irradiance will lead to a good estimation of plantation growth.

A good estimation of solar irradiance on the earth surface requires both the atmospheric and geometric inputs. Atmospheric inputs such as pressure, water vapor, ozone concentration, cloud properties, aerosol concentration and tropospheric constituents are the important key parameters for estimating the absorption and scattering of the atmosphere. These parameters are usually made available through in-situ measurement, satellite measurement, meteorological station or static atmospheric models.

Static atmospheric models are used in radiative transfer model as the source of input parameters in the process of calculating the transmission of the solar irradiance. Calculation of the solar irradiance using RTM masses of atmospheric parameters where these parameters can be provided by the static atmospheric model. For the use of solar irradiance calculation, a simplified atmospheric model which is a static atmospheric model is preferred (Bird and Riordan, 1986). A static atmospheric model is a model that describes the atmosphere without the atmospheric motion. It can be directly derived from atmospheric model with a suitable conversion method. As an example, the static atmospheric model Air Force Geophysics Laboratory (AFGL) atmospheric Constituent Profile is the conversion of the United State Standard Atmospheric 1976 (USSA76) (Anderson *et al*., 1986).

Inputs of the geometric parameters are used for locating the position of the Sun on Earth. It requires parameter such as date, time, longitude, latitude and altitude where these parameters determine the location of the Sun with the value of zenith, azimuth and Earth-Sun distance. The geometric input is calculated with a well established almanac algorithm by the Astronomical Almanac (Bell *et al*., 2005) as described by Michalsky to have variation of 0.01 degree in the range of 100 years (1950-2050) (Michalsky, 1988).

Radiative transfer function is used for the estimation of solar irradiance. The transmission of the solar radiation is calculated by the radiative transfer algorithm together with the geometric algorithm to calculate Earth-Sun distance and path length.

The original works of Christian Gueymard, the Simple Model of Atmospheric Radiative Transfer of Sunshine (SMARTS2) radiative transfer model were modified in MATLAB environment for its capability to adopt the local atmospheric model in its calculation of solar irradiance. The radiative transfer model was modified in a way that it requires minimum input from user to get the irradiance output. The development of the radiative transfer model will be further discussed in chapter 3.

## 1.3 Problem Statement

Over the past few decades, the photovoltaic technology has achieved a maturity where it had become one of the most important instruments for harvesting the solar energy. Interest has been increasingly focused on the study of solar irradiance across the globe. Scientific interest has expanded from the total amount of solar energy to its spectral distribution (Kaskaoutis and Kambezidis, 2009). For appropriate and accurate calculation of solar irradiance, a proper knowledge of the radiative transfer function of the solar radiation is necessary.

Studies of solar irradiance were frequently conducted in Malaysia and neighbouring countries by solar energy researchers (Janjai *et al*., 2009; Janjai *et al*., 2010; Eltbaakh *et al*., 2013). Overall, these studies used various types of empirical function as the main calculation method for the estimation of broadband solar irradiance. These studies produced the total amount of solar energy without the spectral distribution.

Due to the lack of high-resolution spectral measurements, which are possible only with very sophisticated instruments, a radiative transfer model was designed for the prediction of high-resolution solar irradiance. This radiative transfer model needs masses of atmospheric parameters as the input of the model calculation. Atmospheric data such as temperature, density, pressure and molecular weight in the function of altitude are required to estimate the solar irradiance (Iqbal, 1983).

Local atmospheric model are needed to provide localize atmospheric parameter in estimating local solar irradiance. A number of atmospheric models were developed in the past (a comprehensive review of the atmospheric models are provided in chapter 2). These models were not entirely suitable to be used in the RTM as most of the models do not have the requirement of the RTM. The fact is that for Malaysia, there is no specific atmospheric model developed in this region that is suitable to be used in the RTM. With the development of the new local atmospheric model, it allows the estimation of solar irradiance to have better accuracy.

The accuracy of the atmospheric model is crucial in estimating the solar irradiance. The global atmospheric model does provide the overall great accuracy for estimating the solar irradiance globally but not in local scale. The intensities of solar irradiance are affected by both geometrical and atmospheric properties where the requirement of a standard local atmospheric model is important.

## 1.4 Objectives of study

The goal of this study is to provide a radiative transfer model that equips with a local atmospheric model for the prediction of the solar irradiance in Peninsular Malaysia. In order to achieve the goal, the following objectives are proposed.

i. To develop a local atmospheric model for the prediction of solar irradiance.

ii. To validate the output of atmospheric model with local meteorological data.

iii. To estimate solar irradiance using radiative transfer model and validate it with ground data.

## 1.5 Scopes of the study

During the study, certain limitations are stipulated for limiting the scope for this study. The scopes are:

i. A total of ten years atmospheric profiles from AIRS were used in generating the local atmospheric model.

ii. The study area for this study is confined to the Peninsular of Malaysia (N7°0' E99°45' – N1°15' E104°25') due to the data availability.

iii. The atmospheric profiles used in this study are limited to temperature, atmospheric pressure, relative humidity, geo-potential height as these are the basic parameter required by radiative transfer model.

iv. The atmospheric profiles in this study lie within 0 to 16km where it holds 99% of the mass of atmosphere.

v. The active range of wavelength included in the solar irradiance is between 280nm to 4000nm with the spectral resolution of 1nm to 5nm limited by the availability of data.

vi. The radiative transfer model used did not include the calculation of the refraction of the solar radiation in the atmosphere as this will increase the time needed for the calculation of the solar irradiance.

## 1.6 Significance of Study

The atmospheric model developed in this study provides the availability of the atmospheric parameters that are needed in the radiative transfer model. This atmospheric model describes the atmospheric condition in Peninsular Malaysia in a static form with five atmospheric profiles which is geometric height, geopotential height, water mixing ratio, cumulative water column and temperature.

In the field of solar energy, the radiative transfer model from this study allows solar energy to be estimated according to the local atmospheric parameter in Peninsular Malaysia when solar zenith angle is less than 60°. The estimated solar irradiance is suitable to be used by solar energy engineer in optimization and prediction of total available solar energy and the search of best site for harvesting this green energy.

This study provides a way to calculate the solar irradiance in a high spectral resolution (1-5 nm). This data is especially useful in spectrally selective studies. One of the examples of spectrally selective studies is the imaging sensor. The data can be used for remote sensing calibration and to generate the spectral irradiance during the time when the satellite is passing through which allow the analysts to understand the energy content in the satellite data used.

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