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MEASUREMENT AND ANALYSIS OF NEAR ULTRAVIOLET SOLAR RADIATION

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ABSTRACT

Measurements of direct-normal and global-horizontal ultraviolet (280-385 nm) and full-spectrum (280-4000 nm) solar radiation taken in Golden, Colorado over a one-year period are analyzed, and comparisons are made with data generated from a clear-sky solar radiation model (BRITE) currently in use for predicting the performance of solar detoxification processes. Analysis of the data indicates a ratio of global-horizontal ultraviolet to full-spectrum radiation of 4%-6% that is weakly dependent on air mass. Conversely, data for direct-normal ultraviolet radiation indicate a much larger dependence on air mass, with a ratio of approximately 5% at low air mass to 1% at higher air masses. Results show excellent agreement between the measured data and clear-sky predictions for both the ultraviolet and the full-spectrum global-horizontal radiation. For the direct-normal components, however, the tendency is for the clear-sky model to underpredict the measured data. Averaged monthly ultraviolet radiation available for the detoxification process indicates that the global-horizontal component of the radiation exceeds the direct-normal component throughout the year.

1.0 INTRODUCTION

The photocatalytic detoxification of organic contaminants is currently being investigated by a number of laboratories, universities, and institutions throughout the world. The photocatalytic oxidation process requires that contaminants come in contact with a photocatalyst, such as titanium dioxide, under illumination of ultraviolet (UV) radiation in order for the decomposition reaction to take place. Researchers from the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories are currently investigating the use of solar energy as a means of driving this photocatalytic process.

The UV component of the solar spectrum can be delivered to a receiver/photoreactor by means of either concentrating or nonconcentrating collectors. Concentrating solar collectors typically make use of only the direct-normal component of the incident solar radiation. Alternatively, flat-plate solar collectors can be used to gather both direct-normal and diffuse radiation. A large amount of data has been collected describing the seasonal variation of full-spectrum direct-normal and diffuse radiation and is readily available in the literature. UV resource data are available to a lesser degree but in general have been limited to global-horizontal measurements (Al-Aruri et al., 1988; Al-Aruri, 1990; Elhadidy et al., 1990). More recently, Riordan et al., 1990 reported measurements that include ratios of both global-horizontal and direct-normal UV to full-spectrum radiation.

For the past year, researchers at NREL have collected continuous data for both the global-horizontal and the direct-normal components of UV radiation (280-385 nm) at the Solar Radiation Resource Laboratory (SRRL) located near NREL's solar detoxification test facility. These data have been collected in addition to the full-spectrum (280-4000 nm) measurements regularly taken at the site.

This paper describes the effect of air mass and clouds on the direct-normal and global-horizontal UV radiation. The data are presented as absolute values and as percentages of full-spectrum radiation. In addition, a comparison is made with clear-sky predictions from the BRITE atmospheric radiation model (Bird and Hulstrom, 1982). Data generated from this model are currently in use for predicting the performance of the solar detoxification process. Averaged monthly data are presented and compared with predictions based on SOLMET/ERSATZ data for Denver, Colorado (NREL, 1981). A method for using the SOLMET/ERSATZ data for predicting global-horizontal and direct-normal UV radiation is discussed.

2.0 INSTRUMENTATION AND QUALITY CONTROL

2.1 Instrumentation

Measurements of terrestrial solar radiation have been taken at the SRRL (39°44' N, 105°10' W, 1828.8 m) for several years. These measurements include full-spectrum direct-normal, diffuse, and global-horizontal solar radiation as well as global-horizontal UV radiation. Full-spectrum direct-normal measurements are made using an Eppley normal-incidence pyrheliometer (NIP) with an acceptance angle of 5.7°. Full-spectrum and UV global-horizontal measurements are made using an Eppley precision spectral pyranometer (PSP) and Eppley ultraviolet radiometer (TUVR), respectively.

In addition to the instruments described above, a second Eppley TUVR was fitted with a collimating tube (see Figure 1) to allow only the direct-normal component of UV radiation to reach the detector. The collimating tube has an acceptance angle of 5.7°, identical to that of the Eppley NIP. The inside of the tube is black anodized and contains internal baffles to minimize internal reflections. A quartz window is used to seal the collimating tube from the environment, allowing normally incident UV radiation to reach the detector. Condensation within the assembly has been minimized by purging the tube with dry nitrogen before sealing. The entire assembly is located on an Eppley SUN-3 tracker that continuously tracks the sun.

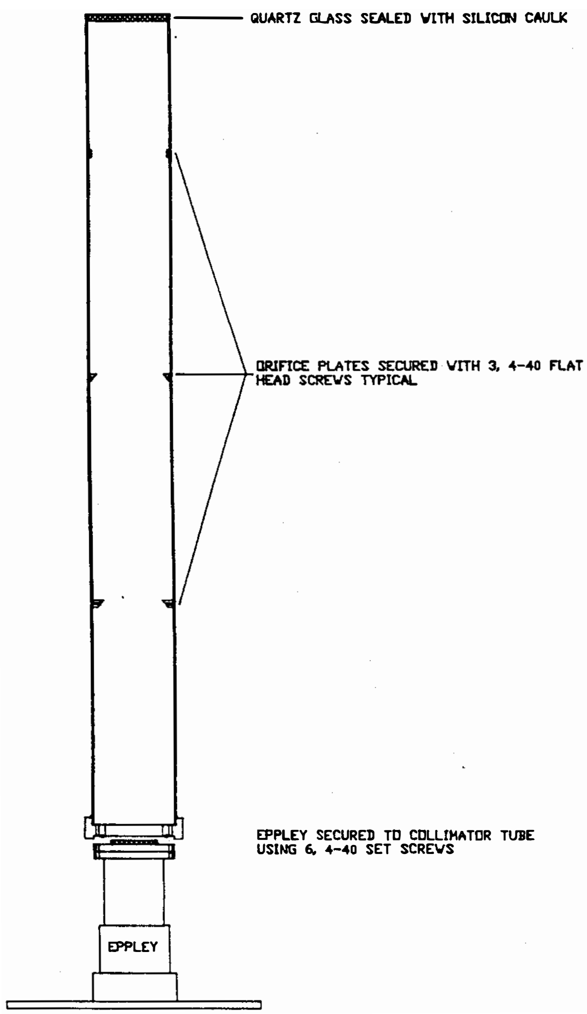

Figure 1. Eppley TUVR Fitted with Collimating Tube

All the solar measurements described in the following sections were taken at 10-sec intervals and averaged into 5-min data points. These measurements were continuously recorded and output to daily files that were accessed later for analysis. All the instruments at the SRRL site were inspected at regular intervals and examined for errors in tracking, dust or moisture over the windows, or other conditions that might have affected their readings.

2.2 Calibration of Instruments

The instruments listed above were calibrated outdoors at the SRRL. The calibrations were performed in the Metrology Laboratory of the Engineering Sciences Branch at NREL. The Eppley NIP and PSP were calibrated using the standard techniques described in the literature (Myers, 1988, 1989). With these techniques, the field measurement uncertainty of the NIP and that PSP were estimated as ±2.3% and ±3.6%, respectively.

Field measurements of direct-normal and global-horizontal UV solar radiation are less certain than those measurements for the full-spectrum counterparts. The TUVRs were calibrated outdoors using an Optronic Laboratories OL752 UV spectroradiometer and an ISA/DH10 spectroradiometer as a reference. Two sets of calibrations were performed over a one-year period. The variability in the results was 7% and a calculated uncertainty in the calibration factor was given as 8%. With the uncertainties associated with the instruments as well as the technique used for calibration, the field measurement uncertainty for both of the Eppley TUVRs was conservatively estimated at ±15%.

2.3 Quality Assurance

The UV solar radiation data were examined using parameters developed by Riordan et al. (1990). Details of the quality assurance procedures are described below.

Full-Spectrum Data. The full-spectrum data, including global-horizontal, direct-normal, and diffuse measurements, were quality checked using a subroutine developed by the NREL Resource and Environmental Assessment Branch.

We first confirmed that the measured value was present and within physical limits; i.e., the global-horizontal measurement was less than extraterrestrial on a horizontal surface. Two methods were used to evaluate the data. First, the routine performed a quality assessment of solar radiation data using specific information developed for Golden, Colorado. K_n and K_t were used to describe the effects of scattering and absorption on the total atmospheric transmittance, where

K_n = direct-normal irradiance at the surface of the Earth divided by the extraterrestrial direct-normal irradiance.

K_t = clearness index, total global-horizontal irradiance divided by extraterrestrial solar radiation on a horizontal surface.

Predetermined monthly bounding values for Kn versus Kt developed for Golden, Colorado, were used as limits for the measured data. If the data fell within a 15% error of the limits, they were accepted.

The second method for evaluating the data involved entering the data into the following equation:

$$GH = DN \times cox(Z) + Diffuse$$

where

GH = global horizontal
DN = direct normal
Z = incidence angle.

The data were accepted if the equation balanced within 15%.

UV Radiation Data. UV measurements presented by Riordan et al. (1990) indicated that global-horizontal UV radiation was, in general, less than 12% of global-horizontal full-spectrum radiation. If the ratio of UV global-horizontal to full-spectrum global-horizontal solar radiation exceeded 12%, the data were considered to be questionable, and therefore, flagged. Flagged data were entered into a separate file in which the suspect data points could be looked at individually before being discarded so that valid points would not be overlooked.

Although data from Riordan suggested that direct-normal UV radiation was less than 5% of the full-spectrum direct-normal radiation available, many of the measured data fell outside these limits. Most of the direct-normal UV measured values fell within a 10% ratio of the direct-normal full-spectrum data; therefore, this was used as the upper limit for the UV direct-normal data. Additionally, data were considered suspect when the ratio of UV to full-spectrum direct-normal radiation was equal to zero, indicating a possible tracking error.

Data that did not pass the limits described above were usually early morning or late evening measurements, within 20 minutes of sunrise or sunset. It is not unreasonable, however, to expect that these data were valid due to the high air mass associated with these time periods. All nighttime values were discarded, and an average of 7% of the daytime values were discarded as a result of the quality control analysis.

3.0 MEASUREMENTS OF SOLAR ULTRAVIOLET RADIATION

Figures 2 and 3 show the 5-min data for the global-horizontal and direct-normal UV measurements versus air mass as a function of the clearness index K_t, where K_t is defined above, and air mass is calculated using the formula (Kasten, 1966):

$$AM = \frac{1}{\cos\theta_z + 0.15 \times (93.885 - \theta_z)^{-1.253}} \times \frac{P}{P_o}$$

where

AM = air mass
Θ_Z = zenith angle
P = measured atmospheric pressure
P_o = pressure at 1 atm.

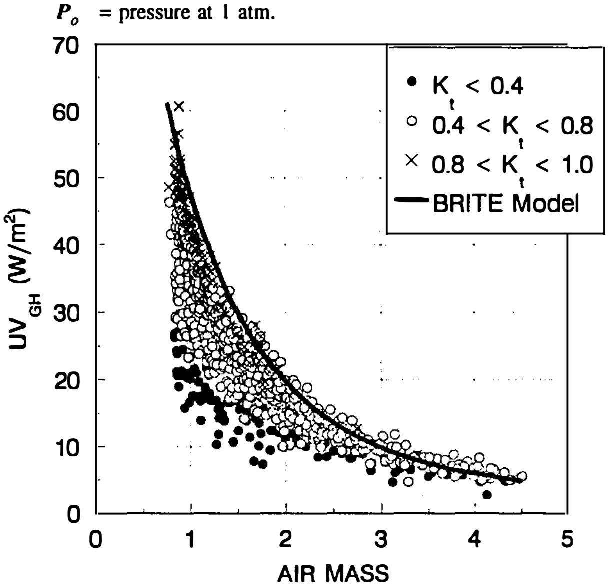

Figure 2. Global-Horizontal UV Radiation versus Air Mass Comparison to BRITE Model

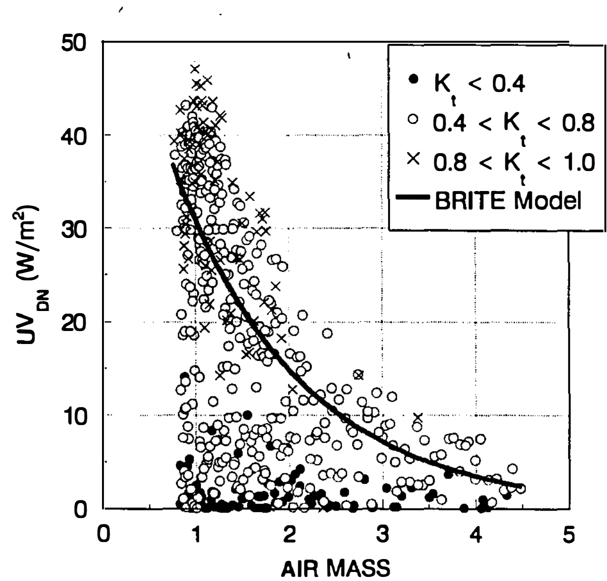

Figure 3. Direct-Normal UV Radiation versus Air Mass Comparison to BRITE Model

The solid line in both figures represents the BRITE model predictions for global-horizontal and direct-normal UV irradiance under clear-sky conditions.

The figures indicate that the global-horizontal UV radiation, which includes both the direct-beam and diffuse radiation, is less influenced by clouds or haze (denoted by smaller values of K_t) than the direct-normal radiation. This is understandable because the effect of clouds or haze is to scatter the direct-beam component of the UV radiation into the diffuse component. In addition to these results, the BRITE model predictions of the global-horizontal UV radiation under clear-sky conditions show excellent agreement with the measured data but underestimate the amount of direct-normal UV radiation.

Figures 4 and 5 show the ratio of 5-min values of UV to full-spectrum radiation for both global-horizontal and direct-normal measurements as a function of K_t and air mass. Figure 4 indicates that the ratio between the UV and the full-spectrum global-horizontal radiation is relatively independent of air mass, yielding a ratio of approximately 4%-6%. Conversely, Figure 5 indicates the ratio of UV to full-spectrum direct-normal radiation is highly dependent on air mass due to Rayleigh scattering from molecules in the atmosphere. In addition, the ratio of UV to full-spectrum radiation is less influenced by clouds for the global-horizontal measurements than for the direct-normal measurements due to the scattering of the direct-normal UV radiation into the diffuse component. An exponential fit of the direct-normal UV to full-spectrum radiation for all the data resulted in the following equation:

$$UV_{DN} = 0.71 \times e^{-0.573 \times AM} \times FS_{DN}$$

where

UV_{DN} = direct-normal UV radiation
AM = air mass
FS_{DN} = direct-normal full-spectrum radiation.

This equation is used in the following section for predicting monthly values of direct-normal UV radiation.

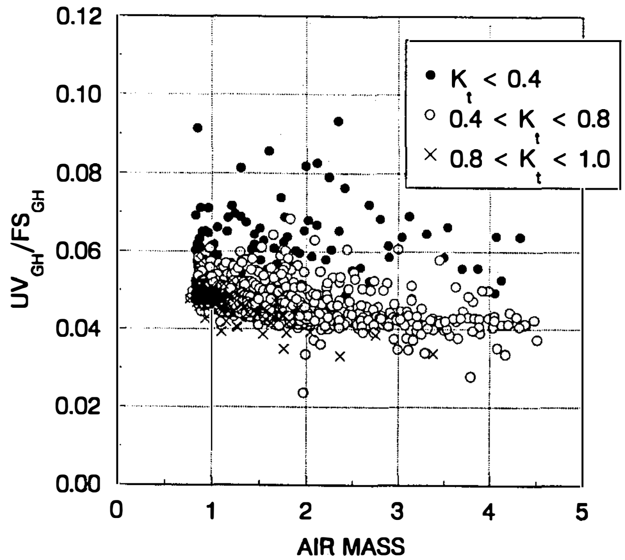

Figure 4. Ratio of Global-Horizontal UV to Full-Spectrum Solar Radiation versus Air Mass

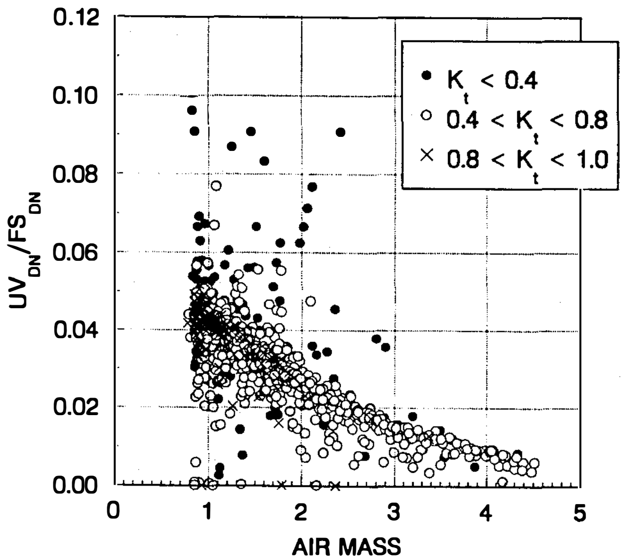

Figure 5. Ratio of Direct-Normal UV to Full-Spectrum Solar Radiation versus Air Mass

4.0 PREDICTIONS OF MONTHLY DIRECT-NORMAL AND GLOBAL-HORIZONTAL UV RADIATION

The 5-min data described above were integrated over each day using the trapezoidal method. These daily radiation values were averaged over each month to produce average monthly values for the period in which data were collected. In an effort to develop a method for predicting the UV resource at any location in the United States, these monthly values were compared to predictions made from the SOLMET/ERSATZ (NREL, 1981) databases using the UV to full-spectrum ratios described above. The monthly SOLMET insolation values were computed from a base of 24-25 years of data from 1952-1975 from 26 SOLMET meteorological stations.

The ERSATZ station in Denver, CO carries radiation values that were derived from corrected SOLMET measurements and relevant meteorological measurements at the station. Two hundred twenty-two ERSATZ stations exist throughout the United States. Monthly global-horizontal UV radiation was predicted using a 5% ratio, an approximate average for all data shown in Figure 4. Figure 6 shows predictions of monthly global-horizontal UV radiation based on a 5% ratio of the measured full-spectrum data and the SOLMET/ERSATZ database for Denver, Colorado. This method resulted in an excellent prediction of the global-horizontal UV radiation from the measured full-spectrum data. Predicting global-horizontal UV radiation as 5% of the SOLMET/ERSATZ total global-horizontal estimate was accurate in the winter months, but the measured global-horizontal UV was overestimated in the summer months. Comparison of the SOLMET/ERSATZ data with the measured global-horizontal full-spectrum data showed a similar pattern. The maximum 35% variation between the SOLMET and measured data is reasonable over any given year.

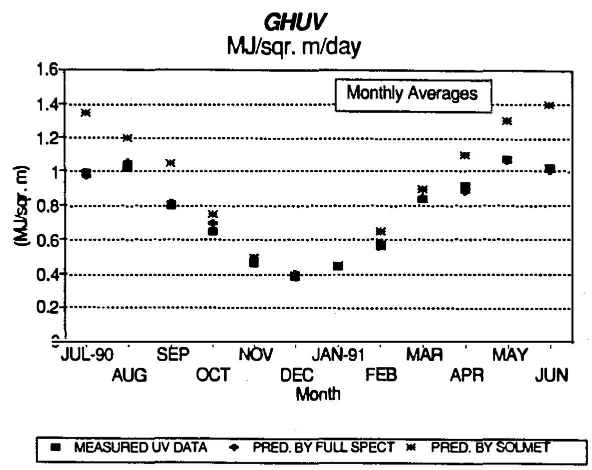

Figure 6. Monthly Averages of Measured and Predicted Global-Horizontal UV Radiation

The ratio of direct-normal UV to full-spectrum radiation was estimated from the total direct-normal radiation recorded using the function described in the previous section. The predictions based on this function only slightly underestimated the measured amount of direct-normal UV radiation. In order to predict direct-normal UV radiation from the SOLMET/ERSATZ database, 3.5% was used as an estimate of the ratio of UV to full-spectrum direct-normal radiation. These results are shown in Figure 7. This resulted in predictions of direct-normal UV radiation that were consistently high throughout the period.

5.0 SUMMARY AND CONCLUSIONS

The solar UV data collected at NREL over the past year should be the beginning of a data base that will help researchers determine the effect of cloud cover and air mass on global-horizontal and direct-normal UV radiation. Because of the limited information available on solar UV radiation, procedures were developed to determine the quality of the measured UV data. However, as researchers gather more information on the UV resource, these procedures should be refined to help ensure the quality of the data being collected.

Analysis of the data taken at Golden, Colorado, resulted in the following observations for the variation of the solar UV radiation with respect to K_t, air mass, and the time of year.

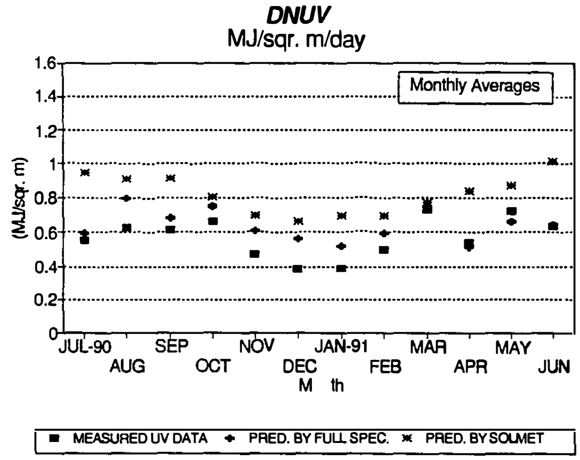

Figure 7. Monthly Averages of Measured and Predicted Direct-Normal UV Radiation

- The ratio of UV global-horizontal radiation (280-385 nm) to full-spectrum global-horizontal radiation (280-4000 nm) decreases only slightly with increasing air mass, yielding a ratio of 4%-6%. The effect of clouds (denoted by decreasing K_t) is to increase this ratio due to scattering of UV radiation.

- The ratio of UV direct normal to full-spectrum direct-normal radiation decreases rapidly with increasing air mass due to Rayleigh and aerosol scattering in the atmosphere. Clouds result in a slight increase in this ratio, but the absolute UV radiation levels are substantially decreased (i.e., there is no direct-beam solar radiation when clouds block the solar disk).

- Measured values of global-horizontal UV radiation under clear-sky conditions show excellent agreement with BRITE model predictions.

  For direct-normal UV radiation, the BRITE model tends to underestimate the measured data under clear-sky conditions.

- Monthly totals indicate that global-horizontal UV radiation is greater than direct-normal UV radiation throughout the year. With ratios derived from the measured data, these monthly totals can be predicted accurately from measured full-spectrum data.

- Predictions of global-horizontal UV radiation based on SOLMET/ERSATZ data for Denver, Colorado, show good agreement with the measured data for the winter months, but the measured data throughout the summer are overestimated. Predictions of direct-normal UV radiation based on the SOLMET/ERSATZ data for Denver overestimate the measured data over the entire year.

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