Conference Paper

August 2004 • NREL/CP-560-36320

Description and Availability of the SMARTS Spectral Model for Photovoltaic Applications

Preprint

D.R. Myers
National Renewable Energy Laboratory

C.A. Gueymard
Solar Consulting Services

To be presented at the International Symposium on Optical Science and Technology, SPIE's 49th Annual Meeting
Denver, Colorado
August 2–6, 2004

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Description and availability of the SMARTS spectral model for photovoltaic applications

Daryl R. Myers[*a], Christian A. Gueymard[+b]
[a]National Renewable Energy Laboratory, 1617 Cole Blvd Golden Co 80401
[b]Solar Consulting Services, 97 Lake Fairgreen Circle, New Smyrna Beach, FL 32168

ABSTRACT

Limited spectral response range of photovoltaic (PV) devices requires device performance be characterized with respect to widely varying terrestrial solar spectra. The FORTRAN code "Simple Model for Atmospheric Transmission of Sunshine" (SMARTS) was developed for various clear-sky solar renewable energy applications. The model is partly based on parameterizations of transmittance functions in the MODTRAN/LOWTRAN band model family of radiative transfer codes. SMARTS computes spectra with a resolution of 0.5 nanometers (nm) below 400 nm, 1.0 nm from 400 nm to 1700 nm, and 5 nm from 1700 nm to 4000 nm. Fewer than 20 input parameters are required to compute spectral irradiance distributions including spectral direct beam, total, and diffuse hemispherical radiation, and up to 30 other spectral parameters. A spreadsheet-based graphical user interface can be used to simplify the construction of input files for the model. The model is the basis for new terrestrial reference spectra developed by the American Society for Testing and Materials (ASTM) for photovoltaic and materials degradation applications. We describe the model accuracy, functionality, and the availability of source and executable code. Applications to PV rating and efficiency and the combined effects of spectral selectivity and varying atmospheric conditions are briefly discussed.

Keywords: Terrestrial, Solar, Spectral, Model, Photovoltaic

1. INTRODUCTION

Routine measurement of natural spectral solar irradiance distributions is expensive in terms of equipment, logistics, and data collection and processing[1]. Thus, the need for models that produce relatively accurate spectral distributions under different atmospheric conditions is apparent. Varieties of radiative transfer models of differing complexity compute radiative transfer through an absorbing, scattering, and emitting medium. For certain applications requiring very narrow-bandwidth, or wider bandwidth but highly resolved spectral information (such as atmospheric correction of remote sensing data, laser propagation, or target signatures) more rigorous, comprehensive and complex models may be required. Well-known examples of these models are the Low resolution Transmittance (LOWTRAN)[2] and Moderate resolution Transmittance (MODTRAN)[3] family of codes developed by the Air Force Research Laboratory (AFRL)[†]. Many technologies associated with solar renewable energy, including daylighting [4,5], solar heat gains through fenestration[6], material response to ultraviolet exposure [7,8], and photovoltaic (PV) performance[9] are affected by the spectral distribution of terrestrial sunlight. The common element among these technologies is a limited spectral response interval, for a material action spectrum, PV spectral response, or the human photopic response. For engineering applications in these fields, lower resolution (on the order of one to five nanometers, nm) spectral distributions are useful for estimating performance under various atmospheric conditions. The model described here addresses clear sky conditions only. An approach to incorporating modifiers for cloud cover can found in Nann and Riordan[10].

* daryl_myers@nrel.gov; phone 303-384-6768; fax 303-384-6391; www.nrel.gov/rredc
+ Chris@SolarConsultingServices.com
† Previously known as the Cambridge Research Laboratory, 1947-1974, renamed the Air Force Geophysics Laboratory from 1974-1991 and named the Geophysics Directorate of the Air Force Phillips Laboratory from 1991-1997.

2. THE ATMOSPHERE AND SPECTRAL MODELS

Solar radiative transfer models modify an extraterrestrial spectrum that is transmitted, absorbed, or scattered by the atmospheric constituents. Thus, the make-up and relative concentration of atmospheric constituents is important. Research into physical and optical properties of the Earth's atmosphere and their effect on the propagation of solar radiation has resulted in the definition of standard atmospheres. These include the United States Standard Atmosphere (USSA) of 1966, revised in 1976[11,12], and supplemental atmospheric models[13].

Radiative transfer through any medium depends upon quantum properties of the medium. High-resolution models that compute spectra from first principles using these quantum properties are called line-by-line or LBL models. An example is the Fast Atmospheric Signature Code (FASCODE), developed by the AFRL[14]. These models are primarily for narrow bandwidth regions and require significant computational resources and storage space. LBL models access databases, such as HITRAN[15], consisting of quantum parameters for many molecular species (more than one million spectral lines for HITRAN). LBL models are too complex and specialized for discussion here. Band models are simplified LBL models as described in Fenn et al.[16]. Band models represent groups of absorption lines as transmittance functions of parameters such as absorber concentration, pressure, and absorption coefficients. MODTRAN (moderate resolution) and LOWTRAN (low resolution) are commercially available band models. "Low" resolution corresponds to 20 wavenumbers (0.2 nm at 300 nm to 32 nm at 4000 nm), and "moderate" resolution corresponds to 2 wavenumbers (0.02 nm at 300 nm to 0.3 nm at 4000 nm). These models can address complex scenarios, including clouds, fog, smoke, many choices of standard and user-defined aerosol properties, atmospheric structure for up to 33 different layers, and a choice of up to six extraterrestrial spectra. The models are designed to compute atmospheric transmittance between two points on or above the Earth's surface. The many combinations of geometry, input parameters, and their interaction require a great deal of understanding by the user. Interpretation of the results can be challenging, as well.

Models based on parameterizations of transmittance and absorption functions for atmospheric constituents are considerably simpler. These functions, which strongly depend on the path length of photons through the atmosphere, in addition to the constituents' optical depth, include molecular (Rayleigh), ozone, water vapor, mixed gases, trace gases, and aerosol transmittances. The product transmittance functions modify an extraterrestrial spectrum to produce the transmitted spectral distribution. Spectral resolution is generally lower (on the order of nanometers) than that of complex models. SPCTRAL2, the simple spectral model of Bird[17], SEDES2[10] (derived from SPCTRAL2)[‡], and the Simple Model for Atmospheric Transmission of Sunshine (SMARTS) of Gueymard [18-22] use this approach. These models require few input parameters and are useful for engineering applications requiring less accuracy and resolution, but more versatility and ease of use. In the next section, we describe the SMARTS model and its relation to MODTRAN.

3. SMARTS MODEL DESCRIPTION

Highly detailed descriptions of the SMARTS model are provided elsewhere[20-22]. A characteristic of this model is its versatility: a large number of applications in various disciplines are possible[23]. This is achieved by providing a number of options in addition to the core calculations. Other features of the model are: (i) it uses accurate and regularly updated spectral transmittance functions; (ii) provides improved spectral resolution over existing transmittance models; (iii) produces spectral irradiances comparable to MODTRAN predictions with far simpler inputs; and (iv) its predictions can be easily and directly compared to spectroradiometric measurements using built-in functions. Here we present a succinct summary of the model elements and their derivation. The philosophy behind the latest model developments is to parameterize the band model transmittance functions used by MODTRAN for water vapor (the strongest absorber in the infrared with very complex absorption features), but at a lower resolution of 0.5 nm in the ultraviolet (UV) less than 400 nm, 1 nm between 400 nm and 1700 nm, and 5 nm between 1700 nm and 4000 nm. Recent spectroscopic data are used to parameterize the temperature-

‡ SEDES2 uses cloud cover and measured broadband global irradiance data to modify clear sky SPCTRAL2 results.

dependent absorption by other gases. Rayleigh scattering is parameterized as a function of wavelength and pressure based on recent depolarization data[24-25]. Aerosol transmittance is parameterized using Ångström's law and band-integrated values of Ångström's turbidity coefficients for a variety of aerosol models. These parameterized transmittance functions are used to obtain the direct beam irradiance from:

$$E(\lambda) = E_0(\lambda)\ Tr(\lambda)\ To(\lambda)\ Tmg(\lambda)\ Ttg(\lambda)\ Tw(\lambda)\ Ta(\lambda). \quad (1)$$

at each wavelength (λ, nm), where E is the terrestrial spectral irradiance, E_0 is the extraterrestrial spectral irradiance, and the spectral transmittances are for: Rayleigh scattering (Tr), ozone absorption (To), mixed gases absorption (Tmg), trace gases absorption (Ttg), water vapor absorption (Tw), and aerosol extinction (Ta). To define the amount of variable gases, five pre-defined pollution levels are selectable (pristine/exceptionally clean, standard/clean, light pollution, moderate pollution, heavy pollution), as well as user-specifiable mixing-layer pollutant concentrations. Table 1 summarizes the form of transmittance functions developed for the SMARTS model.

Table 1. Transmission expressions developed for SMARTS model (versions 2.9 and later).

Extinction Process	Transmittance Expression	Source
Rayleigh scattering	$Tr(\lambda)=\exp\{(P/P_0)/[a_0 (\lambda/\lambda_1)^4+a_1(\lambda/\lambda_1)+a_2+a_3(\lambda/\lambda_1)^{-2}]\}$	Gueymard[20, 22]
Ozone absorption	$To(\lambda) = \exp [- m_o u_o Ao(\lambda)]$	Daumont et al. (1992)[26], Bogumil et al. (2003)[27], Burrows et al. (1999)[28], Anderson et al. (1993)[29]
Mixed Gases absorption (j=1–7)	$Tmg_j(\lambda) = \exp [- m_j u_j A_j(T,\lambda)].$	Various laboratory spectroscopic data for CH_4 CO_2, CO, N_2, N_2O, O_2, and O_4
Trace Gases absorption (k=1–10)	$Ttg_k(\lambda) = \exp [-(m_k u_k A_k(T,\lambda))].$	Mixed: Various laboratory spectroscopic data for BrO, CH_2O, $ClNO_3$, HNO_2, HNO_3, NH_3, NO, NO_2, NO_3, and SO_2
Water Vapor absorption	$Tw(\lambda) = \exp[-(m_w u_w)^n B_w(u_w,\lambda) B_m(m_w,\lambda) B_p(P,\lambda) B_{mw}(m,u_w,\lambda) A_w(\lambda)]$	Gueymard fits to MODTRAN4 Water vapor band models.
Aerosol extinction	$Ta(\lambda) = \exp [- m_a \beta_i (\lambda/\lambda_1)^{-\alpha i}]$	General Ångström relation, visibility or meteorological range based on Koschmeider[30]

Table 1 expression parameters are; P: station pressure; P_0: standard pressure; T: temperature; a_i: fitting coefficients; m_x: optical mass correction for extinction process x; u_x: abundance for absorber x, A_x: absorption coefficient for absorber x, B: water vapor band function or scaling factor; α_i and βi,: Ångström parameters, i= 1 for $\lambda<500$ nm, i=2 for $\lambda\geq500$ nm[⊕], λ_1: reference wavelength (1000 nm or 1 µm)

Figure 1 shows percent difference between SMARTS and MODTRAN results for standard atmospheric conditions. Most differences are caused by absorbing cases considered in one model and not the other (indicated by arrows), by differing spectroscopic data (e.g., for ozone in the UV), and finally by parameterization shortcomings in the water vapor bands for SMARTS.

[⊕] The common assumption the $\alpha_1=\alpha_2=\alpha$ can lead to errors for the urban, maritime, and rural aerosol profiles. The Ångström exponents are determined as a function of aerosol type and relative humidity (appendix B of Gueymard[20])

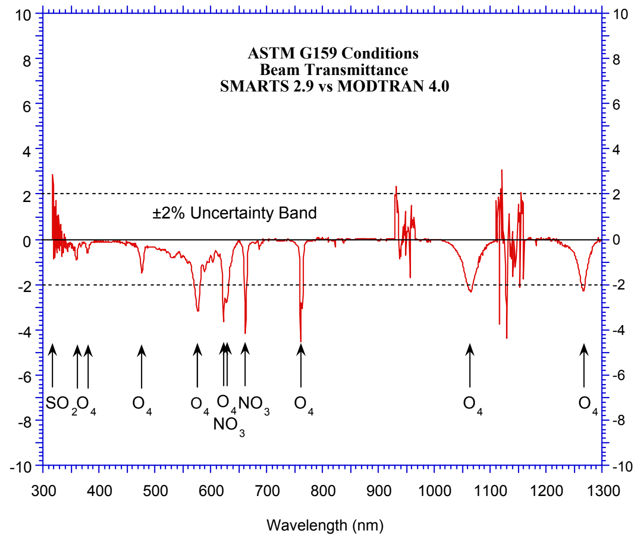

Fig. 1. Percent difference between the direct transmittance predicted by SMARTS 2.9 and MODTRAN 4.0 for standard conditions, showing additional absorption bands (indicated by arrows) considered in SMARTS.

Figure 2 is an example of many comparisons between measured and SMARTS model spectra. Agreement within the uncertainty limits of spectral irradiance measurements (1% in the visible, and 3–5% in the ultraviolet and infrared) can be achieved when the atmospheric conditions (most importantly, aerosol optical depth and water vapor amount) are precisely known.

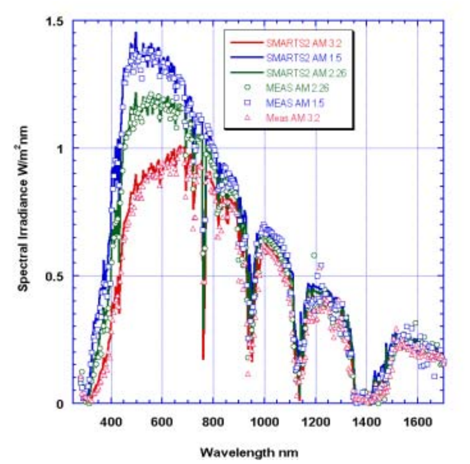

Fig. 2. SMARTS model results (lines) and measurements (symbols) at 5 nm resolution for 3 air masses at NREL, Sept. 18, 2001.

4. REFERENCE ATMOSPHERES

The transmission functions above produce results depending on the atmospheric profile used to provide the absorber concentrations. There is one reference atmosphere: the U.S. Standard Atmosphere (USSA) of 1976. Several supplemental atmospheric profiles have been developed and integrated into the MODTRAN model. These are the Mid-Latitude Summer (MLS), Mid-Latitude Winter (MLW), Sub-Arctic Summer (SAS), Sub-Arctic Winter (SAW), and Tropical (TRO) profiles, described in Anderson et al.[31]. Four additional profiles were added for SMARTS: Sub-Tropical Summer, Sub-Tropical Winter, Arctic Summer, and Arctic Winter. These were based on profiles developed as part of the USSA 1966[11], which preceded USSA 1976. All profiles are defined with vertical increments of 1 km, and linear interpolation for intermediate altitudes. The effective temperature for ozone is an average of the atmospheric temperature profile weighted by concentration of ozone. Relative humidity is computed based on tabulated mixing ratio data and the methods documented in LOWTRAN 5 description of Kneizys et al.[2]. Total column abundances of O_3, NO_2 and other gases were available in the six MODTRAN reference atmospheres. For the four other atmospheres, abundances were computed from available data for 1957-1975[32]. Water vapor totals are obtained in the form of "precipitable water" by integration of water vapor concentration for each specific humidity profile. Each mixed gas scaled amount is computed using scaled temperature, pressure, and density ratios with respect to standard values. The user may define an atmospheric profile by entering assumed or observed air temperature, relative humidity, daily average temperature, which are used to scale the appropriate default atmospheric profile.

5. SMARTS MODEL OPERATION

5.1 FORTRAN Executable

SMARTS is written in FORTRAN on a Macintosh platform, but is available for the PC-Windows platform. For PC-Windows, the 5500 lines of source code are compiled using Lahey FORTRAN LF 90 version 4.5. Switches for the Pentium "target processor", (-tp), optimization level 0 (-O0), and arithmetic processor "on" (-ap) are used so results are identical to those on the Macintosh platform. The program prompts for a default (SMARTS2.INP), or user specified input file with extension INP. Users may create or edit input files with any text editor. The input file, ancillary data (extraterrestrial spectrum, absorption coefficients, etc.) files are read, and up to three output files are generated. Output files consist of (i) descriptive text and calculated results with an echo of input parameters, (ii) spectral results, and (iii) a "scan" file of data degraded by a user-specified filter to simulate a spectroradiometer passband. Output files are ASCII text.

5.2 Input file structure

The SMARTS input file is a list of 15–20 parameters arranged as a stack of input "cards". Table 2 is an annotated input file used to generate the ASTM G173 standard spectra[33]. Not all possible inputs are shown.

Table 2. SMARTS Version 2.9.2 Input File to Generate the Reference Spectra ASTM G173-03

Card ID	VALUE	Parameter/Description/Variable Name
1	'ASTM_G173_Std_Spectra'	Comment line
2	1	Pressure input mode (1 = pressure and altitude): ISPR
2a	1013.25 0.	Station Pressure (mb) & altitude (km): SPR, ALT
3	1	Standard Atmosphere Profile Selection (1 = use default atmosphere): IATM1
3a	'USSA'	Default Standard Atmosphere Profile: ATM (one of eleven choices, including user defined)
4	1	Water Vapor Input (1 = default from Atmospheric Profile): IH2O (may be user specified)
5	1	Ozone Calculation (1 = default from Atmospheric Profile): IO3 (may be user specified)
6	1	Pollution level mode (1 = standard conditions/no pollution): IGAS (for 10 pollutant gases)
7	370	Carbon Monoxide volume mixing ratio (ppm): qCO2
7a	1	Extraterrestrial Spectrum (1 = SMARTS/Gueymard): ISPCTR (one of seven choices)
8	'S&F_RURAL'	Aerosol Profile to Use: AEROS (one of 10 choices, including user specified)
9	0	Specification for aerosol optical depth/turbidity input (0 = AOD at 500 nm): ITURB
9a	0.084	Aerosol Optical Depth @ 500 nm: TAU5
10	38	Far field Spectral Albedo file to use (38= Light Sandy Soil): IALBDX (on of 40 choices, including user defined)
10b	1	Specify tilt calculation (1 = yes): ITILT
10c	38 37 180	Albedo and Tilt variables—Albedo file to use for near field, Tilt, and Azimuth: IALBDG, TILT, WAZIM
11	280 4000 1.0 1367.0	Wavelength Range—start, stop, mean radius vector correction, integrated solar spectrum irradiance: WLMN, WLMX, SUNCOR, SOLARC
12	2	Separate spectral output file print mode (2 = yes): IPRT: Spectral & broadband files
12a	280 4000 .5	Output file wavelength—Print limits, start, stop, minimum step size: WPMN, WPMX, INTVL
12b	2	Number of output variables to print: IOTOT (up to 32)
12c	8 9	Code relating output variables to print (8 = Hemispherical tilt, 9 = direct normal + circumsolar): OUT(8), OUT(9) [up to 32 spectral parameters available for output]
13	1	Circumsolar calculation mode (1 = yes): ICIRC
13a	0 2.9 0	Receiver geometry—Slope, View, Limit half angles: SLOPE, APERT, LIMIT
14	0	Smooth function mode (0 = none): ISCAN (Gaussian and triangle filter shapes can be specified)
15	0	Illuminance calculation mode (0 = none): ILLUM (Luminance and efficacy may be selected)
16	0	UV calculation mode (0 = none): IUV (UVA, UVB, action weighed dosages available)
17	2	Solar Geometry mode (2 = Air Mass): IMASS (zenith and azimuth, date/time/lat/long available)
17a	1.5	Air mass value: AMASS

5.3 Output files

SMARTS produces up to three ASCII output files. The files have the same root name as the input file (SMARTS2 if SMARTS2.INP is the input file, for instance) with extensions of OUT, EXT, or SCN. OUT files produce an echo of the input data and summary of broadband (integrated) and intermediate calculations. EXT files are the spectral output for the selected spectral parameters, including spectral irradiances, photon flux per wavelength (or energy interval), constituent transmission or absorption, spectral albedo, and so on. SCN files are produced when a user-defined filter (with user-defined bandwidth) is specified to simulate spectral data from an instrument of given bandwidth.

5.4 EXCEL graphical user interface.

Constructing a correct input file for SMARTS can be confusing unless a user is intimately familiar with the structure. The National Renewable Energy Laboratory, NREL, developed a graphical user interface, SMARTS.XLS, based on Microsoft Excel® visual basic macros. Figure 3 shows the configuration interface, where each input parameter is selected. For each selection, a separate dialog box appears to allow the user to select or enter inputs. Figure 4 is an example of two of the primary configuration dialog boxes. Each box appears individually, corresponding to the button on the configurations menu. The user fills in the parameters and clicks OK to update the input file "card deck" shown in column A of the spreadsheet. The user

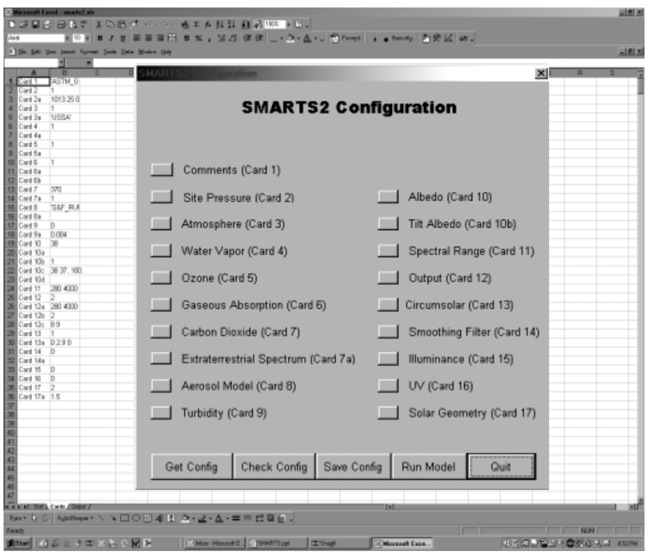

Fig. 3. Input configuration menu for the graphical interface used to construct SMARTS

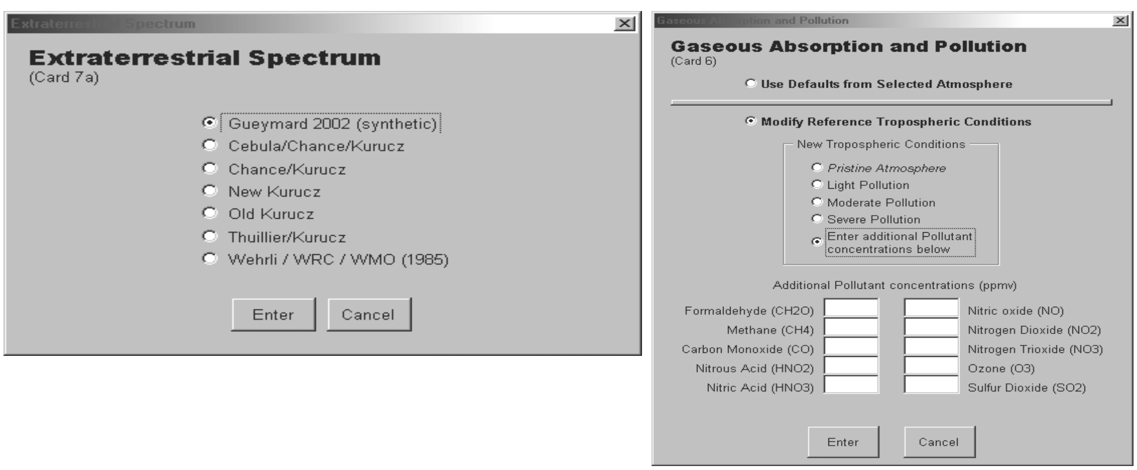

Fig.4. Example of two input dialog boxes for the SMARTS user interface.

may save and retrieve configurations with unique file names. When ready to generate the model results, the "Run Model" button is clicked, and the executable runs. The appropriate output files are generated with the names SMARTS2.OUT, SMARTS2.EXT, or SMARTS2.SCN, as appropriate. The users must manually rename files if they wish to save results; otherwise, the output files are overwritten at the next run. Input configurations may be loaded and run at any time to re-generate desired outputs. The interface is designed for the PC platform only. It is embedded in an Excel file, SMARTS2.XLS, which is loaded into Excel as any other XLS file. The XLS file must reside in the same directory as the executable, ancillary data files (about 30, including extraterrestrial data, albedo files, photopic data, etc.). The interface must be loaded by navigating to that directory, so that file paths are correct.

6. SOME PHOTOVOLTAIC APPLICATIONS EXAMPLES

6.1 Standard Spectra

Standard reporting conditions (SRC) for PV device performance[34, 35] specify the standard reference spectra, which have recently been upgraded [32, 36] as American Society for Testing and Materials (ASTM) G-173-03. Older versions of the reference spectra, first developed in 1982, are based on older radiative transfer calculations that cannot be reproduced. Therefore, ASTM asked the authors to provide a well-documented, easily accessible model for generating the reference spectra, and justification for any revisions in the parameters specifying the conditions for the reference spectra. SMARTS (version 2.9.2) was selected as the appropriate model to accomplish this task, and the model was integrated as a part of the revised standard. Figure 5 compares the new and old versions of the reference spectra. The principal change is the aerosol optical depth (AOD) of 0.084 (at 500 nm) versus the previous significantly higher AOD of 0.27. This change was justified by the results of an analysis of conditions when irradiances on a flat plate met SRC for irradiance of 1000 W m^{-2}, as described elsewhere[37]. The change makes the hemispherical spectral irradiance on a flat plate integrate to 1000 W m^{-2} without the need for adjustment factors that were used in the older versions of the reference spectra. It also raised the direct beam spectrum, and beam total irradiance, to a level comparable with proposed concentrator rating methods[38].

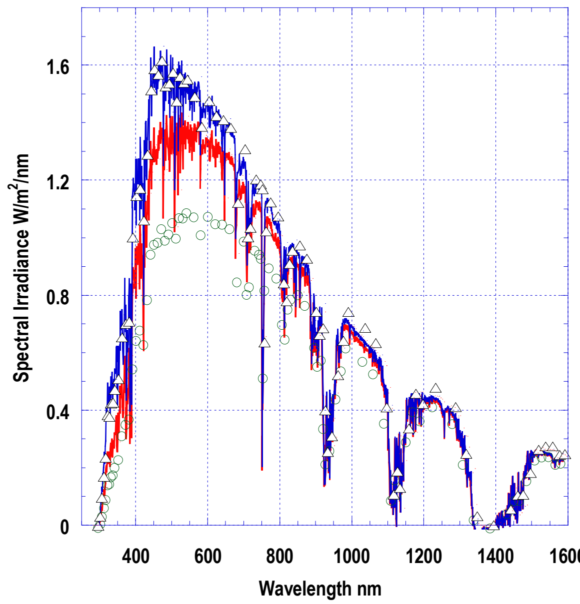

Fig. 5. Old (symbols) and Revised (lines) ASTM direct normal and hemispherical tilted spectra. Upper line is new hemispherical tilt; lower line is new direct normal. Triangles = old 1 kW m^{-2} normalized hemispherical tilt, circles = old direct normal reference tabular data.

6.2 Spectral Mismatch

For evaluating the impact of various spectra on PV performance under different conditions, SMARTS computation of spectra is straightforward. Figure 6 shows the spectral response of a crystalline silicon (x-Si) PV reference cell and an amorphous silicon (a-Si) cell. For instance, assume the two cells are measured outdoors at latitude 40° N, an altitude of 1.8 km, on a 40° tilted 180° azimuth (south facing) tilted surface, with a concrete slab foreground and precipitable water vapor =0.5 atm-cm, aerosol optical depth of 0.18 at 500 nm, with light urban pollution conditions and at a time when the solar airmass = 1.8. Constructing the SMARTS input file and calculating the spectrum under which the actual test was conducted (lower, gray curve of Fig. 7), we compute the spectral mismatch correction factor for adjusting the amorphous silicon photocurrent to that which would be produced under the reference spectrum, or standard reporting conditions (upper curve of Fig. 7). The mismatch factor for this specific example is given by:

$$M = \frac{\int_{\lambda 1}^{\lambda 2} Et(\lambda)St(\lambda)}{\int_{\lambda 3}^{\lambda 4} Et(\lambda)Sr(\lambda)} \bullet \frac{\int_{\lambda 3}^{\lambda 4} Eref(\lambda)Sr(\lambda)}{\int_{\lambda 1}^{\lambda 2} Eref(\lambda)St(\lambda)} \tag{2}$$

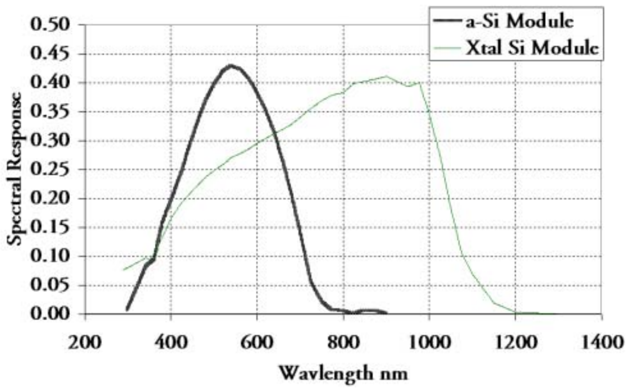

Fig. 6. Spectral response curves for an amorphous silicon test cell (heavy line) and crystalline silicon reference cell (light line). Used with "test" spectrum in Fig. 7.

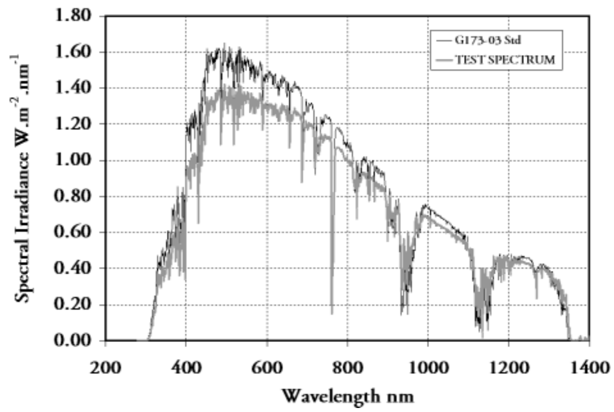

Fig. 7. Standard (top curve) and SMARTS model spectral irradiance on 40° tilt, 180° Azimuth, at 40° N latitude, 1.8 km altitude, water vapor 0.5 atm-cm, lightly polluted urban aerosol profile, aerosol optical depth of 0.18, air mass 1.8, and concrete foreground.

where Et and Eref are the test and reference spectra, Sr and St are the reference-cell and test-cell spectral response, λ_1, λ_2 are the test-cell response limits, and λ_3, λ_4 are the reference-cell response limits. Here, M is calculated to be 0.951. Therefore, the short-circuit current from the amorphous silicon under SRC will be 4.9% higher than measured.

6.3 PV technology sensitivity to aerosols and water vapor

SMARTS may be used for parametric studies of the sensitivity of PV technologies to variable atmospheric constituents that affect spectral conditions. Fig. 8 shows the relative spectral response of an amorphous silicon thin film cell and a triple-layer multi-junction cell. To examine the sensitivity of the two technologies to *aerosol optical depth* and *water vapor* (the two primary atmospheric variables under clear skies) for various air masses, the integrated product of the spectral responses of the cells by the SMARTS-modeled spectra for the conditions in Table 2 were divided by the integrated product of spectral responses and extraterrestrial (space) spectrum. The USSA 1976 atmosphere profiles were used, for latitude 40 °N and sea-level elevation. The table entries are the ratio of variable "terrestrial" conditions to the fixed extraterrestrial condition, showing the sensitivity (or lack of it) of each technology to the two parameters. The wider spectral response range of the multi-junction cell results in a greater sensitivity to water vapor than the amorphous silicon, indicated by lower values of the ratio. Figure 9 compares the relative sensitivity of the two technologies to increasing water vapor and aerosol optical depth. A practical use of these ratios is that they are multiplicative. For example, the combined sensitivity of an MJ cell under very dry (precipitable water = 0.5 cm) and clean (AOD = 0.05) conditions at air mass 1.0 is 0.908*0.869 = 0.789. For an a-Si cell, the sensitivity is 0.920*0.907 = 0.834. The numbers change respectively to 0.756*0.796 = 0.602 and 0.805*0.775 = 0.623 for an air mass of 1.5 and under the humid (precipitable water = 6 cm) and hazy (AOD = 0.35) conditions.

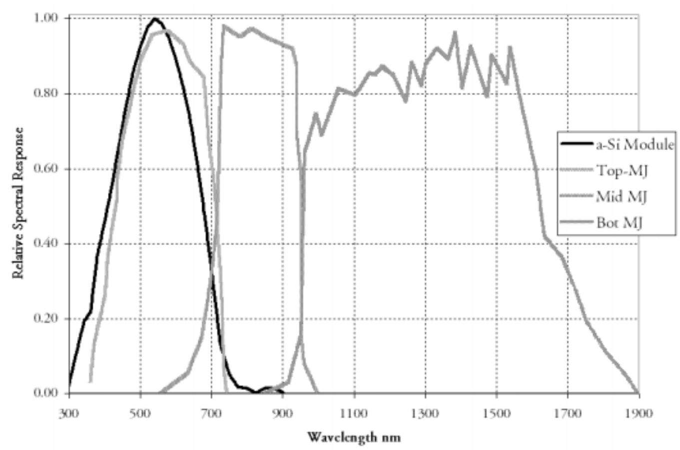

Fig. 8. Relative spectral response of amorphous silicon (a-Si) (dark line) and top, middle, and bottom junctions of multi-junction (MJ) cell (gray lines).

Table 3. Quantitative evaluation of sensitivity of technologies to atmospheric parameters, using SMARTS. Entries are ratio of [terrestrial spectrum x spectral response (SR)] to [extraterrestrial spectrum x SR] for multi-junction (MJ) and amorphous silicon (a-Si) cells with spectral responses shown in Fig. 8. Smaller numbers indicate greater sensitivity.

Air mass		Precipitable Water (cm)						Aerosol Optical Depth at 500 nm					
		0.5	1.0	2.0	3.0	4.0	6.0	0.05	0.15	0.20	0.25	0.3	0.35
MJ	1.0	0.908	0.889	0.863	0.847	0.835	0.817	0.869	0.877	0.885	0.893	0.897	0.901
	1.2	0.885	0.864	0.839	0.822	0.808	0.789	0.855	0.852	0.850	0.847	0.843	0.838
	1.5	0.859	0.837	0.809	0.791	0.777	0.756	0.831	0.824	0.818	0.812	0.804	0.796
	2.0	0.804	0.781	0.751	0.732	0.718	0.696	0.782	0.767	0.754	0.741	0.727	0.714
	2.5	0.750	0.726	0.695	0.675	0.661	0.639	0.734	0.712	0.692	0.673	0.653	0.635
a-Si	1.0	0.920	0.920	0.912	0.920	0.912	0.912	0.907	0.915	0.924	0.933	0.942	0.942
	1.2	0.876	0.876	0.867	0.867	0.867	0.858	0.871	0.863	0.863	0.854	0.854	0.845
	1.5	0.814	0.814	0.814	0.805	0.805	0.805	0.819	0.810	0.801	0.792	0.783	0.775
	2.0	0.726	0.726	0.717	0.717	0.717	0.708	0.739	0.713	0.704	0.687	0.678	0.660
	2.5	0.646	0.646	0.637	0.637	0.628	0.628	0.669	0.634	0.616	0.599	0.581	0.563

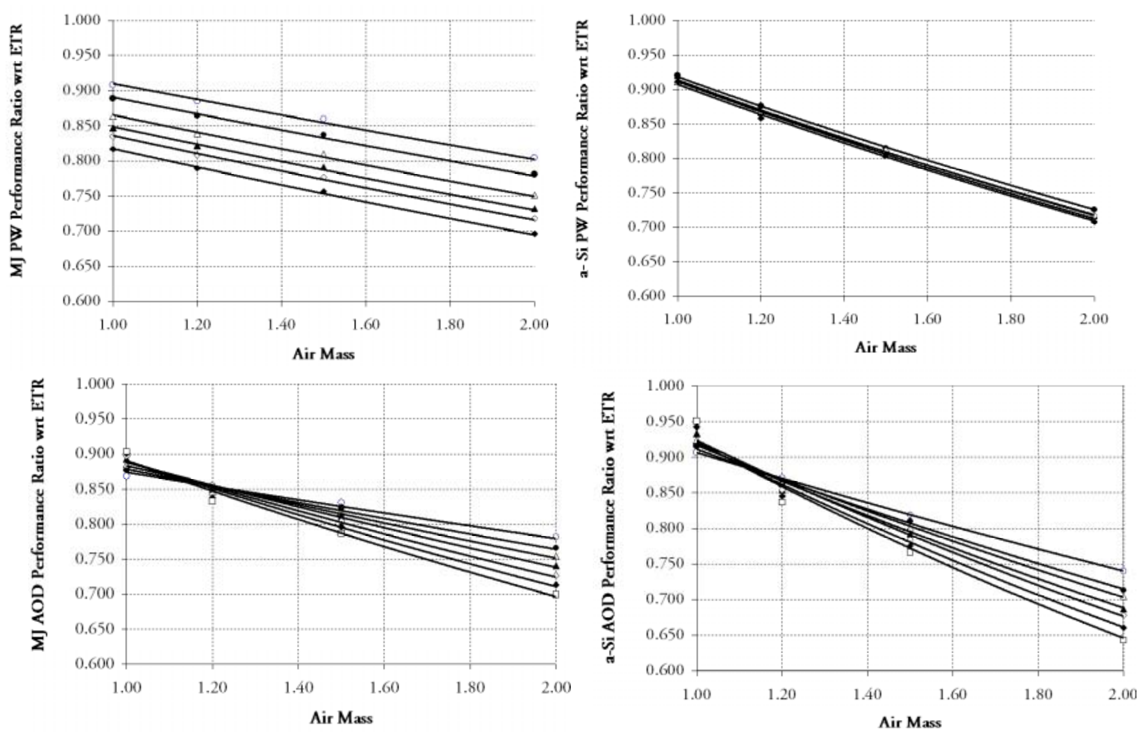

Fig. 9. Ratios in Table 3 plotted vs air mass. Top panel depicts sensitivity to water vapor variations for multi-junction cell (left) and amorphous cell (right). Wider response range of MJ cell results in its greater sensitivity to varying water vapor. Bottom panel depicts sensitivity of MJ (left) and a-Si cell (right) to varying aerosol optical depth. Greater sensitivity to variations in AOD is apparent in the a-Si responses. Curve order from top to bottom corresponds to ascending parameter values (reading left-to-right column headings in Table 3).

These results indicate that (i) air mass increases the sensitivity of MJ-PV cells to both AOD and water vapor, but decreases it in the case of a-Si technologies; (ii) dry-clean areas are ideal locations not only the solar resource is very high but because the PV-cells sensitivity to atmospheric conditions is minimal; and (iii) the difference in sensitivity to atmospheric conditions between MJ and a-Si technologies is small in dry-clean areas but becomes noticeable in hazy-humid areas. Similar work has been done to evaluate the impact of spectral variation on the design of multi-junction cell layer thickness, and module energy ratings with respect to "reference day spectra"[39].

7. AVAILABILITY OF THE SMARTS SPECTRAL MODEL

The author of the model and NREL have agreed to place the model in the public domain, and make it available to all interested users free of charge. A comprehensive 35-page Users Manual describes all model installation and operation, including detailed instructions for constructing the input files. The manual is applicable to both Macintosh and PC platform installations. For PC-platform users, NREL developed graphical interface is available, with a fourteen-page interface instruction manual.

Both versions of the model are available for download from the NREL Renewable Resources Data Center (RRedC) website: http://rredc.nrel.gov/solar/models/SMARTS. Users are required to register with a username and password so that they can sign the user's agreement and can be provided with update notifications if they so desire. Figure 10 shows the website model page, registration form, and download page.

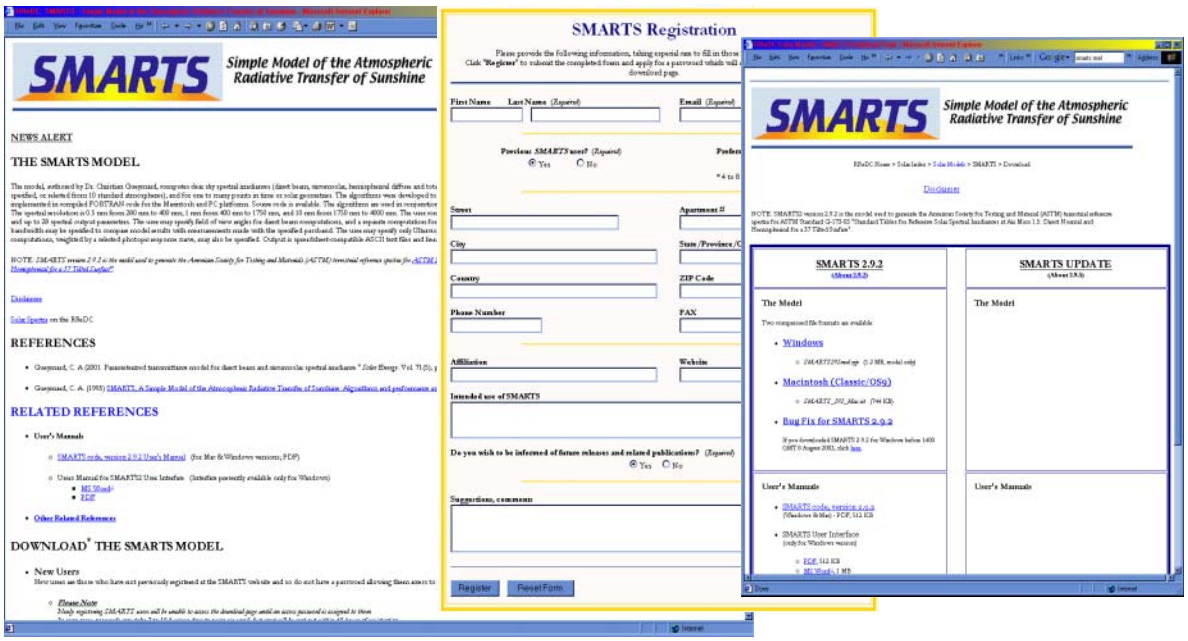

Fig. 10. NREL's World Wide Web SMARTS model access page (left), on-line registration form (center), and the download for acquiring the both the PC and Apple SMARTS model, PC Excel interface, and users manuals (right).

The model is available as a compressed file about 1.2 megabytes (Mb) in size. Decompressed, the model, ancillary files, and manuals occupy about 3 Mb.

CONCLUSION

The SMARTS spectral atmospheric transmission code for clear sky solar renewable energy applications is based on parameterizations of transmittance functions in (or compatible with) the MODTRAN/LOWTRAN band model family of radiative transfer codes. SMARTS computes spectra with a resolution of 0.5 nanometers (nm) below 400 nm, 1.0 nm from 400 nm to 1700 nm, and 5 nm from 1700 nm to 4000 nm. SMARTS computes the spectral direct beam, total, and diffuse hemispherical radiation on horizontal, tilted or tracking surfaces located at any ground site or flying object below an altitude of 100 km. Fewer than 20 input parameters are required to compute spectral irradiance distributions and up to 30 other spectral parameters. NREL developed a spreadsheet based graphical user interface to simplify the construction of input files for the model. The model is the basis for new terrestrial reference spectra developed by the American Society for Testing and Materials (ASTM) for photovoltaic and materials degradation applications. SMARTS is useful for parametric studies related to the sensitivity of PV technologies to varying spectral conditions, especially those related to expected performance in various climates. The model may be obtained at no cost by download from http://rredc.nrel.gov/solar/models/SMARTS**.**

REFERENCES

1. Bird, R.E., RL. Hulstrom, A.W. Kliman, H.G. Eldering, "Solar spectral measurements in the terrestrial environment," *Applied Optics*, **21**(8): pp. 1430-1435, 1982.
2. Kneizys, F.X., et al., "Atmospheric transmittance/radiance: Computer code LOWTRAN5," Rep. AFGL TR-80-0067, Air Force Geophysics Lab., Hanscom AFB, 1980.
3. Anderson, G.P., et al, "History of one family of atmospheric radiative transfer codes," *Passive Infrared Remote Sensing of Clouds and the Atmosphere II*. SPIE, Vol. 2309, Society of Photo-optical Instrumentation Engineers, Bellingham, 1994.
4. Judd, D.B., D.L. MacAdam, G.W. Wysecki, "Spectral distribution of typical daylight as a function of correlated color temperature," *Journal of Optical Society of America*, **54**: pp. 1031-1040, 1964.
5. Hernandez-Andres J., R.L. Lee, J. Romero, "Calculating correlated color temperatures across the entire gamut of daylight and skylight conditions," *Applied Optics*, **38**(27): pp. 5703-5709, 1999.
6. McCluney R. Sensitivity of fenestration solar gain to source spectrum and angle of incidence. ASHRAE Trans. 1996; 102, pt.2, 112-122.
7. Ketola, W.D., J.O. Evans, ed., *Durability 2000,* Vol. STP 1385, 183 pp., American Society for Testing and Materials, West Conshohocken, 2000.
8. Herling, R.J., ed., *Durability Testing of Nonmetallic Materials,* Vol. STP 1294, 234 pp, American Society for Testing and Materials, West Conshocken, 1996.
9. Pearsall, N.M., K.A. Emery, M. Davies, "Influence of reference cell and spectrum on the measurement of solar cells," *Proceedings 7th European PV Solar Energy Conference, WIP Munich and ETA Florence, Italy*, Sevilla, 1986.
10. Nann, S., C. Riordan, "Solar spectral irradiance under clear and cloudy skies: Measurements and a semiempirical model," *Journal of Applied Meteorology*, **30**: pp. 447-462, 1991.
11. Anon, *U.S. Standard Atmosphere Supplements, 1966,* ESSA/ NASA/ USAF, U.S. Gov. Printing Office, Washington, DC, 1966.
12. Anon, *U.S. Standard Atmosphere*, http://nssdc.gsfc.nasa.gov/space/model/atmos/us_standard.html, Washington, DC, NOAA / NASA/ USAF 1976.
13. Champion, K.S.A., et al., "Standard and reference atmospheres," *Handbook of Geophysics and the SpaceEenvironment*, A. S. Jursa, Ed., pp. 14.1-14.36, Air Force Geophysics Laboratory, Washington, D.C., 1985.
14. Anderson, G.P., et al., "Reviewing atmospheric radiative transfer modeling: New developments in high and moderate resolution FASCODE/FASE and MODTRAN," *Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research II*. Vol. 2830, pp. 82-93, Society of Photo-optical Instrumentation Engineers, Bellingham, 1996.
15. Rothman, L.S., et al., "The HITRAN molecular database: Editions of 1991 and 1992," *Journal of Quantum. Spectroscopy and Radiative Transfer*, **48**: pp. 469-507, 1992.
16. Fenn, R.W., et al., "Optical and infrared properties of the atmosphere," *Handbook of Geophysics and the Space Environment*, A.S. Jursa, Ed., pp. 18.1-18.71, Air Force Geophysics Laboratory: Washington D.C., 1985.
17. Bird, R.E., C. Riordan, "Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the earth's surface for cloudless atmospheres," *Journal of Climate and Applied Meteorology,* **25**: pp. 87-97, 1985.
18. Gueymard, C., "Development and performance assessment of a clear sky spectral radiation model," *Solar '93—22nd Annual Conf. American Solar Energy Society, Boulder, CO,* Washington, DC, 1993.
19. Gueymard, C., "Updated transmittance functions for use in fast spectral direct beam irradiance models," *Solar '94 Conf*., American Solar Energy Society, Boulder, San Jose, 1994.
20. Gueymard, C., "SMARTS2, simple model of the atmospheric radiative transfer of sunshine: Algorithms and performance assessment," Rep. FSEC-PF-270-95.Florida Solar Energy Center, Cocoa, 1995.
21. Gueymard, C., "Parameterized transmittance model for direct beam and circumsolar spectral irradiance," *Solar Energy*, **71**(5): pp. 325-346, 2001.
22. Gueymard, C., D. Myers, K. Emery, "Proposed reference irradiance spectra for solar energy systems testing," *Solar Energy*, **73**(6): pp. 443-467, 2002.
23. Gueymard, C.A., "Interdisciplinary applications of a versatile spectral solar irradiance model: a review." *Energy*, (in press), 2004.

24. Bodhaine B.A. et al. ."On Rayleigh optical depth calculations". *Journal of Atmospehirc and Ocean. Technology,* **16**, 1854-1861, 1999
25. Bucholtz A. ,"Rayleigh-scattering calculations for the terrestrial atmosphere." *Applied. Optics.* **34**, 2765-2773, 1995
26. Daumont, D., et al, "Ozone UV spectroscopy I: Absorption cross sections at room temperature," *Journal of Atmospheric Chemistry*, **15**: pp. 145-155, 1992.
27. Bogumil, K., J. Orphal, J.P. Burrows, "Measurements of molecular absorption spectra with the SIAMACHY pre-flight model: Instrument characterization and reference data for atmospheric remote-sensing in the 230 -2380 nm region," *Journal of Photochemistry and Photobiology*, **157A**: pp. 167-184, 2003.
28. Burrows, J.P., et al., "The global ozone monitoring experiment (GOME):Mission concept and first scientific results," *Journal of the Atmospheric Sciences*, **56**(2): pp. 151-175, 1999.
29. Anderson, S.M., "Ozone absorption cross section measurements in the Wulf bands," *Geophysical Research Letters*, **20**: pp. 1579-1582, 1993.
30. Koschmieder, H., "Theorie der Horizontalen Sichtweite," *Beiträge zur Physik der Freien Atmosphäre*, **12**: pp. 33-53, 1924.
31. Anderson, G.P., et al., "AFGL atmospheric constituent profiles (1-120 km)," AFGL-TR-86-0110. Air Force Geophysical Laboratory, Hanscomb AFB, 1986.
32. Pierluissi, J. H., C. M. Tsai, "New LOWTRAN models for the uniformly mixed gases." *Applied Optics*, 1987. **26**: p. 616-618.
33. ASTM, "Standard tables for reference solar spectral irradiance at air mass 1.5: Direct normal and hemispherical for a 37° tilted surface," *Standard G173-03,* American Society for Testing and Materials, West Conshohocken, 2003.
34. IEC, "Photovoltaic devices—measurement principles for terrestrial photovoltaic (PV) devices with reference spectral irradiance data," *International Standard 6904-3b*. 30 pp., International Electrotechnical Commission, Geneva, 1989.
35. ASTM, "Standard test methods for electrical performance of nonconcentrator terrestrial photovoltaic modules and arrays using reference cells," Standard E1036.American Society for Testing and Materials, West Conshohocken, PA: 1989.
36. Myers, D., K. Emery, C. Gueymard, "Revising and validating spectral irradiance reference standards for photovoltaic performance evaluation," *American Society of Mechanical Engineers Journal of Solar Energy Engineering,* **126**: pp. 567-574, 2004.
37. Myers, D.R., et al., "Outdoor meteorological broadband and spectral conditions for evaluating photovoltaic modules." *28th Photovoltaic Specialists Conference, Anchorage AK,* Institute of Electrical and Electronic Engineers, Piscataway, 1997.
38. Whitaker, C.M., et al., "Application and validation of a new PV performance characterization method," *26th Photovoltaic Specialists Conference, Anaheim CA,* Institute of Electrical and Electronic Engineers, Piscataway, 1997.
39. McMahon, W.E., S. Kurtz, K. Emery, M.S. Young, "Criteria for the design of GaInP/GaAs/Ge triple-junction cells to optimize their performance outdoors., ." *29th Photovoltaic Specialists Conference, New Orleans, LA,* Institute of Electrical and Electronics Engineers, Piscataway, 2002.