ARTICLE IN PRESS

Solar Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Solar Energy

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

Measuring diffuse, direct, and global irradiance using a sky imager

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ARTICLE INFO

Article history:
Received 10 January 2016
Received in revised form 17 November 2016
Accepted 20 November 2016
Available online xxxx

Keywords:
Irradiance
Whole sky imager
CCD smear
DNI

ABSTRACT

Sky imaging systems are commonly used for aerosol characterization, cloud detection, and solar forecasting. We present an algorithm for measuring full-sky radiance with a range that exceeds the normal dynamic range of the camera system in question. Extended dynamic range over most of the sky is achieved with multiple exposures and High Dynamic Range (HDR) imaging, while solar beam intensity is estimated using CCD smear. Smear measurements are calibrated to match reference GHI based on pixel position on the sensor, and resulting irradiance measurements are validated. Global horizontal irradiance RMSE (root-mean-square error) for a year-long data set is in the 9–11% range for per-image data and 6–9% for hourly-averaged data when compared against a solid-state pyranometer. In addition, Direct Normal Irradiance (DNI) measurements for clear skies during a five-month period are compared to a non-co-located SPN1 DNI sensor, with RMSE of 8%.

1. Introduction

Global horizontal irradiance (GHI) and direct normal irradiance (DNI) are two essential parameters in solar resource assessment. GHI is the standard measure of total available solar radiation, and is typically measured using a thermopile or photodiode pyranometer. DNI is the intensity of the direct solar beam and is the portion of the solar resource used by concentrating solar technologies; it is also important for calculating total irradiance on a tilted plane. DNI measurement is typically accomplished using a pyrheliometer on a solar tracker. Radiation coming from the rest of the sky, diffuse horizontal irradiance or DHI, can be measured by shading a pyranometer with a shade ball mounted on a solar tracker (Sengupta et al., 2015). Measurements of GHI, DNI, and DHI made with high-quality, well-maintained instruments have 95% confidence intervals around ±2% for DNI and from ±3% to ±10% for GHI, depending on the solar zenith angle (Sengupta et al., 2015). Researchers at the National Renewable Energy Laboratory (NREL) find that compared to standard-class reference measurements of GHI, thermopile pyranometers have 1-h RMSE between 1.5% and 5% depending on the configuration (ventilation, thermal corrections, etc), while silicon-based pyranometers such as the LI-200 have 1-h RMSE of 3.5% (Habte et al., 2014). Accuracy of silicon-based sensors can be improved by correcting for their angular and spectral response. For precise angular measurements, scanning radiometers or spectroradiometers have narrow fields of view and can be positioned at will to sample radiance from various parts of the sky.

Alternative techniques intended to have lower upfront and maintenance costs are often proposed. Rotating Shadowband Irradiometers (RSIs) are devices that have a single pyranometer and a rotating shadowband to measure both GHI and DHI from which DNI can be computed. Typical 95% confidence intervals for the resulting DNI measurement are around ±5% (Sengupta et al., 2015). However, the single axis of rotation and the typical use of a diffuser rather than an optical dome mean that RSIs are much less sensitive to maintenance schedules (Sengupta et al., 2015). Another approach, taken by the SPN1 sunshine pyranometer, involves measurements using seven miniature thermopiles underneath a complex shading dome. The shading dome is constructed so that for any sun position, at least one sensor is fully shaded and at least one is fully exposed, so that in principle direct and diffuse components of the irradiance can be calculated. This eliminates moving parts, but has been found to result in a systematic positive bias in DNI measurements of 1.1–4.1% with 1-min RMSE of 8–14% even after advanced calibration as reported in Badosa et al. (2014). An NREL study found that the SPN1 had reasonable MBE (mean bias error) and RMSE (of 3% and 5%, respectively) on 1-h GHI, but larger errors (MBE 7.2% and RMSE 9.5%) on 1-h DNI (Habte et al., 2014).

There is a long history of using cameras to measure the brightness pattern of the sky. They have an advantage in angular resolution over hemispherical sensors, and an advantage in speed over scanning radiometers. As early as 1970, film cameras (Deepak and Adams, 1983) and later CCDs (Schubnell, 1992; Neumann

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http://dx.doi.org/10.1016/j.solener.2016.11.032
0038-092X/

et al., 2002) were used to measure the sunshapes–the normalized azimuthal average profile of broadband radiance about the sun. Techniques generally involve imaging the sun through one or more dark filters to bring it in range of the camera, and researchers were generally concerned only with relative brightness. However, Kaluza and Neumann detail the use of a CCD in concert with a flux gauge to produce absolute readings (Kaluza and Neumann, 1998). A modern commercial device called the Sun and Aureole Measurement system uses two cameras with different filter settings to image a larger region around the sun, and can be calibrated using a sun photometer to give absolute radiance as well (Wilbert et al., 2013). On the wide angle front, many researchers over the years have used fisheye lenses to measure the radiance distribution of the sky (Shields et al., 2013; Rossini and Krenzinger, 2007; Román et al., 2012; Yatsuzuka and Uetani, 2013; Tohsing et al., 2013), generally with absolute calibrations, but the direct beam is generally either blocked or saturated and therefore not measured, although Tohsing et al. estimated the direct beam at either its clear-sky value or 0 depending on whether the sun was obscured by clouds (Tohsing et al., 2013). Several of these researchers were interested in luminance distributions (weighted for the human visual spectrum) for daylighting applications rather than solar energy production, but the procedures are much the same.

More recently, as whole-sky cameras have become common tools for solar energy forecasting, a few groups have extracted image features (such as textures, colors, and cloud coverage (Schmidt et al., 2015) or cloud locations (Gauchet et al., 2012)) to build empirical models for GHI and DNI without trying to measure the exact spatial distribution of radiance.

We propose a system that allows the use of a camera system described by Urquhart et al. (2015) (the UCSD Sky Imager, or USI) to measure both DHI and DNI based on the photon fluxes incident on the image sensor. This physicality differentiates our method from those which rely on an image classification layer (Schmidt et al., 2015; Gauchet et al., 2012), while our ability to make a non-binary determination of DNI is an improvement over radiance-based methods (Tohsing et al., 2013). After introducing our data sources (Section 2), we proceed with a discussion (Section 3) of the methods used to measure and calibrate irradiance, with particular emphasis on the technique we have developed for measuring DNI using CCD smear. We then compare these results against LI-200 GHI and SPN1 DNI measurements (Section 4) and show good qualitative and quantitative agreement. Finally, we conclude (Section 5) with some ideas for improvement and additional applications.

2. Data

USI images for this study were captured every 30 s during daylight hours beginning on August 18, 2014 and ending on August 17, 2015. Data points corresponding to sun positions less than 20 pixels (2.5°) above the obstructions on the horizon were omitted in order to ensure that both the reference sensor and the USI were unaffected by said obstructions.

The reference GHI sensor, used for both calibrations and validation, is a LI-COR LI-200 silicon pyranometer located approximately 10 m from the camera. Reference data points are 3-s averages of 20 Hz samples centered at the time of the image. The data logger was intermittently overloaded with data acquisition instructions, and occasionally dropped up to a few minutes worth of data. Additionally, there were a few periods of longer downtime. In total, 15% of 3-s average data points at times corresponding to camera images were missing from the data set.

In April 2015, a Delta-T SPN1 sunshine pyranometer was added on a rooftop 1.25 km from the camera in order to be able to compare DNI and DHI as well. The SPN1 uses seven miniature thermopiles and a complex shading mask to measure both GHI and DHI, from which it calculates DNI. Data is sampled at 1 Hz. However, these validation data presented issues due to the spatial displacement. Purely random differences in high resolution data due to spatial displacement could be reduced by temporal averaging, but in this coastal climate (1 km from the ocean) systematic differences in cloud cover exist with a bias towards more cloudy conditions near the ocean. While these clouds are typically thin and do not significantly affect GHI, DNI differences can be large. Since occasionally different cloud conditions persist for several hours these data are therefore suitable for quantitative comparisons only during time periods that are cloud-free. While differences in aerosol loading between the two sites could also change the partition from GHI to DNI, the strong sea breeze flow typically causes air masses of oceanic origin to exist at both sites.

3. Methods

We will decompose GHI into three separate components to be extracted from each set of images.

$$GHI = DHI_{raw} + DNI \cdot \sin(\alpha) - DHI_{stray}, \quad (1)$$

where α is the solar elevation above the horizon. The raw measurement of DHI will be derived from most of the pixels in the 16-bit high dynamic range (HDR) image captured by the camera described in Urquhart et al. (2015). Three images with adjacent exposure times varying by a factor of 4 are combined by averaging pixel readings exposed in the linear range of the detector. Unfortunately, without a filter changer, the camera does not have enough dynamic range to capture the intensities in the solar region directly–the sun is at least 15 times as bright as the brightest object the camera can record at its shortest exposure time. Therefore, pixels near the sun are always saturated when the sun is unobscured. DNI will be measured instead by measuring the intensity of CCD smear that results from the presence of very bright light sources such as the sun. As smear occurs during readout, it is expected to be independent of exposure time. This can lead to complications in the HDR compositing process which expects pixel values to scale with exposure time. For this reason, a single exposure at the camera's shortest exposure time (75 μs) is used for smear measurement. The short exposure time enhances the brightness of smear relative to the rest of the image. Finally, DHI is corrected downward to account for stray light that is scattered off the camera optics when they are illuminated by direct sunlight. Note that the stray light correction does not have to be added back to the DNI measurement since the DNI method utilizes a scaling factor that is also expected to correct for stray light losses to the DNI signal.

Although insufficient to measure the direct solar beam, the dynamic range of the camera is generally sufficient to capture the remainder of the sky scene with a fixed set of exposures under all sky conditions. This simplifies the conversion from pixel values to radiance. Capture time for the sequence of four images (three for HDR plus a minimal-time exposure) is approximately 830 ms, of which roughly 200 ms is delay between frames.

All three components of Eq. (1) require calibration in order to provide values in meaningful physical units. While optical setups could be calibrated in the lab, small changes in focus and alignment can lead to nontrivial changes in calibration factors; our objective is therefore to present an algorithm that can be self-calibrated using field measurements.

Please cite this article in press as: Kurtz, B., Kleissl, J. Measuring diffuse, direct, and global irradiance using a sky imager. Sol. Energy (2016), http://dx.doi.org/10.1016/j.solener.2016.11.032