

## STUDIES ON THE CHARACTERISTICS OF SPECTRAL SOLAR IRRADIATION IN THE TROPICS: A CASE STUDY OF MALAYSIA

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### Abstrak

*A Multifilter Rotating Shadowband Radiometer has been used to monitor the directly transmitted solar irradiance at six wavelength regions (413.9 nm, 494.6 nm, 612.7 nm, 670.8 nm, 868.0 nm and 939.1 nm) for three clear stable days at Bangi. The primary objective of this study is to determine the aerosol optical depth (AOD), total column ozone (TCO) and precipitable water content (PWC). The result shows that the maximum optical depth of aerosol at the shorter wavelength, especially on 24<sup>th</sup> February 2002 with mean value of 0.254 (24<sup>th</sup> February 2002), 0.095 (25<sup>th</sup> February 2002), and 0.072 (26<sup>th</sup> February 2002) while the ozone optical depth shows the mean value 0.0153 on 24<sup>th</sup> February 2002, 0.0174 on 25<sup>th</sup> February 2002 and 0.0175 on 26<sup>th</sup> February 2002 with the average absorption coefficient ( $a$ ), 0.2 (24<sup>th</sup> and 26<sup>th</sup> February 2002) and 0.1 (25<sup>th</sup> February 2002). The mean value of water vapor content shows that  $x = 0.356$  cm and  $k = 0.301$  cm for wavelength 939.1 nm. From the aerosol optical depth, it shows the existence of smoke type of aerosol on February, 24<sup>th</sup> to 25<sup>th</sup> 2002 with Ångström coefficient,  $\tau$ , is 1.534 and 1.5513, respectively, and sea water vapor is 0.9889 on 26<sup>th</sup> February 2002. From the Ångström coefficient, it shows that atmosphere layer of Bangi at that moment is similar to U.S. Standard Atmosphere, with maximum spectral irradiance on black body temperature is 5860 °K.*

### INTRODUCTION

The atmospheric pollutants such as aerosols, ozone and water vapor play important roles in the study of the Earth's climate system, because they directly interact with the solar radiation and modify the climate. Solar radiation is attenuated when passing through the earth's atmosphere. Therefore, solar radiation measured at the surface of the earth's depends on the amount of water vapor, ozone and mixed gases as well as the qualitative characteristics and concentration of aerosols. One of the important property to know the characteristics of atmospheric pollutants is optical thickness which is affecting the transfer of radiant energy in the earth's atmosphere. There is a need to know the spectral characteristic of solar irradiances and the extent to which changes

in environmental factors affect this energy distribution. In this article, the characteristic of atmospheric pollutants is investigated by means of series of measurements done at Bangi, Malaysia. Atmospheric optical properties such as optical depths, spectral transmittances are retrieved in order to establish some "background" characteristics of the atmospheric conditions over the Bangi atmosphere.

### EXPERIMENTAL SET-UP

Studies on the characteristics of solar irradiance measurement has been done at Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia (2°55' North, 101°50' East) using Automated Multi Filter Rotating Shadow-band Radiometer (MFRS). This instrument has been installed at the roof top of a building so that no sun ray obstruction

by any objects in the hemisphere dome vision of the instrument. Figure 1 shows the experimental set-up of this instrumen. The measurement has been done for one year during February 2002 till march 2003. Each

day we took 10 hours of measurement from 7 am till 5 pm. The measurement was taken for interval of 20 seconds and time averaging is done for each 40 seconds.



**Figure 1. Experimental set-up and data measurement**

We used an Automated Multi Filter Rotating Shadow-band Radiometer (MFRS) to measure the total solar irradiance and solar spectral irradiance in total horizontal, diffuse horizontal and direct normal at six wavelengths through the use of an automated shadow-band technique. Because the MFRS only directly measure total and diffuse irradiance, it will use eq.1 to calculate the direct normal component of solar irradiation.

$$I_{total} = I_{diffuse} + \cos(\theta_z) I_{direct} \quad (1)$$

The MFRS have 7 channels of measurements, except for channel 0 , each channel is sensitive for aerosol, rayleigh, ozone and water vapour absorption. The complete range of solar spectrum measured from MFRS is listed in table 1 below.

**Table1. MFRS specifications.**

Channel	Wavelength (nm)	Bandwidth	Sensitivity to
0	300 – 1100	Broadband spectrum	Broadband spectrum

1	413.9	10.5	Aerosol/Rayleigh
2	494.6	9.8	Aerosol/Rayleigh/Ozone
3	612.7	10.7	Aerosol/Rayleigh/Ozone
4	670.8	10.6	Aerosol/Rayleigh/Ozone
5	868.0	11.8	Aerosol/Rayleigh
6	939.1	11.8	Water Vapour

**SPECTRAL SOLAR IRRADIATION**

The observations were made from morning till evening on the days when the sky was nearly free from visible clouds, and none were near the line-of-sight to the sun. Only direct normal spectrum irradiance from channel 1,2,3,4,5 is used for aerosol, ozone analysis and channel 6 for water vapor analysis. The basic formulation of the attenuation of solar irradiance by aerosol, ozone and water vapor is given by the well-known Beer-Bouger-Lambert law as below:

$$I(\lambda) = I_o(\lambda) e^{-\tau(\lambda) m(\lambda, \theta)}, \quad (2)$$

where  $I(\lambda)$  is the monochromatic solar irradiance reaching the instrument detector at wavelength  $\lambda$ ;  $I_o(\lambda)$  the

irradiance incident on the top of the atmosphere ( $\tau = 0$  level) and it can be used to self calibrate the system;  $m(\theta_o)$  the atmospheric air mass, a function of solar zenith angle  $\theta_o$ ; and  $\tau(\lambda)$  the optical depth. Taking the natural logarithm of (2) yields

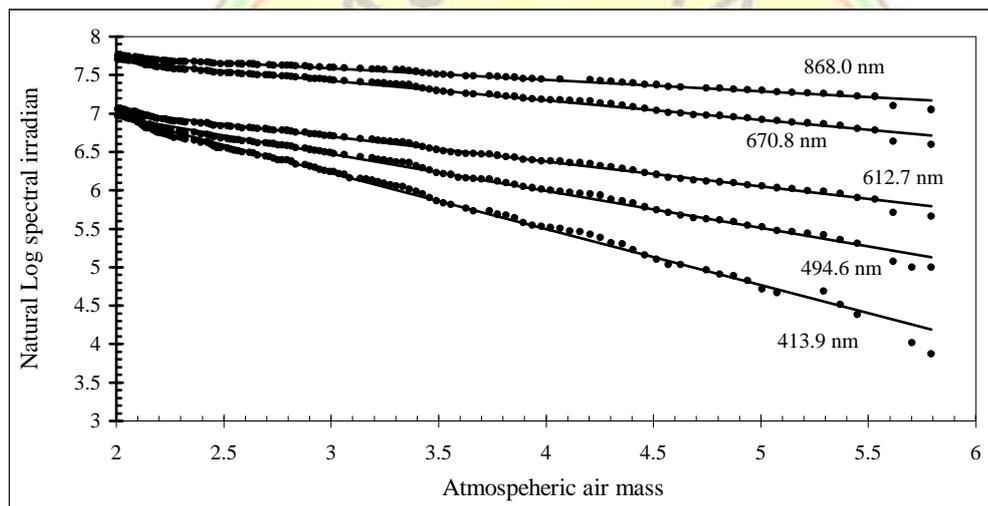
$$\ln I(\lambda) = \ln I_o(\lambda) - \tau(\lambda)m(\theta_o), \quad (3)$$

and thus a plot of  $\ln I(\lambda)$  vs  $m(\theta_o)$  will yield a straight line of slope  $-\tau(\lambda)$ , and y-intercept of  $\ln I_o(\lambda)$ , assuming that the optical depth remains constant during the course of observations.

Because the number of air mass is range from 2 to 6 it is sufficient for us to calculate this value by using cosine zenith angle (Iqbal, 1983).

$$m(\theta_z) = \frac{1}{\cos \theta_z} \quad (4)$$

The number of air mass from 2 to 6 is corresponding to the position of the sun in the sky where the time series data were taken only from morning to local noon or local noon to afternoon. In our case only the morning till noon time series data were taken due to the cloudy and overcast sky condition in the afternoon.



**Figure 2. The linear relationship which exists between the log solar irradiance and the atmospheric air mass for stable conditions.**

Figure 2 illustrates a typical Langley plot [ $\ln I(\lambda)$  vs  $m(\theta_o)$ ] which has been obtained for Bangi at five wavelengths (0.4139, 0.4966, 0.6127, 0.6708 and 0.8680  $\mu\text{m}$ ) on 24 February 2002. The lines drawn in Fig. 2 represent the best fit to the data in a least – squares sense, with the resulting slopes being the negative of the total optical depths.

The total optical depth of the atmosphere is the sum of the optical depths of its individual components:

$$\tau_{tot}(\lambda) = \tau_{oz}(\lambda) + \tau_R(\lambda) + \tau_a(\lambda) + \tau_{wv}(\lambda) \quad (5)$$

From the values of total optical depth  $\tau_{tot}(\lambda)$  and by assuming the water vapor absorption contributed to channel 6 equal to zero one can determine corresponding values of the aerosol optical depth, designated  $\tau_{a\lambda}$ , for each day. This is obtained by subtracting from  $\tau_{tot}(\lambda)$  the contribution due to molecular scattering  $\tau_R(\lambda)$ , known as the Rayleigh optical depth, and the contribution of the ozone Chappuis

absorption band  $\tau_{oz}$ , known as the ozone optical depth. Thus,

The Rayleigh scattering optical depth is a function of surface pressure  $P$ , while the ozone optical depth is a function of total ozone content  $\eta$  measured in atm-cm<sup>1</sup> was estimated from the formula as below:

$$\tau_{oz}(\lambda, y) = ya(\lambda), \quad (8)$$

and thus (6) may be rewritten as

$$\tau_a(\lambda, p, y) = \tau_{tot}(\lambda) - (P/P_o)0.008735\lambda^{-4.08} - ya(\lambda), \quad (9)$$

where  $P$  is the barometric station pressure and  $P_o = 1013.25$  hPa and  $a(\lambda)$  are the ozone absorption coefficients per centimeter of pure gas at STP.

The atmospheric turbidity parameters  $S$  and  $r$  could be derived from the optical thickness due to aerosols  $[\tau_a(\lambda)]$  according to Ångström:

$$\tau_a = S\lambda^{-r} \quad (10)$$

where  $S$  is the “Ångström Turbidity coefficient” and  $\alpha$  is the wavelength exponent which is closely associated to the size of the scattering particles and the frequency of their distribution. We can alter the Ångström Turbidity formula into a linear form by taking the logarithm (10)

$$\ln(\tau_a) = \ln(S) - r \ln(\lambda), \text{ thus} \quad (11)$$

We can determine the value of  $\alpha$  and  $\beta$  by the value for aerosol optical depth for each wavelength in a linear regression. The result of this regression give us the species, concentration and transmittance of the aerosol contained in the atmosphere for that particular day.

King and Byrne (1976) who described a mathematical formulation whereby the O<sub>3</sub> absorption optical depths, and hence total ozone content of the atmosphere, could be

inferred from spectral variation of total optical depth in the visible and near-infrared wavelength regions. In the Chappuis bands outside of other gaseous absorption bands contributions of aerosols and ozone to total optical depth are the unknowns for each channel. Using the priori knowledge of the spectral behaviour of aerosol optical depth the ozone optical depth can be determined. The basic of this technique is described below:

Assuming a Junge size distribution of the form

$$n(r) = cr^{-v^*-1}, \quad (12)$$

where the radius  $r$  extends from 0 to  $\infty$  predicts that

$$\tau_a = S\lambda^{-(v^*+2)}, \quad (13)$$

Note: this is Ångström's empirical formula for the wavelength dependence of aerosol optical depth (see equation 10). Taking the logarithm of (13), this equation becomes

$$\log \tau_a = \log(S) - (v^* + 2) \log \lambda \\ = a_0 + a_1 \log(\lambda) \quad (14)$$

which is linear when  $\log \tau_a$  is plotted against  $\log \lambda$ .

In general the aerosol size distribution will neither be Junge nor have radii extending from 0 to  $\infty$ . Both non Junge size distribution and finite radii limits, introduce a slight curvature on a  $\log \tau_a$  vs  $\log \lambda$  plot instead of the linear dependence as implied by (14). Since (14) implies no curvature, a second-order term was added, and the observations of  $\log \tau_a(\lambda, P, y)$  calculated from (9) were fitted to a quadratic of the form

$$\log \tau_a = a_0 + a_1 \log \lambda + a_2 (\log \lambda)^2, \quad (15)$$

in order to determine the total ozone content  $\eta$  and the coefficient  $a_0$ ,  $a_1$  and  $a_2$ .

Maximizing the probability that the  $\log \tau_a(\lambda, p, y)$  observations have the functional form of (14) is equivalent to minimizing the statistic  $\chi^2$  defined as

<sup>1</sup> 1 atm-cm = 2.687 X 10<sup>10</sup> molecules-cm<sup>-2</sup> in a vertical column.

$$t^2 = \sum_i \frac{1}{\dagger_i^2} \left[ \text{Log}k_a(\lambda_i, p, \gamma) - a_o - \frac{a_1 \text{Log}\lambda_i - a_2 (\text{Log}\lambda_i)^2}{\dagger_i} \right]^2 \tag{16}$$

Minimizing  $\chi^2$  as defined by (16) is equivalent to making a weighted least-squares fit to the data.

In determining the precipitable water vapor (PWV) we only use the channel 6 of MFRSR for wavelength 940-nm.

The basis for retrieving  $u$  from measurements of the attenuation of the direct beam irradiance, relies on knowledge of the variation of transmission with  $u$  over the 0.94  $\mu\text{m}$  MFRSR channel, and correction for attenuation in this band due to aerosol and molecular scattering.

The modified Langley method was used to retrieve  $u$  from MFRSR. The idea behind this method is to assume that the attenuation of the direct beam irradiance follows the Lambert-Beer-Bouguer law for aerosol and molecular scattering, and power law for water vapour absorption. Thus,  $r_{0.94} = r_{t,0.94} \exp[-\dagger_{s,0.94} m - k(um)^x]$  (17)

where  $r_{0.94}$  is the band integrated direct beam irradiance measured by the MFRSR,  $r_{t,0.94}$  is the (band integrated) top-of-atmosphere irradiance,  $m$  is the airmass,  $\dagger_{s,0.94}$  is the optical depth due to aerosol and molecular scattering,  $u$  is precipitable water, and  $k$  and  $x$  are parameters to be determined.

Another, related method can be used to retrieve  $u$  using direct beam irradiances from the 0.87  $\mu\text{m}$  (channel 5) and 0.94  $\mu\text{m}$  (channel 6) MFRSR. At 0.87  $\mu\text{m}$  it is assumed that there is negligible water vapour absorption within the band. Then,

$$r_{0.87} = r_{t,0.87} \exp [-\dagger_{s,0.87} m] \tag{18}$$

where  $\dagger_{s,0.87}$  is the total optical depth (aerosol + molecular scattering) at 0.87  $\mu\text{m}$ . If we assumed that,

$$\dagger_{s,0.94} = \alpha \dagger_{s,0.87} \tag{19}$$

where  $\alpha$  is a constant, then combining (16)-(18) yields, after manipulation

$$\text{Ln} \left[ \left( \frac{r_{0.94}}{r_{0.87}^r} \right) Q_t \right] = -k(um)^x \tag{20}$$

where,

$$Q_t = \frac{(r_{t,0.87})^r}{r_{t,0.94}}$$

$Q_t$  is a constant factor for a given instrument (the earth-sun distance variation cancels out), depending only on the in-band solar extraterrestrial irradiance and the factor  $\alpha$ .

### CONCLUSION

The studies on the characteristics of spectral solar irradiation has been carried out at University Kebangsaan Malaysia (Bangi) since February 2002 till March 2003. We choose three clear stable measurement data for the analysis of spectral behaviour. Data on February, 24<sup>th</sup>, 25<sup>th</sup> and 26<sup>th</sup> 2002 are suitable for Langley analysis due to their clear sky at the morning. These three days data have been filtered using objective algorithms proposed by Harrison et al (1994) and the points that remain are used for a final least-squares regression that yields the total spectral optical depth and extraterrestrial spectral irradiance.

The least-squares regression for three days time series data and the decomposition of the total optical depth for each wavelength yield as shown in tables below;

**Table 2: Total optical depth decomposition on 24<sup>th</sup> February 2002**

Wavelength [ m]	Total optical Depth	R <sup>2</sup>	Ln (I <sub>oλ</sub> )	Ozone absorption coefficient (a)	Total ozone content ( ) (atm-cm)	Ozone column (Ω) (DU)	Optical depth		
							Rayleigh	[ m]	Depth
0.4139	0.7310	0.9949	8.3947	0.2374	1.2645	300.20	0.3194	0.0351	0.3765

Wavelength [ m]	Total optical Depth	R <sup>2</sup>	Ln (I <sub>0λ</sub> )	Ozone absorption coefficient (a)	Total ozone content ( ) (atm-cm)	Ozone column (Ω) (DU)	Optical depth		
							Rayleigh	[ m]	Depth
0.4946	0.4810	0.9959	7.8817	0.2211	0.6251	138.20	0.1544	0.0058	0.3208
0.6127	0.3320	0.9810	7.6944	0.1967	0.2628	51.70	0.0645	0.0142	0.2533
0.6708	0.2548	0.9723	6.8269	0.1722	0.2002	34.48	0.0445	0.0134	0.1969
0.868	0.1450	0.9888	8.0237	0.1224	0.0825	10.10	0.0156	0.0079	0.1215

**Table 3: Total optical depth decomposition on 25th February 2002**

Wavelength [ m]	Total optical Depth	R <sup>2</sup>	Ln (I <sub>0λ</sub> )	Ozone absorption coefficient (a)	Total ozone content ( ) (atm-cm)	Ozone column (Ω) (DU)	Optical depth		
							Rayleigh	Ozone	Aerosol
0.4139	0.4931	0.9906	8.2206	0.1502	2.0746	311.60	0.3194	0.0365	0.1372
0.4946	0.2803	0.9946	7.7352	0.1160	1.2888	149.50	0.1544	0.0063	0.1196
0.6127	0.1856	0.9903	7.5623	0.1122	0.5339	59.90	0.0645	0.0165	0.1046
0.6708	0.1303	0.9913	8.0844	0.0827	0.5054	41.80	0.0445	0.0163	0.0695
0.868	0.0709	0.9884	7.9678	0.0542	0.2657	14.40	0.0156	0.0112	0.0441

**Table 4: Total optical depth decomposition on 26th February 2002**

Wavelength [ m]	Total optical Depth	R <sup>2</sup>	Ln (I <sub>0λ</sub> )	Ozone absorption coefficient (a)	Total ozone content ( ) (atm-cm)	Ozone column (Ω) (DU)	Optical depth		
							Rayleigh	[ m]	Depth
0.4139	0.4416	0.9991	8.0751	0.1130	2.7850	314.70	0.3194	0.0368	0.0854
0.4946	0.2499	0.9985	7.6457	0.0908	1.6652	151.20	0.1544	0.0063	0.0892
0.6127	0.1663	0.9989	7.4980	0.0876	0.7021	61.50	0.0645	0.0169	0.0849
0.6708	0.1188	0.9957	8.0373	0.7190	0.0590	42.40	0.0445	0.0165	0.0578
0.868	0.0696	0.9867	7.9455	0.0527	0.2732	14.40	0.0156	0.0112	0.0428

ln (I<sub>0λ</sub>) is ln ( uncalibrated extraterrestrial direct-normal irradiance)

From the tables above the total optical depth decrease for increasing wavelength. This shows the decrease of concentration for bigger suspended particle. For these days the aerosol optical depth very nearly follow the Angstrom power law. The aerosol and ozone concentration distribution for each wavelength is shown in table below;

**Table 5: Aerosol Concentration**

24 <sup>th</sup> February 2002		25 <sup>th</sup> February 2002		26 <sup>th</sup> February 2002	
Optical depth	Concentration [ g/m <sup>3</sup> ]	Optical depth	Concentration [ g/m <sup>3</sup> ]	Optical depth	Concentration [ g/m <sup>3</sup> ]
0.3765	48.8676	0.1372	31.4131	0.0854	27.6292
0.3208	44.8055	0.1196	30.1279	0.0892	27.9047
0.2533	39.8809	0.1046	29.0352	0.0849	27.5951
0.1969	35.7646	0.0695	26.4734	0.0578	25.6173
0.1215	30.2680	0.0441	24.6178	0.0428	24.5229

**Table 6. Ozone (O3) Concentration**

24 <sup>th</sup> February 2002			25 <sup>th</sup> February 2002			26 <sup>th</sup> February 2002		
Ozone Concentration	Concentration	Ozone Concentration	Concentration	Concentration	Ozone Concentration	Concentration	Concentration	
Optica		Optica			Optica			
l depth	[atm-cm]	[Molecule/cm <sup>2</sup> ]	l depth	[atm-cm]	[Molecule/cm <sup>2</sup> ]	l depth	[atm-cm]	[Molecule/cm <sup>2</sup> ]
0.0351	1.2645	3.40E+19	0.0365	2.0746	5.57E+19	0.0368	2.7850	7.48E+19
0.0058	0.6251	1.68E+19	0.0063	1.2888	3.46E+19	0.0063	1.6652	4.47E+19
0.0142	0.2628	7.06E+18	0.0165	0.5339	1.43E+19	0.0169	0.7021	1.89E+19
0.0134	0.2002	5.38E+18	0.0163	0.5054	1.36E+19	0.0165	0.0590	1.58E+18
0.0079	0.0825	2.22E+18	0.0112	0.2657	7.14E+18	0.0112	0.2732	7.34E+18

From the modified Langley method for retrieving precipitable water vapour (PWV) at 940-nm channel yields the parameter  $k$  and  $\gamma$  as shown in table 7. By using the linier regression, the result shows that there is a little variation of precipitable water vapour through the day and that it is reasonable to assume that the precipitable water vapour measured at Bangi is representative of the precipitable water at all other times during the daylight hours.

To determine the species of the aerosol particle, the Ångström Turbidity formula is used to yields the Ångström Turbidity coefficient  $\beta$  and wavelength exponent  $\alpha$ . This can be done by linear regression between wavelengths and aerosol optical depths. The results of these linear regressions is shown in the table 8.

**Table 7 The results of linier regression on Precipitable water (equation 19)**

Date	R <sup>2</sup>	$\gamma$	k
24/02/2002	0.9982	0.3624	0.3243
25/02/2002	0.9951	0.3515	0.2617
26/02/2002	0.9987	0.3541	0.3357

**Table 8 The results of linier regression on Ångström Turbidity formula**

Date	$\alpha$	$\beta$	R2
24/02/2002	1.534	0.1248	0.9634
25/02/2002	1.5513	0.0689	0.9115

26/02/2002	0.9889	0.046	0.7656
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The results of table 8 above give us an indication that there are smoke and a mix of smoke and sea water vapour during the measurement. This is true where  $\alpha$  is bigger than 1.4 for smoke from forest fire (for 24<sup>th</sup> to 25<sup>th</sup> February 2002) and for  $\alpha$  between 1 to 1.4 is for a mix of smoke from fossil fuel burning and sea water vapour. In fact at that moment of measurement, there were a forest fire around the area due to the dry season. And lastly the average visibility calculated from the data analysis is 28.7 km.

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