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Modelling the clear-sky intensity distribution using a sky imager

Rémi Chauvin [a], Julien Nou [a], Stéphane Thil [a,b], Stéphane Grieu [a,b,*]

[a] PROMES-CNRS (UPR 8521), Rambla de la thermodynamique, Tecnosud, 66100 Perpignan, France
[b] Université de Perpignan Via Domitia, 52 Avenue Paul Alduy, 66860 Perpignan, France

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Abstract

This paper introduces a new empirical formulation of the clear-sky intensity distribution based on images acquired with a sky imager developed at the PROMES-CNRS laboratory (Perpignan, France). Both the formulation and image processing methodology are detailed and stand for key steps in the development of a high quality cloud detection algorithm. The work presented in this paper is a part of a research project which aims at improving solar plant control procedures using direct normal irradiance forecasts under various sky conditions at short-term horizon (5–30 min) and high spatial resolution ($\sim$1 km^2). Modelling the clear-sky intensity distribution in real time allows clear-sky images to be generated. These clear-sky images can then be used to remove the clear-sky background anisotropy on images and so improve cloud detection algorithms significantly. Cloud detection is essential in short-term solar resource forecasting. The new formulation is especially designed for improving performance of the existing models in the circumsolar area. When tested over more than 2200 clear-sky images, corresponding to a solar zenith angle spanning from 24° to 85°, the new formulation outperforms a standard approach based on the All-Weather model (Perez et al., 1993) by 15% on the whole sky and more than 20% in the circumsolar area. Application of the methodology for the real-time cloud detection purpose is discussed at the end of the paper.

Keywords: Sky-imaging system; Clear-sky intensity distribution; Circumsolar radiation; Cloud detection

1. Introduction

It is widely acknowledged by solar companies and plant operators that cost remains the main drawback of Concentrating Solar Power (CSP) systems. In that context, the project CSPIMP (Concentrated Solar Power efficiency IMProvement) has been initiated in 2013 in order to make CSP plants more competitive. Among the different challenges pointed out by this research project, the solar resource assessment and forecasting are essential tasks since they would allow a better real-time management of the solar field, and thus reduce the maintenance activities, while improving the expected benefits. As a consequence, a sophisticated solar resource forecasting model is under development at PROMES-CNRS in order to deal with the plant's behaviour against solar variability. This model will take advantage of a sky-imaging system allowing the cloud cover and the cloud motion to be measured at high spatial and high temporal resolution. Regarding the cloud cover estimation, classical thresholding techniques are widely used due to their simplicity and their ability to identify cloud pixels at low computational cost. However, such techniques suffer from the anisotropy of the clear-sky background. Indeed, with classical thresholding techniques, the circumsolar area and the Sun are systematically identified as clouds, whereas thin clouds are often identified as

* Corresponding author at: PROMES-CNRS (UPR 8521), Rambla de la thermodynamique, Tecnosud, 66100 Perpignan, France.
E-mail address: stephane.grieu@promes.cnrs.fr (S. Grieu).

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Nomenclature

PAA	Pixel/Azimuth or Point/Azimuth Angle (°)	E_p	irradiance reaching the CMOS sensor ($\mathrm{W\,m^{-2}}$)
PZA	Pixel/Zenith or Point/Zenith Angle (°)	I_p	pixel intensity in the sensor coordinate system
SAA	Sun/Azimuth Angle (°)	$I_p^\star$	pixel intensity in the (PZA,SPA) coord. system
SZA	Sun/Zenith Angle (°)	Ω_p	pixel solid angle (sr)
SPA	Sun/Pixel or Sun/Point Angle (°)	Ω_{cone}	solid angle of a cone (sr)
NRBR	Normalized Red/Blue Ratio	f	scattering function
L_p	luminance distribution ($\mathrm{cd\,m^{-2}}$)	b_i	coefficients of the scattering function
l_r	relative luminance distribution	ϕ	gradation function
$R_{p\lambda}$	spectral radiance distr. ($\mathrm{W\,m^{-2}\,nm^{-1}\,sr^{-1}}$)	a_i	coefficients of the gradation function
R_p	radiance distribution ($\mathrm{W\,m^{-2}\,sr^{-1}}$)	CS_p	generated clear-sky image
r_r	relative radiance distribution		

clear-sky pixels. Therefore, removing the clear-sky anisotropy from sky images would significantly improve the cloud detection algorithm. The present paper is dedicated to this issue.

First, a review of the existing sky radiance and luminance distribution models is presented (Section 2). Their potential use for our application is also discussed. The next section gives some details about the sky-imaging systems and focuses especially on both the experimental setup and the camera angular calibration (Section 3). Section 4 introduces the clear-sky intensity distribution function developed for our application. Section 5 is about results, remarks and discussion. The paper ends with a conclusion and an outlook to future work.

2. History and development of sky standards

This section provides extended information about the sky radiance and luminance distribution models developed up to now. First, a few applications of such distributions are given. Then, a review of radiative transfer models and empirical models is presented. Finally, the potential of measuring the distribution using a sky-imaging system is discussed.

2.1. Applications of sky radiance/luminance distribution

Sky radiance and luminance distributions have been studied for many years in architecture to improve buildings' design according to the daylight availability (Vartiainen, 2001; Reinhart and Walkenhorst, 2001; Lehar and Glicksman, 2007). Indeed, the knowledge of these distributions is an important input of ray-tracing models simulating the thermal and luminous indoor environment of buildings. Optimizing the windows' sizes and orientations, for instance, could potentially reduce the buildings energy consumption and has shown strong positive effects on human psyche (Heschong, 2002; van Bommel and van den Beld, 2004). Studies dealing with sky radiance distribution have been also carried out in the field of solar collectors in order to compute the incident energy on inclined surfaces and improve the design of CSP or photovoltaic systems (Siala and Hooper, 1990; Vartiainen, 2000). Finally, because the sky radiance mainly depends on the aerosols properties, measuring this radiance distribution can provide information about the atmospheric particles, like their size distribution, the scattering phase function or the single scattering albedo. As a result, inversion algorithms have been developed in order to retrieve some aerosol optical properties based on measurements or estimation of the sky radiance distribution (Dubovik and King, 2000; Olmo et al., 2008). For these reasons, monitoring and quantifying the daylight availability has become increasingly important during the last decades and have motivated the scientific community to search for a comprehensive and scalable model of the sky radiance/luminance distribution under various sky conditions.

2.2. Radiative transfer models

The sky radiance distribution can be obtained accurately using atmospheric radiative transfer models (Liang and Lewis, 1996; Kocifaj, 2009; Kocifaj, 2012; Kocifaj, 2015). These models are based on the total optical thickness of the atmosphere, the scattering ability of atmospheric layers and also the reflectance of underlying surface. In a plan-parallel atmosphere, the radiative transfer equation can be solved exactly and provides a physically well-founded spectral model of the sky radiance distribution. The sky luminance distribution L_p is then obtained as follows (Eq. (1)):

$$L_p = K_M \int_{380\ \mathrm{nm}}^{780\ \mathrm{nm}} R_{p\lambda} V(\lambda) \mathrm{d}\lambda \tag{1}$$

where $K_M = 683\ \mathrm{lm\,W^{-1}}$ is a conversion constant, $R_{p\lambda}$ is the spectral radiance distribution, and V is a luminous efficiency function corresponding to the daylight spectral response of the human eye. Although L_p can be computed as the integral product of $R_{p\lambda}$ and $V(\lambda)$, it has been experimentally observed that sky radiance and luminance