CPV-6 Conf., Freiburg, Germany, April 2010

Spectral Circumsolar Radiation Contribution To CPV

Christian A. Gueymard

Solar Consulting Services, P.O. Box 392, Colebrook, NH 03576, USA
Chris@SolarConsultingServices.com

Abstract: The prediction of the circumsolar augmentation of the direct normal irradiance incident on a CPV collector is difficult because it depends on many factors, such as solar position (air mass), atmospheric conditions, wavelength, and collector's opening angle. A general assessment of the circumsolar effect is described in this study, based on recently introduced instrumentation to measure the aureole's radiance, and appropriate radiative transfer modeling. Results of parametric simulations obtained with the SMARTS radiative code using variable air mass, aerosol conditions, and concentrator geometries are presented.

Keywords: Solar irradiance, circumsolar, SMARTS, aerosols, CPV, concentration, photovoltaics, radiative transfer, sunshape, sky radiance, atmospheric turbidity
PACS: 42, 44, 84, 88, 92.60.Vb, 92.60.Mt

INTRODUCTION

The performance of concentrating PV (CPV) collectors depends on the intensity and spectral quality of the resource in direct normal irradiance (DNI). However, depending on the opening angle of the collector, some circumsolar radiation emanating from the sun's aureole can be captured. This effect is generally small for systems with high concentration ratios (and thus small opening angles), referred to as HCPV, but can become substantial under specific atmospheric conditions, such as haze or thin clouds, or under all atmospheric conditions for systems with low concentration ratios (LCPV) and large opening angles.

Furthermore, the reported DNI measurements made with pyrheliometers include some circumsolar contribution, so that they may overestimate the actual irradiance incident on HCPV systems and underestimate it for LCPV systems. In addition, most radiation models that are used to predict DNI in practice do *not* consider the circumsolar contribution at all, and therefore tend to underestimate the resource of any CPV system. (A notable exception is the REST2 model [1], but a fixed cone of 3° half-angle is assumed to simulate a pyrheliometer, which may or may not be appropriate.)

Improved characterization of the "sunshape", or radiance distribution, within 10° or more from the sun center may provide better incident irradiance predictions and important information for the optimization of concentrator optics and receiver geometry. Radiance measurements in the solar aureole with specialized instrumentation, and radiative transfer predictions with an appropriate radiative code, are both desirable. This contribution focuses on the synergy of these two approaches, with a goal to obtain fast predictions of either spectral or broadband circumsolar irradiances.

CIRCUMSOLAR RADIATION MEASUREMENT

Direct measurement of the circumsolar radiance is difficult because of its steep decrease (by several orders of magnitude) that occurs between the sun's center and the outer limit of the concentrator's field of view. A special telescope that had been built almost four decades ago to overcome this difficulty and address the needs of the concentrating solar community of the time has collected a lot of data at eleven locations in the USA during the period 1976-81. This historic dataset (known as the Lawrence Berkeley Laboratory Reduced Data Base, or LBL RDB) is still available (http://rredc.nrel.gov/solar/old_data/circumsolar/), and provides useful radiance data from the sun center to a limit of 3° off center. Nevertheless, it cannot be easily used to derive a general model because the simultaneous atmospheric conditions were not recorded in sufficient detail. Still, simple empirical relationships obtained from the aggregated data have been proposed [2-4]. Other experimental setups, using CCD cameras have been built in Switzerland [5] and Germany [6], and have provided data comparable to the LBL RDB, although they did not provide spectral information, since these studies were made for concentrating solar power applications using thermal—rather than PV—electricity conversion methods. These studies introduced the term "sunshape" to describe the profile of sun and sky radiance within the aureole. The sunshape profile affects the Gaussian distribution of solar flux in the focal plane of a concentrator. This, in turn, has to be known precisely to limit non-homogeneities in the flux's spatial distribution, and to optimize the design of the photovoltaic receiver.

With the current renewed interest in electricity generation from concentrating solar power plants throughout the world, it appears important to rebuild some experimental capabilities to monitor the sunshape and its variations over time, particularly in specific regions of the world where the interest for CPV is high, but whose climate might not be ideal. A recently introduced commercial instrument, Visidyne's SAM (Sun and Aureole Measurements), appears to provide most of what is needed in sunshape studies, even though it was actually designed for completely different applications (in atmospheric sciences, see [7]). A complete SAM setup includes a weatherproof collimated silicon sensor with a narrow-band filter centered at 670 nm, an automatic sun tracker, a solar disk imager, an aureolograph, and a spectrometer. The sun radiance is measured from the sun center to 0.25°, whereas the sky radiance is measured between 0.6 and 8° from the sun center. Examples of radiance distributions for very clear sky, hazy sky, and cloudy sky conditions are presented in Figs. 1 and 2. Although the circumsolar radiance increases whenever the sun is obscured by thin clouds (e.g., cirrus), it only recoups a part of the concomitant loss in DNI from the sun itself. Such conditions are therefore not ideal to maximize the energy output of a CPV system.

Although SAM currently makes radiance measurements at a single wavelength only, expanding its spectral range is technically feasible, using additional measurements, radiative transfer calculations, or both.

CIRCUMSOLAR RADIATION MODELING

Under clear-sky conditions, a predictive tool of choice is the SMARTS radiative transfer code [8]. It has been used to derive reference spectra for solar energy standards [9, 10], and offers the CPV community practical tools to evaluate spectral effects (e.g., [11-13]). It can rapidly provide the spectral (280–4000 nm) and broadband DNI, as well as a lot of related radiative information, when clear-sky atmospheric conditions are known. Additionally, SMARTS can predict the spectral and broadband circumsolar irradiance (CSI) within a cone of up to 10° half-angle around the sun center. For a point-focus concentrator, this 10° limit corresponds to a concentration ratio of 33.2.

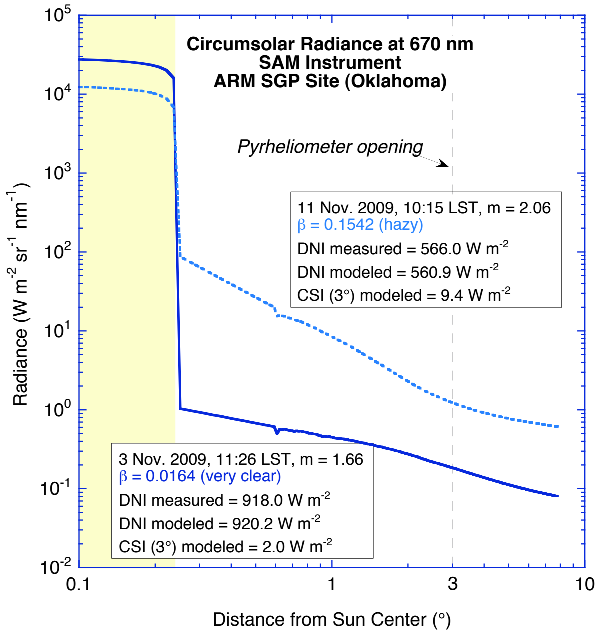

FIGURE 1. Circumsolar radiance up to 8° from the sun's center, as measured by the SAM instrument under very clear conditions (thick line) and hazier conditions (dotted line). Measured DNI values, and modeled DNI and CSI results obtained with SMARTS are indicated. The gap in radiance between 0.25° and 0.6° (due to a switch between two detectors) is filled by extrapolation. The sun's edge is at 0.25°.

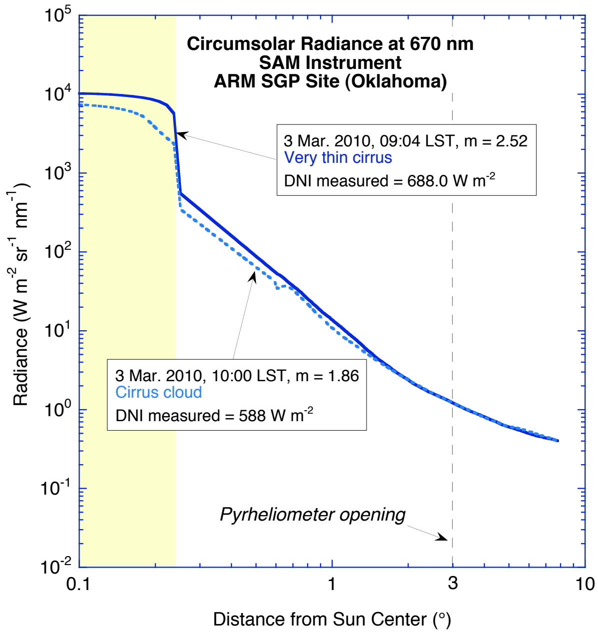

FIGURE 2. Same as Fig. 1, but for two cases of light cloud (cirrus) obscuring the sun.

The current version (2.9.5) of SMARTS does not output the radiance distribution in the aureole, although it is calculated internally and integrated spatially to derive CSI at wavelength λ through

$$E_c(\xi_0,\lambda) = 2\pi \int_{\xi_s}^{\xi_0} N_c(\xi,\lambda) \sin\xi d\xi \quad (1)$$

where $E_c(\xi_0, \lambda)$ is the circumsolar irradiance of diffuse origin emanating from the solar aureole from $\xi_S = 0.25°$ up to a half-angle ξ_0, ξ is the scattering angle, and $N_c(\xi, \lambda)$ is the spectral sky radiance at an angle ξ from the sun center.

Since CSI is produced by scattering effects, which increase when wavelength decreases, it is normal that CSI be larger at shorter wavelengths, particularly below 500 nm. From Eq. (1), CSI is also a direct function of what affects the sky radiance, i.e., the air mass (AM; a pure function of the apparent solar zenith angle) and the scattering optical depth, which is mainly a function of the aerosol optical depth (AOD). AOD is often referred to as atmospheric turbidity. It varies rapidly over time and space, and therefore needs to be either measured or modeled for precise predictions of CSI (and of DNI, if it is not measured locally and must therefore be modeled). Currently, the best possible determinations of AOD are through automated ground measurements using a multiwavelength sunphotometer. Since such measurements are not carried out at all potential CPV sites, an alternate (but less accurate) method is to use clear-sky measurements of both DNI and precipitable water to derive AOD [14].

AOD is a spectrally varying function, often denoted $\tau_a(\lambda)$. It is usually defined at 500 nm (as in the standards that specify the reference AM1.5 DNI spectra; e.g., ASTM E891 and ASTM G173) or at 1 µm (Ångström's turbidity coefficient β). High AOD (hazy) conditions are frequent in various regions of the world, particularly in South America, Africa and Asia, due to smoke clouds from biomass burning, dust clouds from sand storms, or various particles from anthropogenic sources (pollution). Depending on the size distribution of these particles, the dependence of $\tau_a(\lambda)$ on λ may be more or less steep. This can be described by the Ångström wavelength exponent, α, such that, for λ in µm

$$\tau_a(\lambda) = \beta\, \lambda^{-\alpha}. \quad (2)$$

Typical rural (or continental) aerosols are characterized by α values usually in the range 1.1–1.5. A method to evaluate α and β from sunphotometric measurements is described elsewhere [15].

Results of SMARTS calculations with Eq. (1) appear in Fig. 3 for $\xi_0 = 2.9°$. They represent the error in DNI inherent to the use of typical pyrheliometers. These results can be used to evaluate how the measured DNI should be corrected to obtain the actual direct irradiance from the sun only. This correction remains low (≤1%) in the case of the very clear conditions of ASTM G173. These results can also be considered typical for point-focusing systems with concentration ratios of about 390.

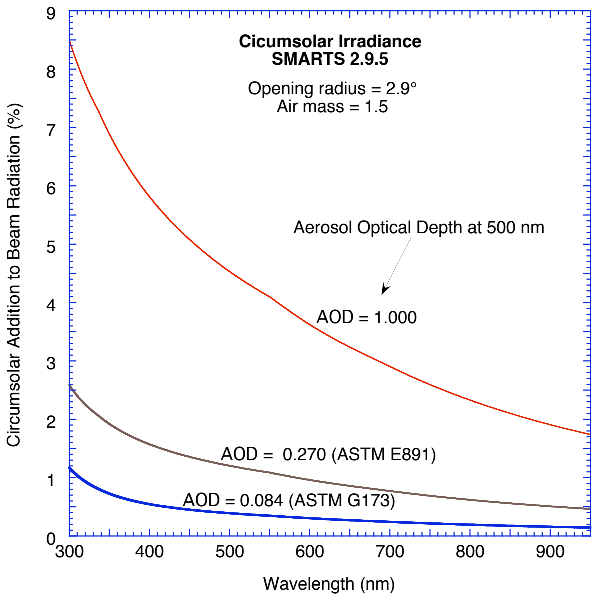

FIGURE 3. Circumsolar contribution (in percent of the theoretical DNI) for an opening of 2.9° and various AOD values. The two lower curves correspond to the atmospheric conditions of reference spectra, from ASTM E891 (1987) and ASTM G173 (2003). The upper curve corresponds to typical hazy conditions.

Similarly, Fig. 4 shows results that apply to opening angles of 1° and 6°, which correspond to concentration ratios of 3280 and 92, respectively, in the case of point-focusing systems. A fixed AOD of 1.0 at 500 nm is considered here to represent hazy conditions, whereas the air mass is varied from 1.5 to 5. It is clear that significant CSI contributions are obtained at short wavelengths, large opening angles and large AM.

The dependence of CSI on the opening angle is shown in Fig. 5 for various AM values (from 1 to 3) and two extreme turbidity cases: very clear conditions (β = 0.025; typical of the southwestern U.S., for instance) and hazy conditions (β = 0.45). It is found that CSI is roughly proportional to the opening angle, for any air mass or turbidity condition. Under hazy conditions, and for the AM values selected here, the incident DNI on HCPV systems may be up to ≈3% *less* than what is measured by a pyrheliometer with an opening angle of 2.9°. Similarly, LCPV systems with a 10° opening angle may get up to ≈12% *more* than the broadband DNI measured with a pyrheliometer.

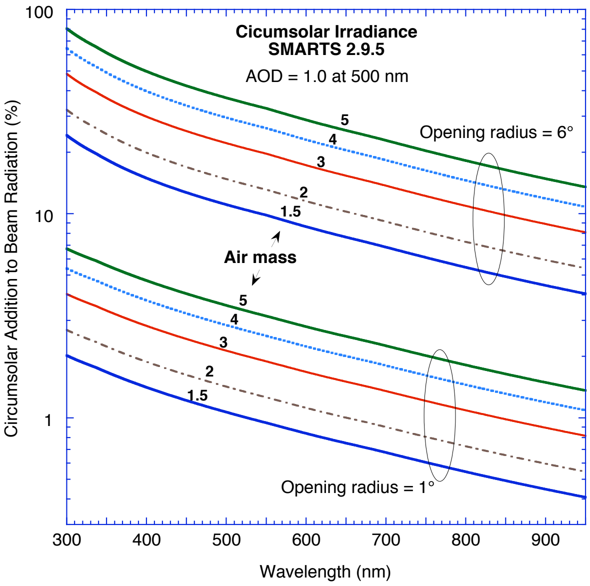

FIGURE 4. Circumsolar contribution (in percent of the theoretical DNI) for openings of 1° or 6°, variable air masses (1.5 to 5) and variable AOD at 500 nm.

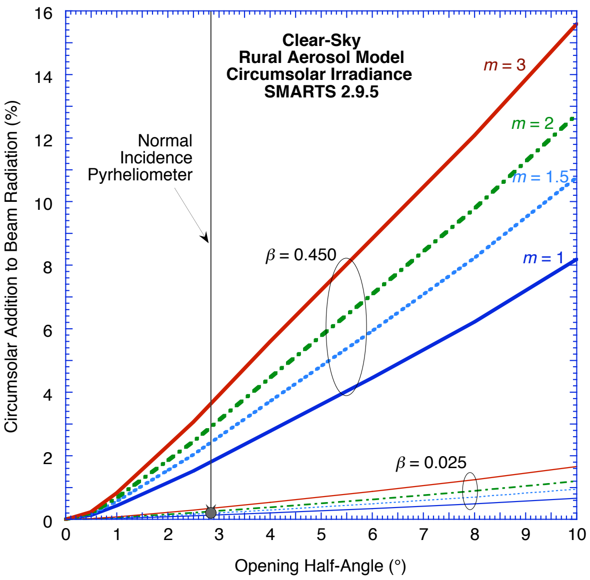

FIGURE 5. Circumsolar contribution (in percent of the theoretical DNI) for openings up to 10°, variable air masses (1 to 3), and *β* of 0.025 (very clear) and 0.450 (very hazy). The opening angle of a typical pyrheliometer is indicated by the vertical thin line. The dot at its bottom indicates the ASTM G173 conditions.

The SMARTS predictions of DNI have been validated against theoretical calculations and experimental measurements (see, e.g., [16]). So far, the corresponding CSI predictions have been only validated against theoretical calculations. Experimental validation is underway, based on SAM measurements in particular.

CONCLUSION

Commercially available instrumentation ("SAM") now exists to monitor the variation in radiance (or "sunshape") from the sun center to 8° at 670 nm. SMARTS, a radiative transfer tool frequently used to evaluate spectral effects on solar cells, can be used either to supplement SAM measurements whenever available, or to predict the clear-sky spectral and broadband direct and circumsolar irradiances when the atmospheric conditions are known. It is found that the broadband circumsolar contribution (up to 10° from the sun center) is roughly proportional to the concentrator's opening angle.

ACKNOWLEDGMENTS

The author thanks Dr. John DeVore for providing important information regarding the SAM instrument, and for kindly selecting some appropriate datasets that were measured with it.

REFERENCES

1. C. A. Gueymard, *Solar Energy* **82**, 272-285 (2008).
2. A. Rabl and P. Bendt, *J. Sol. Energ. Eng., T. ASME* **104**, 237-250 (1982).
3. D. Buie and A. G. Monger, *Solar Energy* **76**, 181-185 (2004).
4. D. Buie, A. G. Monger and C. J. Dey, *Solar Energy* **74**, 113-122 (2003).
5. M. Schubnell, *J. Sol. Energ-T. ASME* **114**, 260-266 (1992).
6. A. Neumann, A. Witzke, S. A. Jones and G. Schmitt, *J. Sol. Energ-T. ASME* **124**, 198-204 (2002).
7. J. G. DeVore, A.T. Stair, A. LePage, D. Rall, S.A. Rappaport, P.C. Joss, and R.A. McClatchey, *J. Atmos. Ocean. Technol.* **26**, 2531-2548 (2009).
8. C. A. Gueymard, *Solar Energy* **71**, 325-346 (2001).
9. C. A. Gueymard, D. Myers and K. Emery, *Solar Energy* **73**, 443-467 (2002).
10. D. R. Myers, K. Emery and C. A. Gueymard, *J. Sol. Energ-T. ASME* **126**, 567-574 (2004).
11. S. Kurtz, D. Myers, W. E. McMahon, J. Geisz and M. Steiner, *Prog. Photovoltaics* **16**, 537-546 (2008).
12. C. A. Gueymard, *Daily spectral effects on concentrating PV solar cells as affected by realistic aerosol optical depth and other atmospheric conditions.* Proc. Conf. Optical Modeling and Measurements for Solar Energy Systems II, SPIE Vol. 7410, San Diego, CA (2009).
13. S. P. Philipps, G. Peharz, R. Hoheisel, T. Hornung, N. M. Al-Abbadi, F. Dimroth and A. W. Bett, *Sol. Energ. Mat. Sol. C.* **94**, 869-877 (2010).
14. C. A. Gueymard, *J. Appl. Meteorol.* **37**, 414-435 (1998).
15. C. A. Gueymard and H. D. Kambezidis, "Solar spectral radiation" in *Solar Radiation and Daylight Models*, edited by T. Muneer, Elsevier (2004).
16. C. A. Gueymard, *Solar Energy* **82**, 260-271 (2008).