Solar Energy 139 (2016) 533–546

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Performance characteristics of a perforated shadow band in the presence of cloud

Michael J. Brooks [a,*], Theodor W. von Backström [b], E. Ernest van Dyk [c]

[a] Department of Mechanical Engineering, University of KwaZulu-Natal, Durban 4041, South Africa
[b] Department of Mechanical and Mechatronic Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[c] Department of Physics, Nelson Mandela Metropolitan University, PO Box 77000, Port Elizabeth 6031, South Africa

ARTICLE INFO

Article history:
Received 11 April 2016
Received in revised form 7 October 2016
Accepted 14 October 2016
Available online 27 October 2016

Keywords:
Perforated shadow band
Diffuse irradiance
Global irradiance
Cloudy conditions
Missing data

ABSTRACT

The perforated shadow band enables the decomposition of global horizontal solar irradiance (GHI) so as to obtain diffuse horizontal and direct normal irradiance components (DHI and DNI). As a single-pyranometer system, it offers a low-cost alternative to dual-sensor radiometric schemes, but a comprehensive performance analysis has only been conducted under clear sky conditions. This study addresses perforated band (PB) behavior in the presence of cloud when the resulting radiometric trace exhibits stochasticity and a sensor exposure model is required to separate resulting fragmented GHI and DHI components prior to reconstitution as continuous time-series. Various interpolation techniques are tested for replacing patches of missing data caused by the band's operation with the aim of minimizing root mean square difference (RMSD) relative to reference data. Given the effect of cloud on performance, uncertainties are reported as a function of daily clearness index, rather than as constants. For GHI, the RMSD uncertainties range between 6% for high clearness indices and around 36% for values between 0.3 and 0.4. Bias is typically negative, and the PB system underestimates GHI by between 1% (clearer skies) and 7% (partly cloudy skies). It is found that deploying interpolation schemes adaptively in response to the prevailing clearness index effectively reconstitutes fragmented GHI curves when cloud is present, while decomposition models assist in replacing missing DHI data under heavily cloudy and overcast conditions. Root mean square differences of around 20% can be expected for DHI measurements with mean bias varying between −5% for overcast conditions and +8% for clearer skies. The DNI results are obtained by calculation from DHI and GHI values, with RMSD peaking at about 200 W/m^2 in the mid-clearness index range, reducing to 30 W/m^2 under mainly overcast conditions and to 90 W/m^2 for high clearness index values. The results of the study also offer insight to the more general problem of replacing missing data in radiometric time series.

1. Introduction

Advances in solar energy engineering and environmental science are driving the need for resource measurements of greater spatial coverage and higher temporal resolution, but obtaining ground-based solar data can be difficult (Vignola et al., 2012; Stoffel et al., 2010). Ideally, ground-stations should utilize optimal measurement schemes (Gueymard and Myers, 2009) in which GHI, DHI and DNI are determined independently with secondary standard thermopile sensors that ensure low measurement uncertainty. Optimal schemes are expensive, however, and instrumentation costs often limit sensor deployment such that new schemes and instruments are continually under development. In some cases these are less expensive but their measurement uncertainties are higher, resulting in 'sub-optimal' solutions that may employ a single radiometer to measure two components of sun strength, from which the third can be calculated. Examples include the SPN1 pyranometer, the Rotating Shadowband Radiometer whose performance was reported by Wilcox and Myers (2008), and the perforated shadow band system.

The PB system represents a low-cost method of measuring GHI and DHI using a single thermopile pyranometer. The band is mounted on a conventional solid shadow band stand and is not automated, therefore it requires manual adjustment for changes in declination angle at regular intervals of one or two days. Apart from this, the reliability of the system is determined by the reliability of the pyranometer used in conjunction with it. Under clear

* Corresponding author.
E-mail addresses: brooks@ukzn.ac.za (M.J. Brooks), twvb@sun.ac.za (T.W. von Backström), ernest.vandyk@nmmu.ac.za (E.E. van Dyk).

http://dx.doi.org/10.1016/j.solener.2016.10.019
0038-092X/

skies, the sensor of the pyranometer is intermittently shaded by a band containing perforations (Fig. 1). The band's mechanical structure, the effect of varying the aperture geometry and the shading mask generated under clear skies were discussed by Brooks (2015). A cost comparison of selected radiometric schemes, including the PB setup, was also given. Shading of the pyranometer occurs naturally as the sun traverses the sky with no movement of the band required other than normal adjustment for changes in declination angle every few days. The resulting sensor output trace comprises alternating fragments of global (exposed) and diffuse (occluded) irradiance that must be separated and reconstituted as continuous, independent time-series. These can be combined to yield direct normal irradiance by calculation. Performance of the PB system was characterized under cloud-free conditions by Brooks (2010), using manual filtering and curve-fitting procedures to reconstitute the GHI and DHI curves. The system produced GHI, DHI and DNI measurements with root mean square differences of 2.7%, 13.6% and 2.0% respectively. Mean bias differences were 0.1% for GHI, 7.9% for DHI and −0.3% for DNI.

This work describes the performance of the PB system under all sky conditions, including partly cloudy and overcast conditions. In the presence of cloud, the PB time series exhibits varying degrees of stochasticity that preclude the manual filtering approach used for clear skies and instead an exposure model is employed to disaggregate the composite trace. A unique feature of the PB system is its creation of data gaps that must be filled to reconstitute the GHI and DHI time-series. In this study, a number of interpolation techniques are compared, including an adaptive approach that responds to the prevailing clearness index to reduce uncertainty. The performance of the system is described by comparison

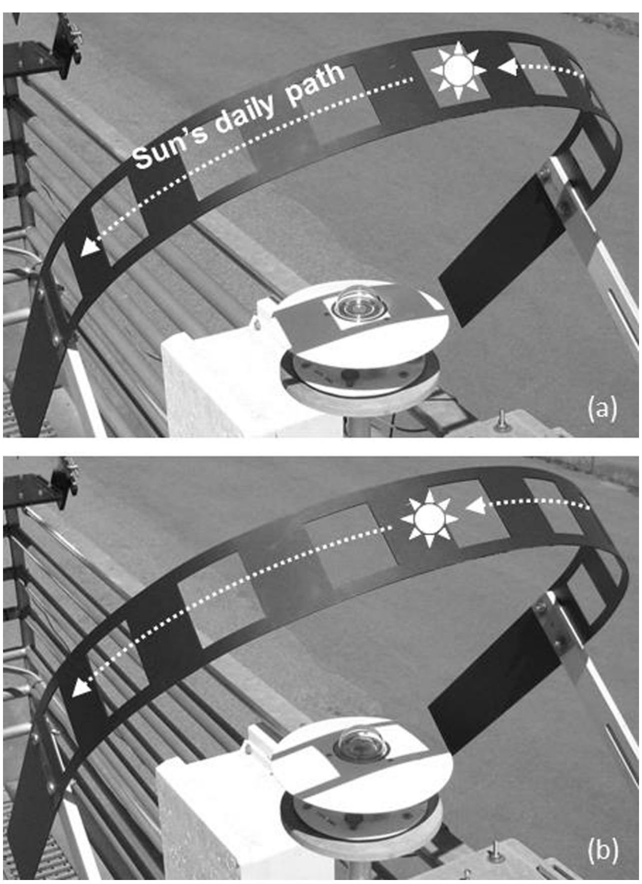

Fig. 1. (a) Exposure of a pyranometer sensor by a perforated shadow band followed by (b) occlusion, under clear sky conditions (Brooks, 2015).

between the PB output irradiance and measurements from collocated reference instruments at 1-min resolution.

2. Sensor output in the presence of cloud

In partly cloudy conditions, the pyranometer under a perforated band experiences varying degrees of shading from the direct normal component of sunlight as clouds obscure the solar disc. Unlike most radiometric schemes, the uncertainty with which a PB system measures irradiance varies with the prevailing cloud field, such that its performance must be correlated with one or more parameters that quantify clearness. A preliminary study by Brooks and Roberts (2010) reported the performance of the PB system as a function of the clearness index, that is the ratio of the measured flux at the planet's surface (E_g) to that component's value at top of atmosphere (E_o) (Myers, 2013):

$$k_T = E_g/E_o \tag{1}$$

Clearness index characterizes relative sun strength when only the global irradiance is known (Perez et al., 1990) and can be defined over a range of time periods, for example daily or hourly. In the case of the perforated band, a patch-wise clearness index, k_{T_patch}, can also be determined using GHI values applicable during exposure of the pyranometer through the band apertures. In this study, overall PB performance is correlated with the daily clearness index, K_{T_day}, calculated with day-averaged values of E_g and E_o, because the parameter is a widely available measure of the atmosphere's transmission efficiency and hence, indirectly, of cloud presence. It can be obtained from ground-based data, satellite imagery and maps such as that provided by Diabate et al. (2004). By linking the band's performance to K_{T_day} it is therefore possible to assess those regions where the perforated system might generate measurements of GHI, DHI and DNI with uncertainties that are acceptable to station operators.

Cloud fields increase stochasticity in the PB output trace and thus reduce the effectiveness of interpolation methods used to fill data gaps in the fragmented GHI and DHI time-series. The frequency and degree of sensor occlusion vary considerably, yielding a range of trace morphologies from near-clear sky curves with minimal disruption for high-K_{T_Day} values (Fig. 2(a)) to stochastic structures in which the DNI is attenuated for all or part of the day (Fig. 2(b) and (c)). Under cloud-free conditions, the clear sky PB trace is strongly coherent and cycles unambiguously between the global and diffuse reference data. Transition data resulting from a partially exposed sensor connect the upper and lower curves. Trace coherency breaks down in the presence of cloud, and under overcast conditions the global and diffuse components are approximately equal.

Separation of the fragmented GHI and DHI curves from the composite PB trace can be done visually, but only in the absence of cloud. For stochastic time-series of the type shown in Fig. 2 (b) and (c), this study employs a model of pyranometer exposure to predict sensor exposure based on a ray-tracing analysis of the sun-band-sensor interaction (Brooks, 2010). The ray trace model is defined as a function of the prevailing hour angle, ω, and identifies the pyranometer state as either exposed (for GHI), occluded (for DHI) or transitory when the sensor is partially exposed.

3. Methodology

The perforated band system was tested at NREL's Solar Radiation Research Laboratory (SRRL) in Golden, Colorado (39.74°N 105.18°W, 1829 m AMSL) from March 2008 to December 2012. Data were provided through the NREL Baseline Measurement