Influences of Atmospheric Conditions and Air Mass on the Ratio of Ultraviolet to Total Solar Radiation

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NOTICE

PREFACE

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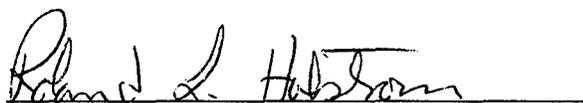
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Approved for

SOLAR ENERGY RESEARCH INSTITUTE
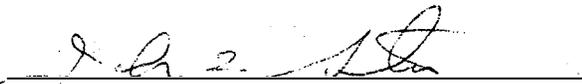
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INTRODUCTION

The technology to detoxify hazardous wastes using ultraviolet (UV)* solar radiation is being investigated by the DOE/SERI Solar Thermal Technology Program. One of the elements of the technology evaluation is the assessment and characterization of UV solar radiation resources available for detoxification processes. Initially, simple methods are needed to establish preliminary estimates of UV solar radiation resources in the United States to evaluate the viability of this technology (for example, process rates). This report summarizes work performed for the Solar Thermal Technology Program by the Solar Radiation Research and Metrology Branch under the UV modeling element of task number ST011253, to assist the program with efforts to make preliminary estimates of UV resources by simply using a percentage of the total incoming solar radiation. Actual UV solar radiation measurements, including the spectral information needed to evaluate processes that use catalysts operating at specific wavelengths, are being addressed under other task elements.

This report describes the major atmospheric variables that determine the amount of UV solar radiation at the earth's surface, and how the ratio of UV-to-total solar radiation varies with atmospheric conditions. These ratios are calculated from broadband and spectral solar radiation measurements acquired at SERI, and obtained from the literature on modeled and measured UV solar radiation. The following sections discuss the atmospheric effects on UV solar radiation and provide UV-to-total solar radiation ratios from published studies, as well as measured values from SERI's data. A summary and conclusions are also given.

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*UV solar radiation is defined for three regions of the spectrum:

    UVA 320 to 400 nanometers (nm)
    UVB 280 to 320 nm
    UVC < 280 nm

Total, or broadband, solar radiation refers to the region from 280 to 4000 nm. However, it is important to note in this report that UV and broadband measurements are obtained using instruments that have specific wavelength responses. The differences in the response regions these instruments, as well as measurement uncertainty, contribute to the variability in reported UV and broadband solar radiation data.

ATMOSPHERIC EFFECTS ON UV SOLAR RADIATION

This section gives a brief overview of major atmospheric variables that affect the amount and spectral distribution of UV solar radiation. It also defines variables that are used later in the report such as air mass and a cloudiness/clearness index called K_t.

The spectral (wavelength) distribution of solar radiation received at the top of the atmosphere is shown in Figure 1 [1]. When this radiation enters the atmosphere, it is absorbed and scattered by atmospheric constituents, such as air molecules, aerosols, water vapor, liquid water droplets, and clouds. Solar radiation that reaches the earth's surface directly from the sun's disk (not scattered or absorbed) is called direct-beam solar radiation, and that which has been scattered out of the direct-beam is called diffuse solar radiation (Figure 2). The sum of the direct radiation and diffuse radiation is called total or global solar radiation.

Air mass (Figure 2) refers to the relative path length of the direct solar beam through the atmosphere. It is approximately equal to the secant of the solar zenith angle for angles less than 60°; for example, air mass is 1.0 when the sun is directly overhead (zenith), 1.5 when the sun is at 48.2°, and 2.0 when the sun is at 60°. A simple expression for air mass is given by Kasten [2] for all solar zenith angles. As air mass increases, the direct beam traverses longer path lengths in the atmosphere, which results in more scattering and absorption of the direct beam and a lower
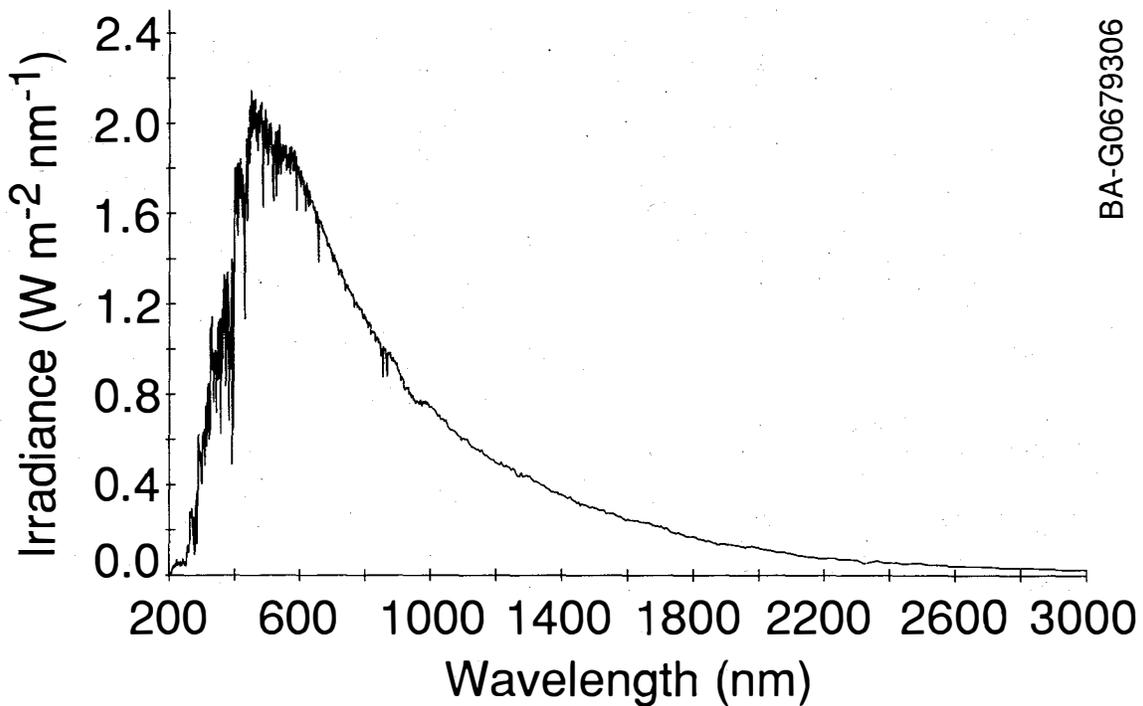
Figure 1. Extraterrestrial spectral solar radiation plotted from 0.2 to 3.0 μm [1]
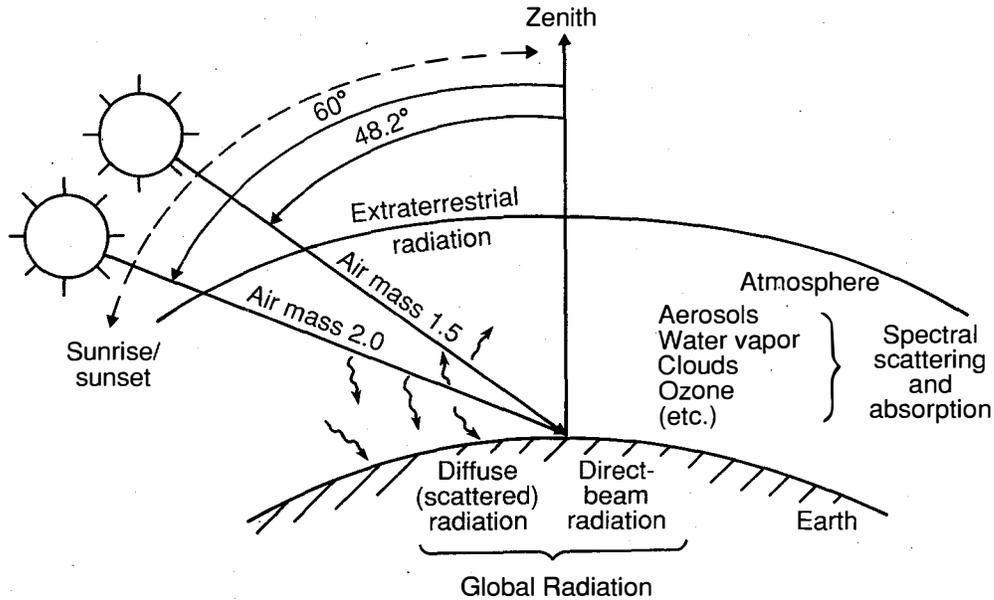
Figure 2. Air mass and solar components

percentage of direct-to-total solar radiation (for the same atmospheric conditions). There is also proportionally more scattering in the shorter wavelengths (UV and visible) compared to longer wavelengths because of the strong wavelength dependence of molecular and aerosol scattering. As will be shown later, this results in a more rapid decrease in the UV and visible wavelengths of the direct beam with increasing air mass values, and a shift in the spectrum toward longer wavelengths.

Solar radiation incident on a collector surface is equal to the direct beam multiplied by the cosine of the incidence angle, plus diffuse solar radiation from the sky and ground-reflected radiation in the collector's field of view. A simple equation is:

$$I_g = I_{dn} \times \cos \text{(incidence angle)} + I_d \text{(sky)} + I_{gr} \text{(ground)}$$

where

I_g = total (global) solar radiation on a flat surface

I_{dn} = direct-beam solar radiation, normal to the sun (direct normal)

I_d = diffuse solar radiation

I_{gr} = ground-reflected radiation

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If the collector is sun-tracking, the direct beam incidence angle is zero and if the collector is horizontal, the incidence angle is equal to the solar zenith angle. For other orientations of the collector, the incidence angle is a function of the azimuth and tilt of the collector and the azimuth and elevation of the sun. Concentrating or focusing collectors use the direct-beam component plus forward-scattered radiation around the sun's disk, called circumsolar radiation. The solar component used by each type of collector is important because the amount and spectral distributions of direct and diffuse solar radiation are different.

A general expression for transmittance (T) of direct-beam solar radiation under cloudless skies at a specific wavelength (λ) is [3]:

$$T_\lambda = T_{r\lambda} \times T_{a\lambda} \times T_{o\lambda} \times T_{g\lambda} \times T_{w\lambda}$$

where

$T_{r\lambda}$ = the spectral transmittance due to molecular (Rayleigh) scattering

$T_{a\lambda}$ = the spectral transmittance due to scattering and absorption by aerosols

$T_{o\lambda}$ = the spectral transmittance due to absorption by the atmospheric ozone layer

$T_{g\lambda}$ = the spectral transmittance due to absorption by uniformly mixed gases, such as carbon dioxide and oxygen

$T_{w\lambda}$ = the spectral transmittance due to absorption by water vapor

The major cloudless-sky attenuation processes in the UV region of the spectrum are molecular (Rayleigh) scattering, aerosol scattering and absorption, and ozone absorption. Various expressions have been derived to calculate transmittance due to these processes. Examples [3] are:

Rayleigh scattering

$$T_{r\lambda} = \text{Exp} \left[-0.008735 \, (\lambda^{-4.08}) \, M' \right]$$

where

M′ = air mass values that have been pressure corrected to account for the decreased density of air molecules at different elevations

Aerosol scattering and absorption

$$T_{\alpha\lambda} = \text{Exp} \, (-\beta \lambda^{-\alpha} \, M)$$

where

β = the turbidity coefficient
α = the wavelength exponent
M = air mass

Ozone absorption

$$T_{o\lambda} = Exp\ (-k_{o\lambda}\ 1\ M)$$

where

$k_{o\lambda}$ = the spectral absorption coefficient $\ddot{Y}$
1 = ozone amount

An example of the relative transmittance for these three processes (and others) is shown in Figure 3. Ozone absorption can be considered relatively constant in the UV region because it
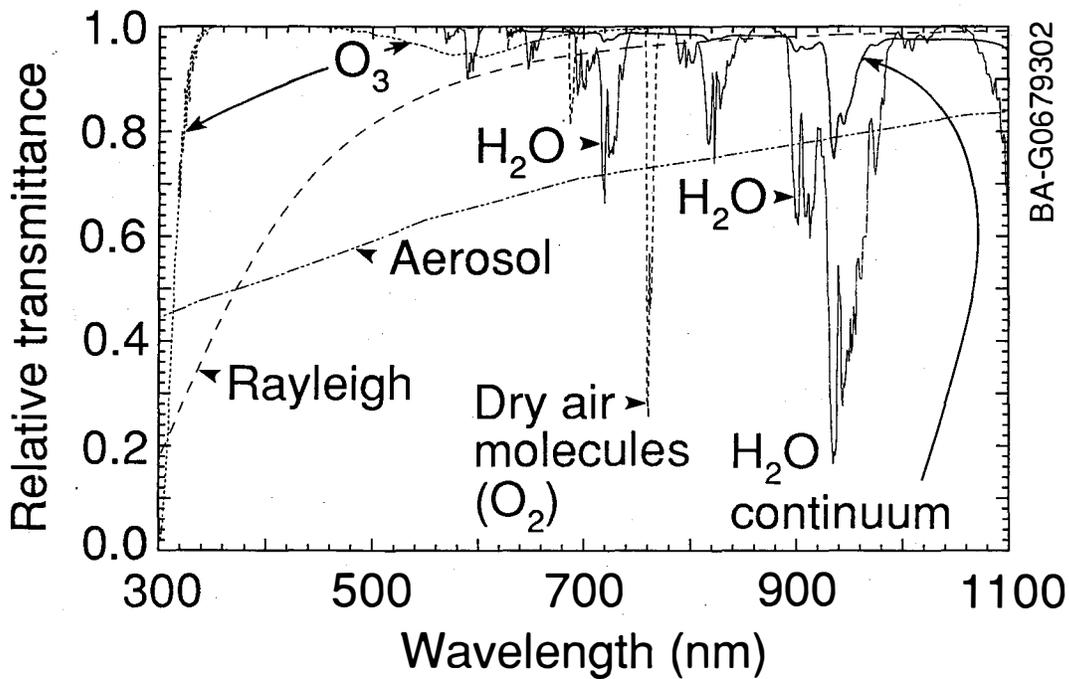
Figure 3. **Relative transmittance for different atmospheric constituents, calculated with the Air Force Geophysics Laboratory LOWTRAN-7 Direct-Normal Atmospheric Transmittance Code (midlatitude summer atmospheric model, rural aerosol profile, 40° zenith angle)**

is a strong absorber in the Hartley (200 to 300 nm) and Huggins (300 to 360 nm) bands. Rayleigh scattering can be considered constant for a given altitude; it is a strong function of wavelength (inverse fourth power) and M'. Rayleigh scattering decreases with increasing elevation because of fewer air molecules, which is accounted for in Rayleigh scattering calculations by the pressure correction to relative air mass. Aerosol attenuation varies with the amount and type (size, composition) of aerosols; it generally increases with decreasing wavelength in the UV region.

Water vapor absorption (which is related to relative humidity and temperature) occurs outside of the UV region, so it affects the total broadband (280 to 4000 nm) solar radiation values and therefore causes variability in the UV-to-broadband ratios. Relative humidity affects aerosol attenuation because hygroscopic particles take up water, grow larger, and increase the scattering by aerosol particles (e.g., haziness in high-humidity regions).

There are other gas absorption regions outside the UV region (e.g., oxygen absorption at 762 nm), but their effects on solar radiation variations are small compared to effects of Rayleigh, aerosol, ozone, and water vapor.

The dominating attenuator of solar radiation is clouds. Under overcast skies there is no direct-beam radiation, and under partly cloudy skies there is intermittent direct-beam solar radiation when clouds are not obscuring the sun's disk. Diffuse solar radiation is about 10% to 20% of the total amount of solar radiation under clear skies and 100% under overcast skies.

Clouds are often assumed to have a wavelength-independent attenuation function in the UV and visible region of the spectrum; but, in the near-infrared region they cause increased absorption due to water vapor and liquid water. There is some evidence that transmission is relatively higher in the UV and blue regions of the spectrum compared to a wavelength-independent function [4,5]. Increased ratios of UV-to-total solar radiation with increased cloud cover can be due to both decreased solar radiation in regions of the spectrum outside of the UV (caused by water vapor and liquid water absorption) and to relatively higher UV transmittance compared to wavelength-independent transmittance.

An index called K_t is used in this report to describe total atmospheric transmittance due to all absorption and scattering processes

where

K_t = total global (direct + diffuse) solar radiation on a horizontal surface divided by extraterrestrial solar radiation on a horizontal surface.

This is called a cloudiness or clearness index because it decreases with increasing atmospheric attenuation of solar radiation, which is mostly determined by cloudiness.

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RATIOS OF UV-TO-TOTAL SOLAR RADIATION

This section gives UV-to-total solar radiation ratios (converted to percent UV) reported in the literature, as well as measured values from SERI data. The relationships of these UV percentages to atmospheric conditions and air mass are also shown. Instrument descriptions and spectral response regions are described as they are reported in the various studies.

Elhadidy, et al. [6] analyzed measurements of UV solar radiation from January 1985 to December 1987 at Dhahran, Saudi Arabia (26° 32′ N, 50° 13′ E). Total global solar radiation on a horizontal surface was measured with an Eppley Precision Spectral Pyranometer (PSP) and UV solar radiation on a horizontal surface was measured with an Eppley UV radiometer (photometer) having a response region from 295 to 385 nm. The percentage of UV for monthly mean total radiation on a horizontal surface is given in Table 1.

Table 1.   **UV Percentage of Monthly Mean Total Global Solar Radiation on a Horizontal Surface at Dhahran, Saudi Arabia [6] .**

MONTH	1985	1986	1987
January	3.50	3.39	3.39
February	3.34	3.50	3.57
March	3.42	3.55	3.48
April	3.50	3.65	3.45
May	3.47	3.49	3.39
June	3.39	3.47	3.22
July	3.29	3.35	3.31
August	3.45	3.43	3.40
September	3.44	3.43	3.33
October	3.46	3.42	3.42
November	3.54	3.46	3.41
December	3.53	3.39	3.45
Mean	3.44	3.46	3.40
Overall Mean		3.44	

Results reported in this study were:

- For days with a clearness index (K_t) of more than 0.65, the UV percentage of total solar radiation on a horizontal surface was approximately constant with about 95% of the values in the range of 3.3 to 3.8. The UV percentage was a very weak function of K_t for days with K_t greater than 0.65.

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- For days with K_t less than 0.65, the UV percentage of total horizontal radiation depends on K_t and on atmospheric conditions (for example, rain, clouds, and dust). The UV percentages were typically high for low K_t (<0.50) but show more scatter than observed in the K_t range of 0.50 to 0.65. Examination of meteorological data revealed that the high UV percentages on days with K_t less than 0.50 occurred on rainy or cloudy days while the low UV percentages occurred on dusty days.

- Comparison of clear- and cloudy-day data revealed higher UV percentages of total solar radiation on the cloudy days.

- The UV percentage of monthly-average-total solar radiation on a horizontal surface was nearly constant for the 3-year period (Table 1).

Al-Aruri, et al. [7] report results of UV measurements at the Kuwait Institute for Scientific Research (29° 20′ N, 47° 57′ E) from July 1985 to June 1987. Total global solar radiation on a horizontal surface was measured with a PSP, and UV solar radiation on a horizontal surface was measured with an Eppley UV radiometer (photometer) model TUVR with a response region from 295 to 385 nm. Ratios of the monthly-mean-UV-to-monthly-mean-total solar radiation on a horizontal surface (in %) are given in Table 2.

Table 2. **UV Percentage of Monthly Mean Total Global Solar Radiation on a Horizontal Surface at the Kuwait Institute for Scientific Research [7]**

MONTH	1985	1986	1987
January		4.3	4.3
February		4.4	4.4
March		4.7	4.3
April		5.0	4.4
May		4.5	4.5
June		4.4	4.2
July	4.6	4.6	
August	5.2	4.6	
September	5.1	4.6	
October	5.0	4.6	
November	5.1	4.9	
December	4.7	4.3	

Results reported in this study were:

- On average, 4.62% of the monthly-daily total solar radiation received on a horizontal surface is UV.

- The daily total UV is approximately 44% lower on dusty days.

Al-Aruri developed an empirical relationship between UV and total global horizontal solar radiation using a least-square linear regression of the monthly average daily measurements for the 3 years [8]. The relationship he derived between monthly average daily total global (X) and UV solar radiation (Y) is

$$Y = 0.048\,X - 0.014$$

with a ±3% standard error of the estimate and a coefficient of determination of 93%. Similar regression analysis has been performed by Webb and Steven [9], Rao, et al. [10], and Stewart [11].

Rao, et al. [10] report UV and total global solar radiation measurements on a horizontal surface taken at Corvallis, Ore. (44° 34′ N, 123° 14′ W, at 65.5 m) for 3 years (1980 to 1982). An Eppley UV radiometer (photometer) Model TUVR (response region 295 to 385 nm) was used to measure the UV radiation, and an Eppley PSP to measure the total. Mean daily values of the UV-to-total horizontal radiation ratios (in %) are given in Table 3.

Table 3.   Mean Daily UV Percentage of Total Global Solar Radiation on a Horizontal Surface at Corvallis, Ore. [8]

Season	Mean
Winter	5.7
Spring	5.3
Summer	5.0
Fall	5.6
All	5.4

For fractional sunshine values less than 15% (cloud amount > 6 oktas), the percentage of UV was 6.3%; between fractional sunshine values of 15% and 85% the percentage of UV was 5.1%, and for fractional sunshine values greater than 85% (cloud amount < 2 oktas) the percentage of UV was 4.6%. The results of other measurements referenced by Rao, et al. are given in Table 4.

Modeling results from Rao, et al. indicated that the UV solar radiation was relatively more sensitive to changes in atmospheric turbidity and surface albedo than to changes in the total amount of ozone in the atmosphere. The transition of the model atmosphere from "molecular" to "clear" resulted in decreases of up to 5% in UV solar radiation as the solar zenith angle varied from 6.3° to 77.6°; decreases were larger (5% to 15%) when the transition was from a "molecular" to "hazy" atmosphere over the same range of zenith angles. Changing the surface albedo from 0% to 25% resulted in UV enhancements of 8% to 10%. In comparison, decreases of 2% to 4% in UV solar radiation were found for increases in ozone amount from 0.280 atm cm to 0.380 atm cm.

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Table 4. UV Percentage of Total Global Solar Radiation on a Horizontal Surface (Computed Three Different Ways) Cited in Reference Number 10

Reference	Measurement/Location	UV/Total Horizontal
Kvifte, et al. [12]	*Monthly mean* ratios at various subarctic locations (latitude range 55° N to 75° N) in the Nordic countries	4.4%-5.6%
Schulze and Grafe [13]	*Monthly mean* daily UV (315-400 nm) at Hamburg (53° 33′ N, 9° 59′ E)	5%-6%
Baker-Blocker, et al. [14]	*Hourly average* value of the UV component *under clear skies* during the austral summer of 1979-1980 at the Amundsen-Scott station, Antarctica	4%-5%

Measurements of UV and total global solar radiation, as well as other solar radiation and meteorological data, have been acquired at SERI's Solar Radiation Research Laboratory (SRRL), Golden, Colo. (39° 44′ N, 105° 10′ W, 1828.8 m) for several years [15]. The data acquisition system records 5-min averages of 10-s scans of all channels. Total solar radiation measurements on a horizontal surface are made with an Eppley PSP, and UV measurements on a horizontal surface are made with an Eppley UV radiometer (photometer) model TUVR with a response region of 295 to 385 nm. The measurement uncertainty for the PSP is less than ±5%, and the estimated measurement uncertainty for the TUVR is ±15%; thus, the uncertainty in the ratio of these two measurements is on the order of ±20%. Figure 4 shows the ratio of 5-min UV-to-total horizontal measurements (in %) versus K_t for 1989 at SRRL. These data show an average UV percentage of about 4.5% to 5% for clear skies ($K_t > 0.60$), with a general increase in the percentage of UV (with much scatter) with decreasing K_t as observed by others referenced here.

Direct-normal spectral UV solar radiation measurements have been made at SERI to obtain wavelength-specific information needed for the Solar Thermal Technology Program's evaluation of processes that use concentrated direct-normal solar radiation and catalysts operating a specific wavelengths to detoxify hazardous wastes. Several of these spectral measurements are shown in Figure 5 together with the estimated spectral measurement uncertainty (bottom of the figure). Rather than a total UV measurement on a horizontal surface, the measured spectra in Figure 5 are for a 5.7° field of view looking directly at the sun's disk (direct-normal). The spectra were acquired with an ISA/DH10 spectroradiometer (Table 5). The broadband direct-normal data were acquired with an Eppley normal-incidence pyrheliometer (NIP), also with a 5.7° field of view, with a measurement uncertainty of less than ±2%.
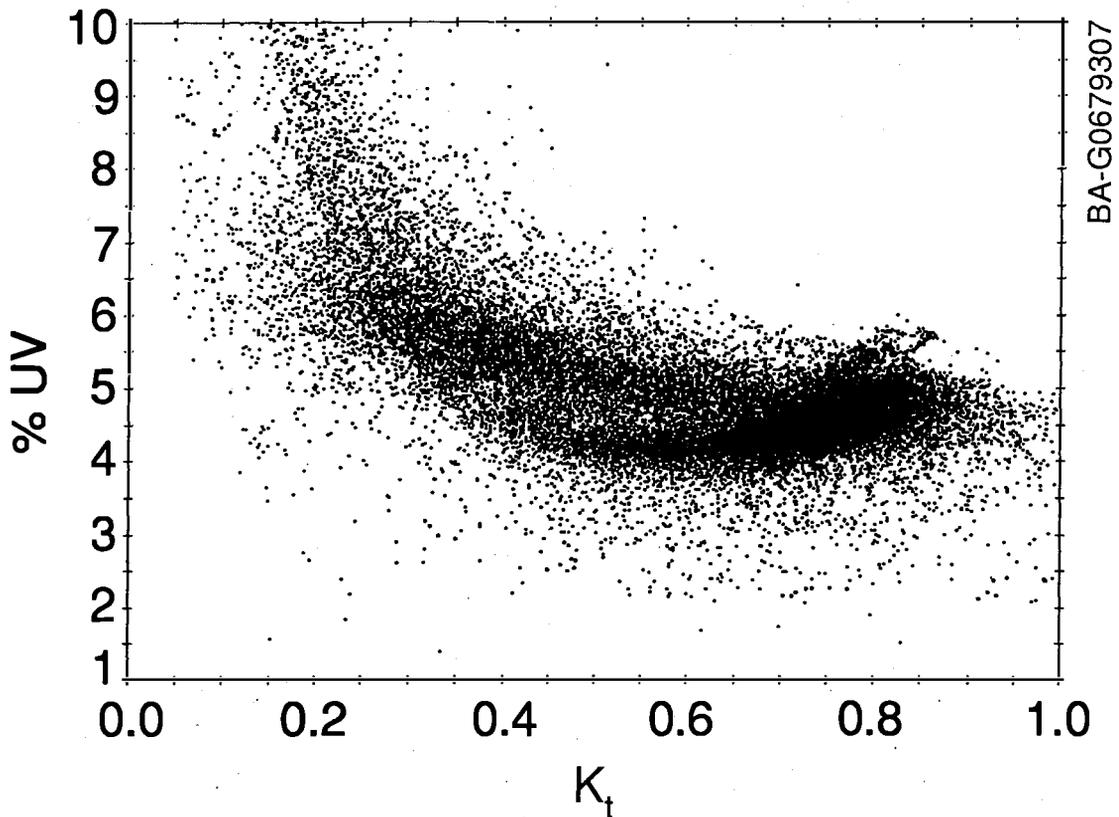
Figure 4. Ratio of 5-minute values of UV global horizontal to total global horizontal solar radiation versus K_t (measured at the SERI Solar Radiation Research Laboratory, January through December 1989)

The results of integrating the direct-normal spectra from 280 to 385 nm and from 280 to 400 nm, and dividing by the broadband direct-normal (NIP) measurement are shown in Table 6. Because the measurement uncertainty in the spectra beyond about 310 nm is on the order of 10% to 20%, the uncertainty in the ratios of integrated spectra to NIP values is on the order of 10% to 20%.

The direct-normal UV measurements decrease rapidly with increasing air mass because of increased Rayleigh and aerosol scattering with longer path lengths through the atmosphere. The shorter (UV) wavelengths are scattered more than the longer wavelengths as shown by the wavelength-dependent Rayleigh and aerosol transmission functions given in Section 2. Total-horizontal (direct + diffuse) UV solar radiation is reduced to a lesser extent because some of the radiation that is scattered out of the direct beam is scattered toward the earth's surface and received as diffuse irradiance by a flat surface.

BA-G0679301

Preliminary UV 280-400 n Solar Spectra
Solar Radiation Research & Mtrology Branch, SERI

SRR Branch 21S
SERI / Golden Co
Lat 39.74 Lon 10S.18

DAY TIM		AM
92	1206	1.22
90	0940	1.SO
90	0902	1.70
90	0840	1.91
OS	132S	2.36
OS	13SO	2.S9
OS	1412	2.81
OS	143S	3.12
OS	1SOS	3.84
OS	1S22	4.SO

Watt/Sqm/nm
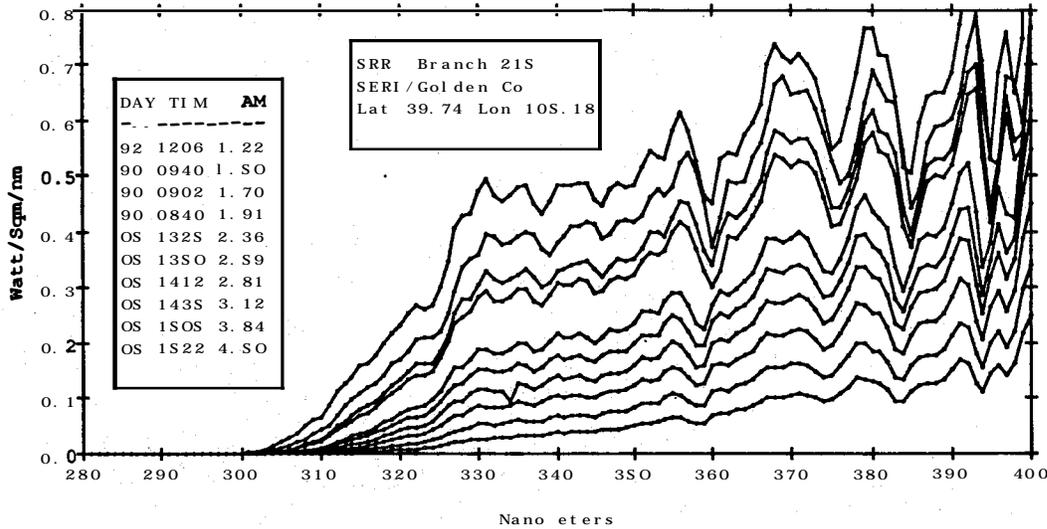
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			Integrated Spectru (Watts/sq mtr)		Broadband Instru ents (Watts/sq mtr)		
DAY	HR	Air M ss	ISA/DH1O		TUVR(+/-1S%)	NI P (+/-2%)	
			280-38S	280-400	[GH]	[DN]	29S-3000 nm
92	12:06	1.22	36.9	47.4	43.4	----	1007.1
90	09:40	1.SO	31.6	40.S	3S.1	----	983.S
90	09:02	1.70	27.0	3S.3	30.2	----	980.2
90	08:40	1.91	24.7	32.6	26.2	----	9S7.7
OS	13:2S	2.36	18.0	24.2	19.6	18.0	9S9.S
OS	13:SO	2.S9	1S.3	20.8	17.7	1S.9	938.S
OS	14:12	2.81	12.S	17.4	1S.4	13.8	898.8
OS	14:3S	3.12	9.7	13.7	13.0	10.7	849.0
OS	1S:OS	3.84	6.7	9.8	9.8	7.S	780.4
OS	1S:22	4.SO	4.3	6.4	8.2	4.9	723.3

STATED M ASUREM NT U CERTAI NTY I NCLUDES ALLOWA CES FOR THE A PA ENT
1.0 TO 1.S NM SHI FT BET EEN M ASURE NT SETS @ 3SO-400 NM

ESTIM TED ISA/DH1O Uncertainty

PERCENT OF READING UNCERTAINTY

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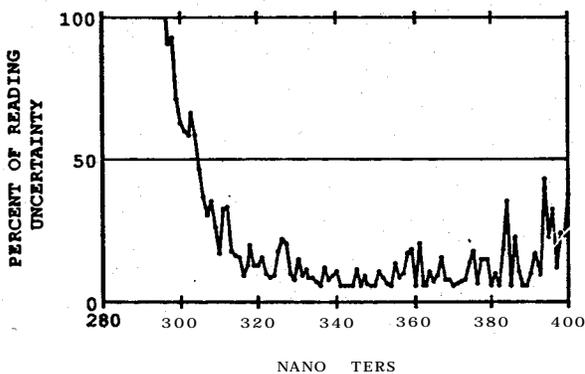
SR 1 n Wave Bias-(CA & Meas.)
SR O.S n Wave Ran -(CAL & Meas.)
CAL Sources: Ar ARC, FEL (NIST)
CAL Current Monitor (DM s)
CAL Current Shunt
CA Distance
CAL Air Pressure
CAL Power Supply
CAL Argon Purity
CA Argon Flow Rate
CAL Arc Align ent
SR PM Voltage (Ti e, Te p.)
SR Integ. Ti e Linearity (Tem.)
SR Stray Light
SR A/D conversion

Figure 5. **Instantaneous direct-normal UV spectral solar radiation measurements and supporting data acquired at SERI in January and April 1990 (upper graph); spectral measurement uncertainty (lower graph) where CAL indicates calibration error sources and SR indicates spectroradiometer error sources**

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Table 5. Some Characteristics of the ISA/DH10 Spectroradiometer

Spectral range	200 to 800 nm
Passband	2 nm
Linear dispersion	4 nm per nm
Wavelength accuracy	±1 nm
Calibration	a) National Institute of Standards and Technology (NIST) Argon Arc from 250 to 330 nm
	b) NIST 1000-watt type FEL incandescent lamp from 330 to 500 nm

Table 6. UV Percentage of Total Direct Normal Solar Radiation for Instantaneous Measurements at Golden, Colo.

Air Mass	Pressure Corrected Air Mass	280-385 nm ---------- NIP	280-400 nm ---------- NIP
1.22	1.01	3.7%	4.7%
1.50	1.24	3.2%	4.1%
1.70	1.41	2.8%	3.6%
1.91	1.58	2.6%	3.4%
2.36	1.96	1.9%	2.5%
2.59	2.15	1.6%	2.2%
2.81	2.33	1.4%	1.9%
3.12	2.59	1.1%	1.6%
3.84	3.18	0.9%	1.3%
4.50	3.73	0.6%	0.9%

Other spectral measurements are available from SERI's spectral solar radiation data base produced under the DOE/SERI Resource Assessment Program [16-18]. This data base contains about 3000 measured spectra covering the spectral region from 300 to 1100 nm at 2-nm steps. Broadband solar radiation and meteorological data were recorded at the same time as the spectra. Measurements were acquired at the Florida Solar Energy Center, Cape Canaveral, Fla.; the Pacific Gas and Electric Co., San Ramon, Calif.; and by SERI in Denver and Golden, Colo. Several different measurement modes were used to acquire the spectra, including direct normal and global on a horizontal surface. The spectroradiometer used to acquire these data was not designed specifically for UV measurements, and the measurement uncertainty of the data in the region from 300 to 400 nm is high (> ±20%); however, these data can be used to examine the variability in the UV-to-total ratios with respect to air mass and K_t.

Figure 6 shows the total (direct + diffuse) integrated global-horizontal spectral solar radiation from 300 to 400 nm divided by total global-horizontal solar radiation measured with an Eppley PSP (in %) as a function of K_t. These data show an increasing UV percentage for cloudy skies as indicated by others referenced here. The mean UV percentage for clear skies ($K_t > 0.60$) is 6.1%, the mean percentage for cloudy skies ($K_t < 0.40$) is 8.6%, and the overall mean is 6.3%. The Denver site, which is at a higher elevation (about 1555 m) and is drier than the California and Florida sites, shows a lower percentage of UV (about 5% versus 6.3%), although the differences could be due to measurement uncertainty.

Figure 7 shows the integrated direct-normal spectral solar radiation from 300 to 400 nm measured by the LI-COR spectroradiometer divided by the total direct-normal solar radiation measured with a NIP (in %), as a function of air mass (air mass is pressure-corrected for the Denver measurements included in the data set). Also shown are the UV percentages of total direct normal solar radiation measured by the ISA spectroradiometer (from Table 6). Quadratic fits to
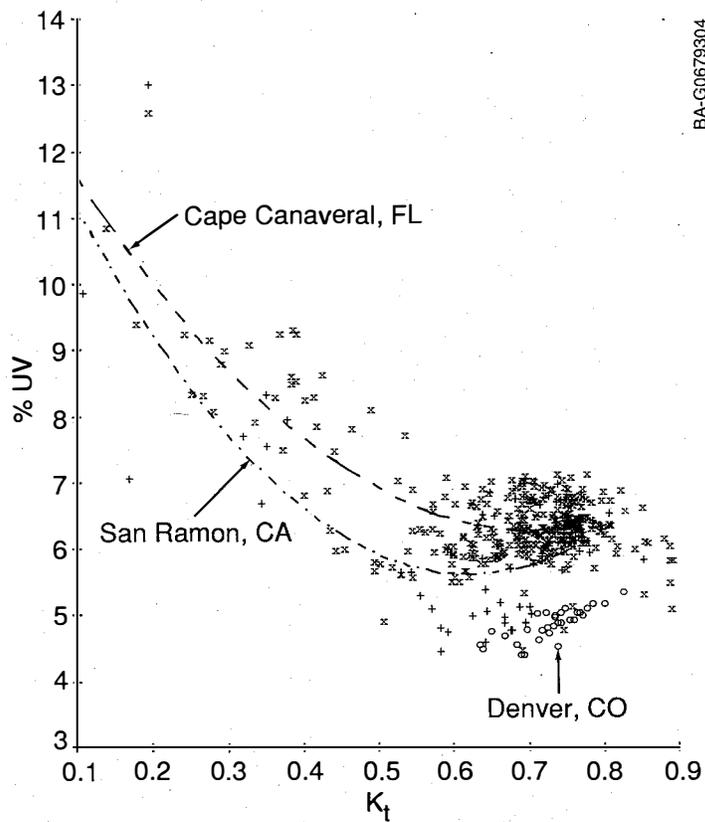
Figure 6. Ratio of integrated UV (300-400 nm) global horizontal solar radiation (measured with a LI-COR model LI-1800 spectroradiometer at 2-nm steps) to total global horizontal solar radiation measured with a PSP versus K_t

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these data show the relative percentage of UV solar radiation in three slightly different UV wavelength regions. These data show the air mass dependence of direct-normal UV solar radiation with mean values of about 4% at low air mass values to about 0.5% to 1% at high air mass values. The scatter in the UV percentages calculated from the LI-COR data is due to measurement uncertainty and differences in atmospheric conditions (aerosols, water vapor, etc.) at the time of these instantaneous measurements.
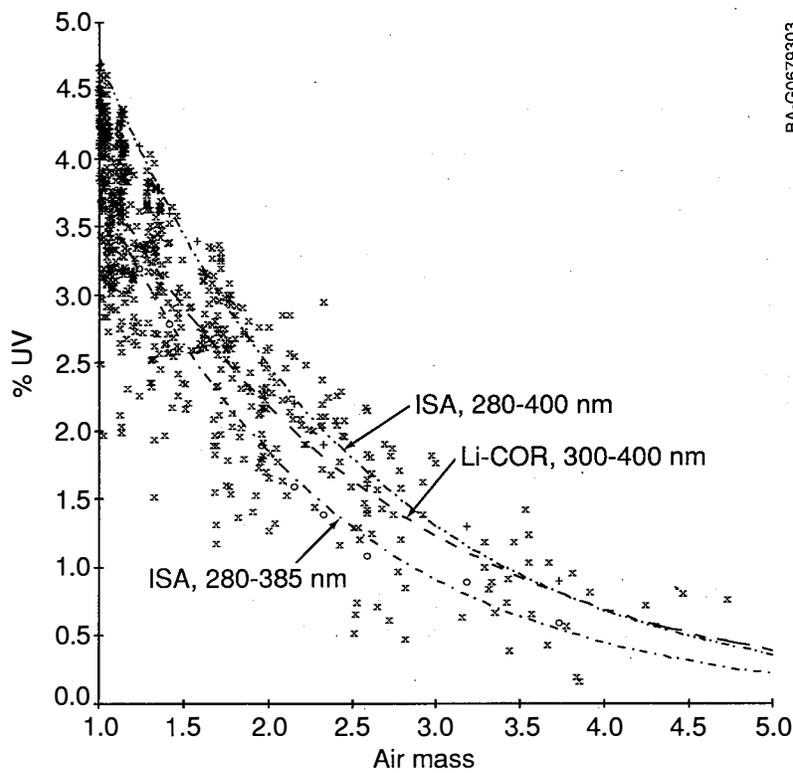
Figure 7. Ratio of integrated UV (300-400 nm) direct-normal solar radiation to total direct-normal solar radiation measured with an NIP. The top and bottom curves are quadratic curve fits to the ratios based on data measured with the ISA UV spectroradiometer integrated between 280 and 400 nm (top) and between 280 and 385 nm (bottom). The middle curve is a quadratic curve fit to data measured with a LI-COR model LI-1800 spectroradiometer and integrated between 300 and 400 nm.

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SUMMARY AND CONCLUSIONS

The major atmospheric variables that determine the UV percentage of total solar radiation are molecular (Rayleigh) scattering, aerosol absorption and scattering, ozone absorption, water vapor absorption, and scattering and absorption by clouds. A general index of atmospheric transmittance due to all of these processes is K_t, which is mostly determined by cloudiness. However, the spectral selectivity of the different atmospheric attenuators causes the ratio of UV-to-total solar radiation at a specific K_t to vary. In addition, ratios of UV-to-total direct normal solar radiation are a strong function of air mass because of the strong wavelength and air mass dependence of Rayleigh scattering. Also, there is no direct-beam solar radiation when clouds obscure the sun's disk.

UV measurements reported in the literature and acquired by SERI show the following relationships to K_t and air mass.

- The UV percentage of total global (direct + diffuse) solar radiation on a horizontal surface generally increases with decreasing K_t (i.e., lower atmospheric transmittance mostly due to clouds, but also to aerosols or dust); but, the amount of scatter in the ratio increases with lower K_ts.

- Mean monthly values for the UV percentage of total global horizontal solar radiation generally range from about 3.5% to 8% for the sites reported here. The UV percentages for Dhahran, Saudi Arabia, are noticeably lower than percentages reported for the other sites but the differences could be within the measurement uncertainty. Mean values for the percentage of UV for cloudy skies are about 2 percentage points higher than mean clear-sky percentages [for example, 4.6% (clear) versus 6.3% (cloudy) or 6.1% (clear) versus 8.6% (cloudy)]. As expected, the scatter in the values increases for instantaneous versus monthly mean values.

- The mean value of the UV percentage of total direct normal solar radiation decreases with air mass. SERI measurements show mean percentages of about 4% to 5% for air masses near 1.0, decreasing to about 0.5% for air masses near 4 for cloudless sky conditions. Under overcast skies there is no direct beam, and under partly cloudy skies there is intermittent direct-beam when the clouds are not obscuring the sun's disk.

Preliminary estimates of average monthly global UV solar radiation on a horizontal surface for various locations could be based on total global solar radiation and the mean ratios of UV-to-global solar radiation as a function of K_t. Estimates of direct-normal solar radiation for various locations could be based on total direct-normal solar radiation and the mean ratio of UV-to-direct normal solar radiation as a function of air mass, where air mass is a function of the latitude, time of day, and day of the year. The shortcomings of these methods are that the mean ratios have been shown to vary with location due to measurement uncertainty and different atmospheric conditions (for example, water vapor absorption outside of the UV region affects the ratio of UV-to-total ratio; and, water vapor varies by site, time of day, and season), and there is no spectral detail. If the absolute amounts and spectral distributions of UV solar radiation are critical to analyze processes that depend on UV solar radiation (atmospheric chemistry, biological processes,

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or solar detoxification of hazardous wastes), more accurate and precise measurements and measurement uncertainty analysis are required.

In the specific case of UV solar radiation resource assessment in the United States for the Solar Thermal Technology Program's solar detoxification of hazardous wastes, the following actions are recommended to obtain a preliminary estimate of UV solar radiation resources.

- Total global horizontal UV solar radiation resource assessment (flat, horizontal surface processes).

   Obtain SOLMET (SOLar METeorological) data from the U.S. National Climatic Data Center for selected sites in the United States, extract hourly global-horizontal solar radiation values, calculate K_t, and multiply the global-horizontal values by an average percentage of UV as a function of K_t. Both conservative and optimistic estimates can be made. Based on the data reported here, a conservative estimate might be based on UV percentages of 4% (clear) to 6% (cloudy), and an optimistic estimate might be based on UV percentages of 6% (clear) to 8% (cloudy).

- Direct-normal UV solar radiation resource assessment (concentrator collector processes).

   Obtain SOLMET data for selected sites in the United States, extract hourly global-horizontal solar radiation values, calculate direct-normal solar radiation from the global-horizontal values using the DISC model [19] (an improved model for deriving direct-normal from global-horizontal solar radiation), calculate hourly air mass values, and multiply the modeled direct-normal values by an average percentage of UV as a function of air mass derived from Figure 7. Conservative and optimistic estimates of UV resources can be made using high and low percentages from Figure 7.

- Obtain global-horizontal, direct-normal, and UV data for sites with actual measurements.

- Perform a sensitivity analysis to determine if the UV resource uncertainty is a critical factor in the viability of the solar detoxification technology, which will necessitate more precise measurements and resource assessments for the technology evaluation.

Both Sandia National Laboratories, Albuquerque, N. Mex., and SERI, Golden, are taking direct-normal UV and broadband measurements that will be used to develop UV data bases for their two sites.

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