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Generating high dynamic range images using a sky imager

Rémi Chauvin * Julien Nou * Stéphane Thil *,** Stéphane Grieu *,**

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

Abstract: One way to optimize their operation of Concentrated Solar Power (CSP) plants is to obtain accurate short-term forecasts of Direct Normal Irradiance (DNI). To do so, the use of sky imagers is developing. They should provide high-quality images, especially in the circumsolar area, where pixels are usually saturated. To reduce the saturated area around the Sun, High Dynamic Range (HDR) imaging is needed. This paper describes the steps required to obtain HDR images from a sequence of low dynamic range images acquired using a sky imager. Since the HDR image will be used to study the sky radiance and the circumsolar area, a particular care is taken to maintain a linear sensor's response throughout the process.

Keywords: High dynamic range, sky imager, image processing, image sensors, image modelling, measurement noise.

1. INTRODUCTION

In a context of sustainable development, clean energy is strongly promoted in the European energy mix. Among the various solar energy technologies, Concentrating Solar Power (CSP) will play a key role in the future: its share of global electricity is envisioned to reach 11% in 2050 (IEA, 2014). The main drawback of CSP technologies is their costs, that drop slower than those of photovoltaics. Better competitiveness of CSP plants must thus be achieved.

To this end, one challenge is to forecast at very short-term (up to 30 min) the Direct Normal Irradiance (DNI), as it would help to optimize CSP plant operation and efficiently manage electricity generation according to the grid needs. DNI is the only component of solar irradiance that is truly intermittent, since it can vary from its maximum value to zero in seconds. Because DNI is affected by changeable factors, such as the position, optical depth and speed of clouds, it is extremely difficult to forecast accurately. This task cannot be achieved using satellite imagery or numerical weather predictions, due to their limited spatial and temporal resolutions (Chauvin, 2016). The use of sky imagers has thus been emerging in the last few years (see e.g. (Quesada-Ruiz et al., 2014; Bernecker et al., 2014; Chu et al., 2015; Chauvin et al., 2016)). However, to accurately apprehend the high variability of DNI, results obtained so far still need to be improved.

In particular, since the circumsolar area is of great interest for CSP systems, occulting devices masking the Sun are not used, which results in large saturated areas in the images. Indeed, the maximum dynamic range of the sky can be defined as:

$$\mathrm{DR}_{sky} = 20\log_{10}\left(\frac{L^{sun}}{L^{cloud}}\right) \tag{1}$$

where L^{sun} is the maximum radiance emitted by the Sun and L^{cloud} is the minimum radiance emitted by a thick cloud. Typical values are $L^{sun} \simeq 10^7\,\mathrm{W\,m^{-2}\,sr^{-1}}$ and $L^{cloud} \simeq 10\,\mathrm{W\,m^{-2}\,sr^{-1}}$. As a result, the dynamic range of the sky is $\mathrm{DR}_{sky} \simeq 120\,\mathrm{dB}$. Since the dynamic range of most camera sensors in the market is around 60 dB, they cannot give in one shot details both in the circumsolar area and in darker areas of the sky. Such images are thus called Low Dynamic Range (LDR) images. The large saturated areas on LDR images induce a loss of information in the circumsolar area, but also errors in cloud detection and cloud motion estimation when clouds are close to the Sun.

To reduce the saturated area on the images, the idea is to acquire several LDR images using different exposure times, then combine them to generate a high dynamic range (HDR) image. Fusion of LDR images has been studied a lot these last few years (Debevec and Malik, 1997; Mitsunaga and Nayar, 1999; Mertens et al., 2007; Granados et al., 2010; Hasinoff et al., 2010; Aguerrebere et al., 2014). The present work is influenced by techniques preserving a linear relationship between incident radiance received by the sensor and pixel value. Indeed, non linear approaches can make hard, or even impossible, estimation of sky's radiance, which is highly desirable in a context of CSP plant operation.

This paper describes the steps needed to obtain a high-quality HDR image when using a sky imager. In particular, since the HDR images will be used to study the sky radiance and the circumsolar area, a particular care is taken to maintain a linear sensor's response throughout the process. The paper is organized as follows: in Section 2 the sky imager used in this study is described. Section 3 depicts the necessary steps to obtain an HDR image from a sequence of LDR images; the main results of this work

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are presented in that Section. Since this work is made in a framework of real-time optimization of CSP plants' operation, there are computation time constraints. As a result, before concluding, the HDR algorithm's execution time is given in Section 4.

2. PROMES-CNRS SKY IMAGER (PSI)

2.1 Description of the system

A sky imaging system has been developed at PROMES-CNRS laboratory. It consists in a 4-megapixel color camera equipped with a fisheye lens and protected by a waterproof and thermoregulated enclosure (see Fig. 1). A maximum of 29 frames per second can be acquired, at a resolution of 2048×2048 pixels, with 10 bits per channel. The system is not equipped with a solar occulting device to reduce the light intensity reaching the sensor. Indeed, although this device improves the sky visibility by reducing pixel saturation, it occults the circumsolar area, which provides vital information about the very short-term solar irradiance fluctuations. To reduce the considerable amount of incident radiance on the CMOS sensor, a neutral density filter of transmittance T_f has been installed. Finally, since the final purpose is real-time forecasting of DNI, there is a constraint on computation time: image acquisition and all the processing must be performed in less than 20 s.

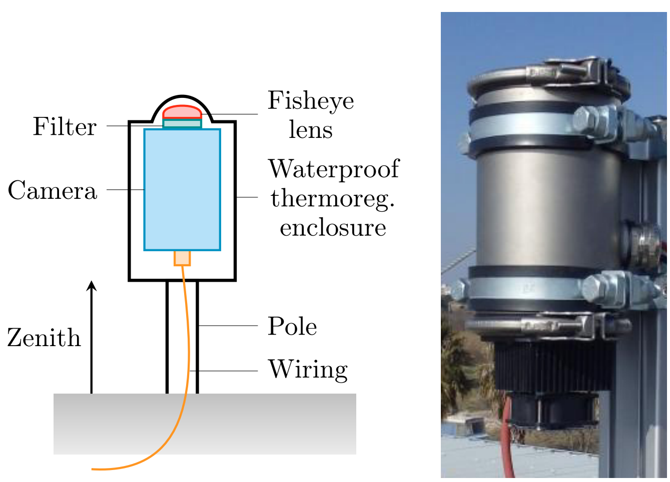

Fig. 1. Diagram and photograph of PROMES-CNRS Sky Imager (PSI).

2.2 Sensor's exposure

The exposure Q of a sensor can be defined as follows:

$$Q = \mathbb{t} \cdot I^{sensor} \tag{2}$$

where $\mathbb{t}$ is the exposure time and I^{sensor} the incident radiance received by the sensor. The incident radiance can be approximated as (Miyamoto, 1964):

$$I^{sensor} \simeq L \cdot T_f \cdot \left(\frac{n}{n'}\right)^2 \cdot \frac{\pi}{4} \cdot \frac{D^2}{\mathrm{d}S} \cdot \mathrm{d}\Omega \tag{3}$$

where L is the scene radiance, T_f is the filter transmittance, D is the diameter of the aperture, n and n' are the indices of refraction of object and image space, respectively, S is the surface of the sensor and Ω is the solid angle. Now, in order to limit disturbances due to diffraction (Airy disk, starburst effect), the PSI has a constant (maximal) aperture. As a result, I^{sensor} cannot be changed and reducing the exposure time $\mathbb{t}$ is the only way to attenuate the sensor's exposure (see equation (2)).

3. HDR IMAGE GENERATION

The steps for HDR image generation are:

(1) acquisition of a sequence of LDR images taken at different exposure times;
(2) suppression of under- and overexposed pixels in each LDR image;
(3) correction of remaining pixels' value so that it corresponds to a 'reference exposure';
(4) combination of corrected LDR images to obtain the HDR image.

Each of these steps is described in the sequel.

3.1 Acquisition of a sequence of LDR images

Here, two criteria have to be taken into account: (a) the number of images in the sequence and (b) the exposure time of each of those images.

Number of images in the sequence Since the maximum frame rate of PSI is 29 fps, it is possible to use as much as 29 LDR images to generate an HDR image. In this work, the number of LDR images has been set to 24, i.e. a total acquisition time around 0.8 s. The total acquisition time has to be short enough for the scene radiance to stay constant, i.e. for the clouds' motion between each LDR image to be negligible.

Exposure time of each LDR image First, it is necessary to define the minimum exposure time $\mathbb{t}_{\min}$ and maximum exposure time $\mathbb{t}_{\max}$, so that each pixel is correctly exposed on at least one of the LDR images, regardless of the weather condition. Since the Sun is saturated even with the camera's minimum exposure time, one can easily deduce that $\mathbb{t}_{\min}$ must be equal to this value: $\mathbb{t}_{\min} = 25.8\,\mu s$. The maximum exposure time must be defined so that each pixel is correctly exposed for the darkest overcast skies. Tests showed that this is the case for $\mathbb{t}_{\max} \simeq 15\,000\,\mu s$.

The theoretical dynamic range of the HDR image is thus:

$$\mathrm{DR}_H = \mathrm{DR}_L + 20\log_{10}\left(\frac{\mathbb{t}_{\max}}{\mathbb{t}_{\min}}\right) \simeq 60 + 55 = 115\,\mathrm{dB} \tag{4}$$

where DR_H et DR_L are the dynamic ranges of HDR and LDR images respectively. One can see that, in this configuration, DR_H is close to DR_{sky}.

In order to maintain a good overlap between two successive LDR images, and since the camera model is linear (cf. section 3.2) each intermediate exposure time should be chosen to be proportional to the previous one. However, generating an HDR image using 24 LDR images taken at 24 different exposure times is time-consuming (remember that an image is taken every 20 s). For this reason, it has been decided to use batches of LDR images taken at the same exposure time. That way, computation time is limited while preserving a high signal-to-noise ratio (due to the averaging in each batch). In the end, $N_{batch} = 6$