SURFACE LEVEL SOLAR ULTRAVIOLET-B RADIATION AT PENANG

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NOMENCLATURE

β	Ångström turbidity coefficient
τ	Atmospheric optical depth
ϕ	Geographic latitude, north positive (degrees)
ω	Local hour angle
φ	Phase constant (day number 80)
δ	Solar declination
α	Wavelength exponent in Ångström turbidity equation
λ	Wavelength of radiation
ρ_λ	Sky albedo
ρ_λ'	Ground albedo
τ_λ	Total optical depth at wavelength λ
α_1	Coefficient of skewness
$\tau_{a,\lambda}$	Atmospheric aerosol optical depth
θ_n	Day angle
$\tau_{NO2,\lambda}$	NO_2 optical depth
ω_o	Single scattering albedo
$\tau_{oz,\lambda}$	Ozone optical depth
ω_s	Sunrise hour angle
$\tau_{SO2,\lambda}$	SO_2 optical depth
θ_z or θ	Solar zenith angle
a	Radius of a spherical particle
$a_{oz,\lambda}$	Spectral absorption coefficient for ozone
c	Percent cloud cover
D_c	Effective UV-B dose when percent cloud cover is c
D_n	Day number of year, 1 on 1 January, February is counted as having 28 days
D_o	Clear sky effective UV-B dose
e	Eccentricity correction factor of the Earth's orbit
E	Mean erythemal dosage
EQT	Equation of time
F_r	Forward scatterence factor associated with Rayleigh scattering
GMT	Greenwich mean time
H_A	Daily total UV-A radiation
H_B	Daily total UV-B radiation
H_G	Daily total Global radiation
H_o	Extraterrestrial daily total radiation on a horizontal surface
I	Extraterrestrial solar irradiance
I_λ	Spectral extraterrestrial irradiance at wavelength λ
$I_{d,\lambda}$	Directly transmitted spectral irradiance

$I_{d,\theta,\lambda}$	Direct spectral UV irradiance of solar radiation on a horizontal surface
$I_{g,\theta,\lambda}$	Spectral global UV irradiance of solar radiation on a horizontal surface
I_o	Solar irradiance on a horizontal surface
$I_{o,\lambda}$	Spectral irradiance of solar radiation on a horizontal surface above the atmosphere
$I_{s,\theta,\lambda}$	Diffuse spectral UV irradiance
$I_{s,a,\lambda}$	Diffuse spectral UV irradiance produced by aerosol scattering
$I_{s,m,\lambda}$	Diffuse spectral UV irradiance produced by multiple reflections between the ground and the atmosphere
$I_{s,R,\lambda}$	Diffuse spectral UV irradiance produced by Rayleigh scattering
K	Global clearness index
$k_{i,\lambda}$	Spectral attenuation coefficient for a single atmospheric process i
L	Longitude
MMS	Malaysian Meteorological Service
m	Air mass between the surface and top of the atmosphere
m_c	Pressure-corrected relative air mass
m_r	Relative optical air mass
n	Refractive index of particle
P	Measured surface pressure
P_o	Atmospheric pressure at sea level (1013 mb)
R_n	Earth-Sun distance on day D_n
R_o	Average Earth-Sun distance
S	Solar constant
ρ	Surface albedo
T_λ	Spectral atmospheric transmittance
$T_{a,\lambda}$	Transmittance of the direct spectral irradiance for absorption due to scattering and absorption by aerosol particles
$T_{aa,\lambda}$	Spectral transmittance of aerosols due to absorption
$T_{as,\lambda}$	Spectral transmittance of aerosols due to scattering
$T_{i,\lambda}$	Transmittance due to a single atmospheric process i
$T_{ma,\lambda}$	Total spectral transmittance due to molecular absorbers
$T_{NO2,\lambda}$	Transmittance of the direct spectral irradiance for absorption by nitrogen dioxide
$T_{oz,\lambda}$	Transmittance of the direct spectral irradiance for absorption by ozone
$T_{R,\lambda}$	Transmittance of the direct spectral irradiance for absorption due to scattering air by molecules (Rayleigh scattering)
$T_{SO2,\lambda}$	Transmittance of the direct spectral irradiance for absorption by sulphur dioxide
u_{oz}	Ozone column in atm-cm

TERMINOLOGY

Absorption cross-section is a measurement of an atom or molecule's ability to absorb light at a specified wavelength, measured in square cm/particle.
Albedo is a measure of reflectivity of a surface or body. It is the ratio of electromagnetic radiation reflected to the amount incident upon it. The fraction, usually expressed as a percentage from 0% to 100%
Dobson units (DU) are the standard way to express ozone amounts in the atmosphere. One DU is 2.7×10^{16} ozone molecules per square centimetre, or 2.7×10^{20} m^{-2}. One Dobson unit refers to a layer of ozone that would be 10 micrometre thick under standard temperature and pressure.
Equinox - Twice during the year, September 21 and March 21, the length of day and night are equal because the tilt of the Earth's axis (in relationship to the sun) is nullified and both the Northern and Southern Hemispheres receive equal quantities of sunlight.
Extinction coefficient is a measure of the rate of the reduction of transmitted light through a substance.
Intensity is a measure of the time-averaged energy flux. (Unit: watt/m^2).
Irradiance is the total radiant flux received on a unit area of a given surface. Also called the radiant flux density.
Optical depth is a measure of transparency, and is defined as the fraction of radiation that is scattered between a point and the observer.
Radiance is a physical quantity used to measure the intensity of a light beam, defined as power per unit solid angle per unit projected area. The SI unit of radiance is the watt per steradian per square metre ($W\ m^{-2}\ sr^{-1}$).
Radiant energy is energy in the form of electromagnetic waves. Radiant energy may be calculated by integrating radiant power with respect to time. Radiant energy is usually expressed in joules.
Radiation generally means the transmission of waves from a source into a surrounding medium.
Refractive index of a material is the factor by which electromagnetic radiation is slowed down (relative to vacuum) when it travels inside the material.
Transmittance is the fraction of incident light at a specified wavelength that passes through a sample.
Turbidity is a cloudiness or haziness of the atmosphere caused by individual particles that are too small to be seen without magnification.
Zenith is the point in the sky which appears directly above the observer. More precisely, it is the point on the sky with a altitude of +90 Degrees.

ABSTRAK

SINARAN ULTRALEMBAYUNG-B (UV-B) SURIA PADA PERMUKAAN BUMI DI PULAU PINANG

Pengukuran fotometrik jalur lebar bagi sinaran ultralembayung-B (UV-B), ultralembayung-A (UV-A), global dan berbaur suria telah dibuat di Universiti Sains Malaysia (USM) dari tahun 1994 sehingga 2001. Kajian ini menunjukkan bahawa variasi besar temporal untuk ukuran sinaran suria adalah disebabkan kesan dominan sudut zenit suria dan awan. Bagi semua jenis keadaan langit, min jumlah sinaran harian untuk sinaran UV-B, UV-A dan global ialah 1.514 x 10^4 J m^{-2}, 4.69 x 10^5 J m^{-2} dan 1.80 x 10^7 J m^{-2} masing-masing. Pada hari tanpa awan, keamatan sinaran maksimum harian bagi UV-B dan global ialah 1.372 W m^{-2} dan 1.423 kW m^{-2}. Ukuran sinaran UV-B berkesan telah ditukarkan kepada fluks UV eriterma untuk dikaitkan dengan kesan keupayaan berbahaya akibat pendedahan UV. Aras tertinggi fluks UV-B adalah antara masa 1030 dan 1530 jam waktu tempatan.

Kajian variasi harian untuk sinaran UV-B, UV-A dan global menunjukkan bahawa bagi sudut zenit yang sama, sinaran suria selepas tengah hari adalah lebih besar berbanding dengan sinaran sebelum tengah hari. Kesan tak simetri ini adalah disebabkan penyerakan sinaran suria oleh awan. Kajian mengenai variasi musim untuk sinaran UV-B, UV-A dan global menunjukkan perubahan berkala dengan sinaran suria maksimum

pada bulan Mac dan September. Kesan-kesan terhadap aras sinaran UV-B di permukaan Bumi juga telah dikaji dengan menggunakan parameter meteorologikal yang sedia ada. Satu model matematik untuk menganggarkan aras sinaran UV-B di permukaan Bumi juga telah dihasilkan dan dibandingkan dengan dua model terkenal. Pencapaian model spektral didapati adalah baik dengan ralat min sebesar 9.9%. Sebagai kajian tambahan, suatu model empirik yang ringkas telah dihasilkan dengan menggunakan kaedah analisis multivariat. Ralat min bagi model empirik adalah 2.5%

ABSTRACT

SURFACE LEVEL SOLAR ULTRAVIOLET-B RADIATION AT PENANG

Broadband photometric measurements of solar UV-B, UV-A, global and diffuse radiation were made at Universiti Sains Malaysia (USM), Penang from 1994 to 2001. Results from this study show that the large temporal variations for the measured solar radiation is due to the dominant effect of solar zenith angle and clouds. Under all sky conditions, the mean daily total radiation values for the UV-B, UV-A and global radiation were 1.514 x 10^4 J m^{-2}, 4.69 x 10^5 J m^{-2} and 1.80 x 10^7 J m^{-2} respectively. For cloudless sky days, the daily maximum UV-B and global irradiance were 1.372 W m^{-2} and 1.423 kW m^{-2}. The measured effective UV-B irradiance was converted to the erythemal UV flux to relate it to the potential harmful effects due to UV exposure; UV-B flux level is in the High or Extreme ranges between 1030 and 1530 hours local time.

A study of the diurnal variation of the solar UV-B, UV-A and global radiation show that for similar zenith angles, the solar irradiance after solar noon is larger than that before solar noon. This assymmetrical effect is attributed to the scattering of solar radiation by clouds. Seasonal variation studies show a constant periodicity for the solar UV-B, UV-A and global flux with maximums in March and September. Using available meteorological parameters and total column ozone data, their effects on the surface level solar UV-B radiation was investigated. A mathematical model to estimate

the surface level solar UV-B radiation was also developed and compared with two established model. The spectral model performance is good with a mean error of 9.9%. To compliment the spectral model, a simple empirical model was also formulated using multivariate analysis. The mean error of the empirical model was 2.5%.

Chapter 1 : Introduction

Almost all the radiative energy entering the earth's atmosphere comes from the sun. The incoming solar radiation covers the entire electromagnetic spectrum from gamma and X-rays, through ultraviolet, visible, and infrared radiation to microwaves and radiowaves. Of the solar energy reaching the earth, 99 percent has a wavelength between 150 and 4000 nm, with 9 percent in the ultraviolet ($\lambda < 400$ nm), 49 percent in the visible ($400 < \lambda < 700$ nm) and 42 percent in the infrared ($\lambda > 700$ nm) (Houghton, 1985). As shown in Figure 1.1, of the total incoming solar radiation, 16 percent is absorbed by ozone in the stratosphere (stratospheric ozone), tropospheric water vapour and aerosols, 3 percent by clouds, and 51 percent by the earth’s surface. The remaining 30 percent of solar radiation are backscattered by the air (6 percent), reflected by clouds (20 percent) and reflected by the earth’s surface (4 percent) (Peixoto and Oort, 1992). The shaded areas in Figure 1.2 represent absorption of radiation due to various gases when it travels vertically through the atmosphere under clear conditions.

The UV spectra is usually divided into three groups: UV-C ($\lambda < 280$ nm), UV-B (280 nm $< \lambda <$ 320 nm) and UV-A (320 nm $< \lambda <$ 400 nm) (Meier et al., 1997). There is virtually no solar radiation reaching the earth's surface at wavelengths of less then 295 nm, as a result of strong absorption by atmospheric ozone and oxygen, whereas at UV wavelengths greater than 320 nm (UV-A range), the ozone absorption is small, and Rayleigh scattering and line absorption by other constituents are the main extinction processes (Kudish and Evseev, 2000). The UV radiation spectrum at the top of the atmosphere and at the surface of earth for 300 Dobson Units of ozone is shown in

Figure 1.3. Any depletion of ozone in the stratosphere will increase the ultraviolet flux reaching the biosphere (Pérez et al., 2002). This increase will be completely contained within the UV-B (Frederick at el., 2001) range. The inverse relationship between decreasing ozone amount and increasing level of UV-B radiation has been well established in both theory and measurements (Kerr and McElroy, 1993; Feister and Grewe, 1995; Varotsos et al., 1995; Kirchhoff et al., 1997a).

1.1 Attenuation of Surface Level Solar Ultraviolet Radiation

The intensity of solar ultraviolet radiation at ground level is dependent on earth-sun geometric factors and on a variety of atmospheric factors. Among the factors that contribute to UV-B attenuation are: Earth-Sun distance, solar zenith angle, total column ozone concentration, total column aerosol concentration, cloud properties, tropospheric constituents (such as nitrogen dioxide and sulphur dioxide), altitude above mean sea level and UV surface albedo (WMO, 1994; McKenzie et al., 2001; Lam et al., 2002; Palancar and Toselli, 2004). Because of the combined involvement of all these parameters in controlling the surface level solar UV radiation, it is difficult to determine absolutely the role of each parameter. Stratospheric components which effect the ground level UV-B irradiance are molecular scattering, absorption by ozone and scattering by aerosols (Pérez et al., 2002). Tropospheric factors include molecular scattering, absorption by gaseous pollutants, and scattering by aerosols and clouds (Acosta and Evans, 2000; Kaufman et al., 1998). Irradiance reaching the earth's surface at wavelengths greater than 330 nm is dominated by molecular and aerosol scattering, with ozone absorption being the major influence at wavelengths below 310 nm (Wang and Lenoble, 1994).

1.2 Relevance of Solar Ultraviolet Radiation Measurements

Ozone depletion and the associated increase in solar ultraviolet radiation reaching the earth’s surface is a major environmental, medical and scientific issue. A change in UV climate can cause adverse effect on the biosphere. On humans, all exposed tissue, especially the skin and eyes, can be harmed by ultraviolet radiation (Diffey and Oakley, 1987; Rosen et al., 1990; Leyden, 1990; Armstrong and Kricker, 1993; Wee et al., 1997). On terrestrial ecosystems, elevated levels of UV-B are known to inhibit plant growth, development and physiological processes (Caldwell et al., 1998; Pinto et al., 1999). Photodegradation of materials, such as synthetic polymers (plastics and elastomers), are mainly due to ultraviolet-B radiation (Halvorson and Kerr, 1994; Andrady et al., 1995). These potential effects of enhanced ultraviolet radiation on photobiological and photochemical processes could lead to sosioeconomic consequences. In assessing this impact, studies on the modification of solar ultraviolet-B by stratospheric ozone, and geometric and environmental factors are important. This will require accurate and sustained monitoring of UV fluxes.

Although solar UV-B irradiance data collection for the higher latitudes have been carried out intensively at many locations for many years now (Wardle et al., 1994; Diaz et al., 1997; WMO, 1999), however it is not the same for the equatorial/tropical regions. At the tropical latitudes, the erythemally-weighted irradiance far exceeds that incident at higher latitudes (Frederick and Erlick, 1994). At the Antarctic latitudes, even during the occurance of the ozone hole, direct transmission of UV radiation of wavelength higher than 290 nm remains lower than at the tropics (Davies, 1993; Ilyas et al., 1999).

To understand the relationship between factors that influence ground level ultraviolet radiation, reliable data of good quality is required. Development of a sound ultraviolet climatology will provide the user community (environmentalists, medical scientists, ecologists, meteorologists, policy makers) much needed information to enable them to study the effects, understand responses of living systems and to develop strategies, evaluate possible ultraviolet trends and for forecasting purposes. Therefore, it is essential to obtain spatial and temporal changes of UV radiation. Data that is of known quality will be an important tool in predictive capabilities, verification of modeled estimations and improve our understanding of atmospheric processes, especially in the equatorial region. To this effect, a reliable calibration of the instrument is required to compare results from different observation sites. This will then help the international scientific community to form a global ultraviolet climatology picture.

One of the important byproduct of solar ultraviolet measurement and research will be to create public awareness to the risks of overexposure to solar ultraviolet radiation. According to WMO (1994), the erythemal UV irradiance in the low latitudes are more than twice the values measured in the high latitudes. The possible detrimental health effects of exposure or overexposure to solar ultraviolet radiation is well documented (UNEP, 1989, 1994 and 1998; WHO, 1994). Measures have to be taken to educate the public to change their behavior in the amount of time exposed to sunlight. This can be done in the form of a UV Index (detailed discussions are in Chapter 5). Solar UV data has also been increasingly used to study air pollution (Galindo et al., 1995).

1.3 UV Measurements

The discovery of the ozone hole over Antarctica in 1985 (Farman et al., 1985) and subsequent reports that confirm the depletion of the stratospheric ozone (WMO, 1989; WMO, 1992) brought world-wide concern of the possible impacts of increased surface level ultraviolet radiation. Since then many establishments and countries have initiated programmes to monitor surface level ultraviolet radiation (Weatherhead and Webb,1997). Various types of instruments are been used for this purpose - broadband, narrowband or spectral. These instruments are stationed on ground or mounted on aircraft or satelite (Meerkoetter et al., 1997; Lubin et al., 1998). Extensive research on the physics of solar ultraviolet radiation and their variations due to natural and anthropogenic causes have also been carried out (Forster, 1995; Bodeker and McKenzie, 1996; Kirchhoff et al., 2001). Two world bodies, World Health Organization (WHO) and United Nations Environment Programme (UNEP) have been actively involved in solar ultraviolet study activities.

In the United States, there are four main agencies monitoring UV-B radiation, namely the United States Department of Agriculture (USDA) (Gibson, 1994), the Environment Protection Agency (EPA) (Barnard and Cupitt, 1994), the National Science Foundation (NSF) (Booth et al., 1994) and the National Oceanic and Atmospheric Administration (NOAA). Environment Canada (EC) measures spectral ultraviolet irradiance at twelve locations in Canada (Wardle et al., 1994). In Europe, most countries have initiated programmes to monitor solar ultraviolet radiation since the seventies and eighties. The Nordic countries have established a working group for ozone and UV research in 1988 (NOG). Other European countries do have their own monitoring systems (Webb, 1992;

Wester, 1992; Borkowski, 1994; Matthes, 1994; Leszczynski et al., 1994). The Australian Radiation Laboratory (ARL) has been involved in the measurement of solar ultraviolet radiation since the early 1980's (Gies et al., 1994). In the late 1980's, a New Zealand-wide network of filter instruments (International Light Inc.) was established (McKenzie et al., 1993). This ultraviolet radiation programme was initiated by the National Institute of Water and Atmospheric Research (NIWA). In South America, there exists a network for monitoring the solar ultraviolet-B radiation. The network stations are located at Punta Arenas (Chile) (Kirchhoff et al., 1997a), La Paz (Bolivia) (Andrade et al., 1997) and Natal (Brazil) (Kirchhoff et al., 1997b). In the polar regions, the National Science Foundation of America has installed a network for UV-B measurements in 1988. Presently it includes three stations in Antarctica (South Pole, McMurdo and Palmer), one at Ushuaia (Argentina) and one in Alaska (Barrow) (Diaz et al., 1997).

Many countries in Asia have also started monitoring of solar ultraviolet radiation. Japan Meteorological Agency (JMA) started routine observations of solar spectral ultraviolet irradiance at Tsukuba since 1 January 1990 and at Sapporo, Kagoshima and Naha since 1 January 1991 (Ito et al., 1994). China have been conducting UV-B measurements at Mt. Waliguan (36.387^{o} N, 100.898^{o} E) since 1991 (Song et al., 1994). UV-B measurements in India were initiated around 1980 at the National Physical Laboratory (NPL), New Delhi and the Centre for Earth Sciences Studies (CESS) (Subbaraya, 1994). The magnitude of erythemal UV radiation levels measured at some of these sites are tabulated in Table 4.4. It is obvious that surface level UV radiation decrease with latitude. However, for similar latitudes, UV radiation levels increase with altitude.

In Malaysia, the Malaysian Meteorological Services (MMS) have been monitoring solar UV radiation since 1995 using a Brewer spectrometer. However, no papers have been published by MMS on this subject matter. At Universiti Sains Malaysia measurements of ground level solar ultraviolet radiation have been undertaken since 1978 (Ilyas and Appandi, 1979; Ilyas and Barton, 1983; Ilyas et al., 1988; Ilyas, 1992; Ilyas, 1993). In these previous studies, it was found that the global UV radiation is very high and that cloud cover is the dominant factor affecting the surface level radiation. But the lack of supporting *in situ* measurements of other meteorological parameters limited the discussions. The data could not be compared with other sites because calibration procedures were not discussed extensively in the reports produced. There were no measurements of surface level UV-B and diffuse solar radiation in the previous studies. However this study is the first comprehensive and integrated study over a time period of solar UV-B radiation in Malaysia.

1.4 Research Objectives

The objectives of this research are:

(a) to produce good quality data of surface level solar ultraviolet-B radiation at Penang under well controlled parameters, and monitor solar ultraviolet-A, total global and total scattered radiation to provide reference information on solar radiation climatology,

(b) to determine bench marks for solar UV-B and total global radiation at Penang so that it can be used for trend and/or impact studies in the future and in the design of solar energy applications,

(c) to analyse the data obtained to interprete diurnal and seasonal variations,

(d) to investigate the effects of ozone and other relevant meteorological parameters on the surface level UV-B radiation levels in an equatorial environment, and

(e) to develop a mathematical model to estimate surface level solar UV-B irradiance for the equatorial /tropical regions using the Penang data as a case study.

1.5 Thesis Overview

This thesis consists of six chapters. A brief description of the literature survey on solar ultraviolet radiation is presented in Chapter 1. The research materials and methodology used is presented in Chapter 2. Besides detailed descriptions on installation, maintenance, and data retrieval and storage procedures, the various steps taken to calibrate the instruments have also been explained. Chapter 3 consists of results and discussions on global and scattered radiation, and UV-A radiation. An empirical model for the global solar radiation have also been developed.

Chapter 4 details the data analysis procedures, UV-B radiation observational results and the effect of some major UV-B attenuating factors on the surface level UV-B radiation are discussed. For practical consideration, the basic UV-B irradiance has also been related to erythemal UV-B dosage for some discussions. In Chapter 5, a mathematical model is developed to estimate the surface level UV-B radiation at Penang. Chapter 6 concludes this thesis with a summary of the findings followed by recommendations for future research in this challenging field.

Chapter 2 : Experimental

A series of photometers have been used for studying the solar ultraviolet and total radiation. In this chapter, the details of various techniques available and the types of instruments used to measure the various solar radiation component fluxes reaching the surface level are discussed. Their principle of operation and optical characterization, installation, maintenance and data retrieval procedures used, together with method of calibration and sources of errors are briefly presented.

2.1 Introduction

The two main spectral bands of solar radiation received at the earth's surface are the short-wave ultraviolet (UV) and visible radiation. These radiation components are received both directly from the sun and from scattering in the clouds and atmosphere. Of particular interest is the UV portion of the solar radiation because of its negative effects on humans, terrestrial and aquatic ecosystems, and air quality (see section 1.2). The direct and diffuse irradiance from the upward hemisphere is measured using a pyranometer.

Generally, the accuracy of solar radiation measuring instruments depend on:

(i) instrument's sensitivity, stability, linearity, spectral response and response time;

(ii) change in response due to variation in ambient temperature, effect of auxiliary equipment, the directional response of the sensor on the elevation (cosine effect),

(iii) azimuth of the sun (azimuth effect) and the effect of inclination of the pyranometer (Iqbal, 1983).

The main problems in obtaining reliable solar radiation climatology measurements include (Iqbal, 1983):

- ambiguities in detector construction which fairly represents the sensitivity of different biological and chemical targets,
- difficulties of maintaining accurate field instrument calibrations over a period of many years, and
- the absence of a baseline, long-term historical solar radiation record.

Solar radiation measuring instrument detectors can be classified as calorimetric, thermomechanical, thermoelectric, or photoelectric (Iqbal, 1983).

- In the calorimetric instrument, the radiant energy is incident on a high-conducting metal with a nonselective black paint of high absorptance. The radiant energy is converted into heat that can be measured by a variety of means.
- In the instruments based on the thermomechanical principle, the radiant flux is measured through bending of a bimetallic strip.
- A thermoelectric device consists of two dissimilar metallic wires with their ends connected. An electromagnetic force (e.m.f.) is developed when the two junctions are at different temperatures.
- In the photoelectric sensors, a semiconductor p-n junction is used. When radiation at an energy level capable of ionizing the atoms is incident on the p-n junction, an electrical current arises from the continuous movement of excess electrons and

holes. This kind of detectors are lower in cost but have faster response times for instantaneous measurements.

Ground-based instruments measuring solar radiation components can be divided into three types (WMO, 1999):

(i) Broadband instruments

- the spectral response of these instruments matches that of a particular action spectrum. The main attractive feature of these instruments are its low cost and rapidity of measurements. Broadband meters provide an important source of information over wide geographic areas and over long time periods.

(ii) Multi-channel medium-spectral-resolution instruments

- the main advantage of these filter instruments are their ability to make nearly simultaneous measurements at many wavelengths. Therefore, they can be very useful for separating cloud and aerosol effects from ozone effects.

(iii) high-resolution spectrometers

- there are two types, namely filter and grating instruments. Their increased cost and maintenance is offset by the wealth of spectral detail available and their ability to independently determine ozone and aerosol amounts, and to estimate the extraterrestrial UV flux.

However in recent years, the role of satellites in measurements of surface level solar radiation, especially UV climatology is gaining wide acceptance. Frederick and Lubin (1988) have demonstrated that satellite measurements of atmospheric ozone and cloud reflectance may be used in conjunction with radiative transfer theory to compute the budget of UV radiation in the Earth-atmosphere system. But such application will still need surface level data for validation.

2.2 Types of Radiation Instruments Used

In the present study, basically three different types of instruments were used for obtaining the solar radiation data. They are UVB-1 Pyranometer, Eppley UV Photometer and the CM 11 Pyranometer. The instrumentation utilized to measure the various solar radiation components in this study measures the radiation incident on a plane horizontal surface.

2.2.1 Solar UV-B Radiation

The solar UV-B radiation was measured using a Model UVB-1 Ultraviolet Pyranometer (Figure 2.1a) (the manufacturers are Yankee Environmental System, Inc.). The UVB-1 Pyranometer measures the power per unit area of UV-B radiation received by a horizontal surface from the entire hemisphere of the sky (global solar UV-B irradiance). It is a broadband UV-B detector with a spectral response range of 280 to 330 nm. The cosine response of the instrument is ±5% for 0 - 60 degree solar zenith angle, and a response time of 0.1 second. It's sensitivity is 1.97 Volt/(Watt/m^2) of effective UV-B irradiance.

(a) Principle of Operation

The operation principle of the instrument is shown in Figure 2.2 (Dichter *et al.*, 1993). The measurement technique employed in the instrument utilizes colored glass filters and a UV-B sensitive phosphor to block all of the sun's visible light and convert the UV-B light into visible (green) light. The resulting green light is in turn measured by a solid state detector (photodiode). A two-stage amplifier circuit then converts the photodiode output current into a useable output voltage span (0-5 Vdc). The performance of the detector and phosphor are temperature dependent. They are therefore equipped with an internal temperature control system to maintain them at a fixed temperature. The instrument had been calibrated in the factory.

(b) Model UVB-1 Characterization

The instrument have been characterized using the calibration theory proposed by Grainger, Basher and McKenzie (1993). Comparisons of the spectral response of the instrument with the Parrish and CIE erythemal action spectra is shown in Figure 2.3. It can be seen that the spectral response is very similar to the International Commission of Illumination (CIE) human erythemal action spectra (Dichter *et al.*, 1993).

(c) Instrument Calibration Constant

A plot of UVB-1 instrument readings against the concurrently measured integrated spectral data is shown in Figure 2.4. The gradient of the linear regression line fitted to the points gives the calibration constant, K which has the value 1.968 ± 0.011 V W^{-1} m^2. After correction for the 5% uncertainty of the spectral irradiance measurement, the best value for K is 1.97 ± 0.16 V W^{-1} m^2.

To convert the instrument output signal (in volts) to the irradiance of interest (total UV-B or erythemal, in W m^{-2}), the signal voltage is multiplied by a conversion factor provided by the manufacturer (Yankee Environmental Systems, 1991). The conversion factor is just the ratio of the energy measured by a detector with an ideal cosine and spectral response to the energy measured by the UVB-1 instrument. The conversion factors, which are relative to the value at solar zenith angle of 30^{o}, are tabulated in Table 2.1 (The calibration angle to force the cosine error to be zero is 30^{o}). The relative correction factor as a function of the solar zenith angle for the different types of irradiance is shown in Figure 2.5.

2.2.2 Solar UV-A Radiation

The solar UV-A radiation was measured using a TUVR Eppley ultraviolet photometer (serial number : 28289) (Figure 2.1b). The spectral range of this instrument is 295-385 nm. This photometer is widely used to monitor solar ultraviolet irradiance and has been extensively described (Drummond and Wade, 1969; Coulson, 1975). These authors have found that the instrument response is centered between 340 nm and 370 nm, and that ranges of 380-390 nm and 390-400 nm contribute only minor amounts to the total radiometer output, while significantly contributing to UV-A irradiance.

(a) Principle of Operation

The main component of the photometer are a Weston selenium barrier-layer photoelectric cell with a sealed-in quartz window, a bandpass filter and a Teflon diffuser disc. The bandpass filter serves to restrict the wavelength response of the photocell, which is 295 - 385 nm. The Teflon disc fulfills two different functions: (i) it reduces the light intensity incident on the photocell, prolonging its stability; (ii) it improves the instrument response towards the cosines law that introduces errors lower than 2 per cent for solar altitudes higher than 10^o.

(b) Model TUVR Characterization

The instrument was factory calibrated in its completely assembled form by comparison with an Eppley standard. The calibration constant is 191 μV per W m^{-2}. Linearity test on the photometer shows that the incident radiation varies linearly with the photometer output to better than ±2% over a range of 90^o - 10^o solar elevation. The spectral response of the photometer was determined in the factory using narrow bandpass filters and a non-wavelength selective detector (Figure 2.6). Temperature dependence testing has shown that the instrument exhibits a temperature coefficient of -0.2% per degree Celcius with 25 ^oC as reference point between -20 to +40 ^oC (The Eppley Laboratory, Inc.). In these conditions Mehos *et al*. (1991) and Riordan *et al*. (1990) have established that errors associated with the experimental data are less than 15 per cent, which is not in accordance with the expectation of the manufacturer (5%).

2.2.3 Global Solar Radiation

The pyranometer CM 11 was used to measure the total global radiation (Figure 2.1c). This instrument measures the solar irradiance from the direct solar radiation and from the diffuse radiation incident on a plane surface from the hemisphere above. It has a spectral response with 95% points over 335-2200 nm and 50% points over the wavelength range 305-2800 nm. The instrument sensitivity is between 4 and 6 μV per W m^{-2}, with a response time of between 4 s (63% response) and 24 s (99% response). The cosine response of the instrument is maximum ±1% deviation from ideal at 60^{o} sun's zenith angle, and maximum ±3% from ideal at 80^{o} sun's zenith angle.

(a) Construction and Physical Principles

The pyranometer has a sensor with 100 thermocouples imprinted on it to form a thermopile. When the pyranometer is illuminated, the radiant energy is absorbed by the sensor and the generated heat then flows radially through a thermal resistance to the heatsink (the pyranometer body). The temperature difference across the thermal resistance of the disk is converted into a voltage. The spectral range of the pyranometer is limited by the transmission of the glass domes.

(b) Characterization

The sensitivity value of the pyranometer was determined in the manufacturer’s laboratory by comparison against a standard pyranometer at an ambient temperature of 20 ^{o}C. It is dependent on the temperature, level of irradiance, vector of incidence, directional response, spectral selectivity and zero offset (Kipp & Zonen Instruction Manual, 1991). However, being classified as a secondary standard instrument by the World Meteorological Organization (WMO), the maximum errors in the hourly radiation totals is 3%, and for the daily total it is 2%. The sensitivity variation of the pyranometer with irradiance is shown in Appendix A (Figure 1). The temperature dependence of the sensitivity is an individual function. For a given CM 11 the curve is somewhere in the shaded region of Appendix A (Figure 2).

2.2.4 Diffuse Global Radiation

A CM 11 pyranometer mounted with a shadow ring stand (CM 121) was used to measure the downward diffused solar radiation received on a horizontal surface from the forward front hemisphere. The purpose of the shadow ring is to block the direct radiation of the sun throughout the day without the need for readjustment. Operating instructions and a list of the correction factors for uniform sky conditions and a view angle of 10.6^{o} is given in the Kipp & Zonen Instruction Manual for Pyranometer with Shadow Ring.

2.3 Instrument Activation

The solar radiation measuring instruments were mounted on a raised platform on the tower block (Figure 2.7) at the Astronomy and Atmospheric Science Research Unit Building at Universiti Sains Malaysia Main Campus, Penang (5.34^{o} N, 100.30^{o} E, altitude: 50 m above sea level). The platform is free of shadow causing obstructions at all time and is 20m above the ground and 5 m above the building's roof. A summary of the instruments used and their startup and calibration schedule is shown in Table 2-2. Efforts to measure solar radiation and other related meteorological parameters at Pantai Acheh (a small rural town on the west of Penang Island) was initiated in January 1997. Unfortunately, due to logistics and frequent electrical supply breakdown problems, the exercise was terminated towards the end of 1997. Data obtained during the measurement period was little and irregular with frequent breaks in the series. Thus, the data obtained is not used in the analysis. Another factor which prompted the discontinuation was the disclosure by the former Director of the Malaysian Meteorological Services, Dr. Lim Joo Tick that the Pantai Acheh site can not be classified as a clean air environment due to its proximity and fast transport of pollution (antropogenic trace gases and other aerosol particles) from the Georgetown city and its surrounding industrial hubs towards the site.

(a) Laboratory Checkout

Before the photometers were installed on the radiation platform tower, they were checked in the laboratory. In the absence of UV-B radiation indoors, the UVB-1 instrument reads zero. Next, light from an incandescent lamp (Philips, 60 W frosted) was incident on the sensor to verify that it is not sensitive to visible light. The instrument was then brought outdoors to be exposed to direct sunlight. The instrument showed a reading which was then compared to calculated values using the UV-CALC software package (UV-CALC Instruction Manual, 1991). A similar check was also carried out for the Eppley ultraviolet photometer (UV-A).

(b) Field Installation

The radiation photometer mounting bench is made of wood laminated with aluminium sheets and mounted on top of the metal platform block. The separation of each of the photometer is more than one meter. The instruments were connected to a datalogger placed in a laboratory at the Unit's building using pre-wired waterproof connecters and shielded electrical cables. The length of each cable is 35 meters and the impedance level is within acceptable limit.

(c) Data Logging System

The YESDAS-1 data logger (Yankee Environmental Systems, Inc.) was used for data acquisition and logging. This data logger can collect, store and display data from six different sensors. The sensor signal cables are connected to the YESDAS-1 hardware box placed in the laboratory. The datalogger is then connected to a personal computer's (PC) serial port using a four conductor cable.

The datalogging operations and data retrieval is controlled by the Datalogger Support Program (DSP-1) which resides and runs on the PC. To begin collecting data, the required data acquisition parameters (sensor sampling time, data recording interval and calibration constants) are keyed in. The YESDAS-1 system then autonomously collects and stores data. The sensor data is retrieved fortnightly or monthly and stored in ASCII files on the PC hard disk for data processing.

2.4 Instrument Maintenance and Data Acquisition

To obtain quality data, the following routine procedures for maintenance was undertaken.

(i) The photometer sensor domes were cleaned on a regular basis to prevent soiling. A soft cotton cloth cleansed with etanol was used to wipe the domes.

(ii) The pyranometer's correctness of level is maintained by ensuring that the bubble of the spirit level is within the ring.

(iii) The humidity indicators on the instruments are checked for discolouration.

(iv) The connectors and associated cables are firmly secured to minimize spurious response during inclement weather. They are also inspected regularly for physical damages or general deteriorations.

The setup used for the YESDAS-1 data logger is shown in Figure 2.8. Using the operating software (provided by the manufacturer) the instruments readings are sampled every 60 seconds, their signals digitized and placed in temporary storage in the datalogger. At the end of every 30 minutes, the sampled instrument readings are averaged and converted to usable units. This data is then stored in the datalogger memory. Data acquisition commences automatically each day at 0600 hours (slightly before sunrise) and ends at 2000 hours (slightly after sunset) local time.

The stored data is generally retrieved fortnightly or monthly by the user using the DSP-1 software program available with the system. The DSP-1 program is used to write the binary format data from the logger to a disk file. The binary format data files are then converted to ASCII data files using the Program Utilities function so that it can be imported into spreadsheet and graphic programmes easily for further data analysis and usage.

2.5 Calibration and Stability of the Photometers

(i) UV-B Radiation

Data acquisition for UV-B was started in April 1994. Calibration of the UVB-1 instrument was done at half-yearly intervals on clear days using a reference unit (Serial Number: 930405). The days chosen were such that the solar declination was similar. At the time of installation, the difference between the instrument and the reference unit was 1.8%. Photometric stability of the instrument for the first two years was very good. The difference between the measurement unit and the reference unit came up to only 2.1% at the end of 1994 (Table 2.3a). This difference increased slightly to 3.8% at the end of 1995. Thereafter, degradation quickened. The following procedure was then used to correct the measured readings.

(a) The data for the reference unit was normalized to the measurement unit using the formula:

Normalized reference data = Reference data x (10.746/10.943) (2.1)

(b) The calibration factor, k was computed by determining the ratio of the normalized reference unit data to that of the measurement unit data.

(c) A correction formula was derived using the computed calibration factors (Figure 2.9). Least squares was used to fit the data points to a second order polynomial from day 376 onwards (Draper and Smith, 1981) and the following expression was obtained:

$$f(x) = b(0) + b(1)x + b(2)x^2 \tag{2.2}$$

where,

$b(0) = 1.2363258503$

$b(1) = -1.2146400569 \times 10^{-3}$

$b(2) = 1.9566490432 \times 10^{-6}$

The excellent closeness of fit can be seen from the coefficient of determination (r^2 = 0.994).

(d) The measured irradiance (I_m) was then corrected for instrument degradation using the correction formula derived in (c):

$$I = k\, I_m \tag{2.3}$$

where k is the calibration factor, and I is the degradation corrected UV-B irradiance.

To ascertain the stability of the reference unit, comparison of measurements were done for similar solar declination angles. The differences were always less than 2%. This implies that the reference unit was stable throughout the calibration period.

For the purpose of practical consideration, the basic UV-B irradiance data is then related to erythemal UV-B dosage for the McKinlay-Diffey (1987) spectrum. This would allow us to evaluate the degree of danger to human health due to UV-B radiation as well as comparisons with measurements made at other locations which are generally presented in erythemal dosages (refer to section 4.3).

A direct inter-conversion has been established between the UV-B irradiance and erythemal dosage with the help of calibration information given by the manufacturer as follows:

$$\text{Effective UV-B irradiance} = 0.5076 \text{ W m}^{-2} \times \text{ signal in volts} \tag{2.4}$$

$$\text{Erythemal dosage} = 0.141 \text{ W m}^{-2} \times \text{ signal in volts} \tag{2.5}$$

Hence for the same signal,

$$\frac{\text{Erythemal dosage}}{\text{Effective UVB irradiance}} = \frac{0.141}{0.5076} = 0.27778 \tag{2.6}$$

For zenith angles smaller than 65^o, the accuracy of the calibration factor is within 4% (refer to Instruction Manual). Bodhaine et al. (1998) have shown that the calibration of the instrument depends strongly on total ozone for smaller solar zenith angles (sza) (< 65^o) and also a strong sza dependence at larger sza's. According to the manufacturer, the Model UVB-1 pyranometer was subjected to three types of absolute calibration, details of which are given in the Instruction Manual. The absolute calibration was done at the factory for total ozone values of about 322 Dobson Units (DU). The mean daily total ozone for 1994 as measured by the Total Ozone Mapping Spectrometer (TOMS) on the satellite Meteor-3 is 256 DU for Petaling Jaya (Malaysia) (3.10^o N, 101.65^o E), which is close enough to Penang. Measurements by Bodhaine et al. (1997) at Mauna Loa (Hawaii) with a Yankee UVB-1 broadband pyranometer (similar to the unit used in present study) suggest that the calibration as provided by the manufacturer was within about 3% of spectroradiometer measurements for effective UV-B irradiance. Errors as high as 10% can occur if the effects of total ozone are not taken into account in the calibration of the instrument (Bodhaine et al., 1998). Using the calibration factors worked out by Bodhaine et al. (1998) for various values of solar zenith angles and total column ozone (data used is from TOMS), it was found that the error due to changes in total ozone at Penang was less than 3%. This error is expected to remain small throughout the year due to the small seasonal variability in total ozone at low latitudes. The spectral error of the instrument will change with the solar zenith angle. This is due to the change of the UV portion of the solar spectrum with zenith angle at the earth's surface. However, this error is not expected to be more than 2% for effective UV-B irradiance and 4% for erythemal irradiance (Dichter et al., 1993).

(ii) UV-A Radiation

The Eppley UV photometers used in this research has been factory calibrated using an NBS standard tungsten-iodine calibration lamp. Further information on the method used can be found in a paper by Ångstrom and Drummond (1962). Since the Calibration Report for the TUVR Eppley UV photometer with Serial Number 28671 (reference unit) was not available, the same sensitivity value as the TUVR Eppley UV photometer with Serial Number 28289 was applied. The output of the UV-A instrument is in millivolts, with calibration of 0.191 mV equal to 1 W m^{-2}. Using a plot of the half-hourly irradiance during similar solar declination (September 1994 and March 1999) the sensitivity of the Reference UV-A unit over the 1994-1999 period was found to be stable (Figure 2.10).

Although the measurement unit's sensitivity degradation was rapid between 1994-1999, however the instrument's sensitivity became quite stable after that period. The stability problem of the measurement unit could be due to the opaque quartz diffusing disc whose function is to increase the stability of the instrument with exposure time. Due to insufficient intermediate sensitivity checks during this period of rapid degradation, the measurement unit was recalibrated in March 1999 (Table 2.3b). A new series of measurement was commenced to obtain quality data. During the second series of measurements, stability checks against the reference unit were carried out on a