SYSTEM FOR MEASURING COMPONENTS OF SOLAR RADIATION

The present invention relates to the field of solar radiation and properties of the atmosphere.

The invention relates more particularly to a system for measuring solar radiation.

For some applications, it is necessary to know the different components of solar radiation. In particular, we want to know the following components:

- The direct component of solar radiation.

When the solar radiation which does not interact with the Earth's atmosphere during its passage and is measured under normal incidence, we speak of normal direct illumination or DNI (Direct Normal Irradiance). The DNI is expressed in Wm^{-2} .

A pyrheliometer is generally used to measure the DNI; this is in the form of a tube the dimensions of which define the opening angle, and at the bottom of which is placed a thermopile. The pyrheliometer must be aligned with the axis of the sun; this is why a solar tracker is necessary if one wishes to automate the acquisition of the DNI. The cost of a pyrheliometer is around 2.5 k€, while that of a solar tracker is close to 10 k€. In addition and to function optimally, this instrument must be maintained daily. Faced with these constraints of cost and maintenance, less expensive and more robust instruments have been developed. Among them, the instrument most used is the rotating band pyranometer (see below). However, the pyranometer has the disadvantage of requiring an accurate spectral calibration of the photodiode. This calibration is complex and produces a higher uncertainty on the DNI than for a pyrheliometer.

- The diffuse component of solar radiation.

When the solar radiation that interacted with the Earth's atmosphere during its passage is measured on a horizontal surface, we speak of Horizontal Diffuse Irradiance (DHI). The DHI is expressed in Wm^{-2}.

Most often and in order to measure DHI, a pyranometer and a solar tracker equipped with an element that masks the Sun are used together (thus allowing the suppression of the direct component of solar radiation). For example, a rotating band periodically obscures the photodiode in order to measure the DHI.

- Global solar radiation is defined as the sum of direct and indirect radiation received on the ground. If this radiation is measured horizontally, we speak of Global Horizontal Irradiance (GHI).

The GHI is expressed in Wm^{-2}.

A pyranometer is generally used to measure GHI, and includes a horizontally-mounted photodiode.

The DNI can be determined from measurements of GHI and DHI and knowledge of the position of the Sun.

In fact, GHI, DNI and DHI are linked by the following relationship:

$$GHI = \cos(SZA) \cdot DNI + DHI$$

where SZA is the angle between the Sun and the zenith.

In some cases, we also want to know the duration of sunshine.

The duration of sunshine of a geographic area refers to how long this geographical area is illuminated by the sun.

The World Meteorological Organization (WMO) defines the duration of sunshine as the time during which the direct solar radiation exceeds the threshold of 120 Wm^{-2}.

In some cases, we also want to know the atmospheric disorder.

The atmospheric disorder relates to the attenuations of solar radiation during its passage through the Earth's atmosphere. This attenuation is mainly due to the phenomena of diffusion by aerosols and subsequent absorption by the various atmospheric components (ozone, water vapor, oxygen ...).

The atmospheric disorder gives a reliable indication of the quality of the solar resource or the atmosphere for a given site.

For example, an estimate of the atmospheric disorder (TA) is performed using the relationship:

$$TA = 11{,}1\frac{\ln\left(b\frac{I_0}{I_{cc}}\right)}{m} + 1 \quad \text{with } b = 0{,}664 + 0{,}163 \cdot \exp\left(\frac{-h}{8000}\right)$$

where h is the altitude of the site in question, I_0 is the extraterrestrial solar illumination (Wm^{-2}), I_{CC} is the DNI with a clear sky (Wm^{-2}), and m is the relative optical air mass.

In certain cases, we also want to know the solar profile, i.e. the distribution of the luminance L in the circumsolar zone, i.e. the zone comprised between the exterior of the solar disk (about 0.26°) and the conventional half-angle of the DNI measuring instruments. In practice, the circumsolar zone is therefore defined by the condition $0.26° < SPA < \beta$, where SPA is the angle between the pixel and the Sun, and β is between 1° and 5°.

The energy luminance, noted and expressed in $Wm^{-2}.sr^{-1}$, is the flux radiated per unit of solid angle and surface. The luminance energy L is tied to the illuminance I by

the relationship:

$$I = \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} L(\theta, \varphi) \cos\theta \cdot d\Omega$$

where dΩ is the elementary solid angle, θ and φ defining the direction of propagation of the light.

For isotropic radiation, we have $I = \pi \cdot L$.

The most accurate instrument for this measurement is the SAM (Sun Aureole Measurement) instrument. This instrument presents the disadvantage of a very high cost (about 80 k€).

Each of the above-mentioned instruments has a minimum cost of several thousand euros and requires regular maintenance, both for the solar tracker and for the sensors themselves. Measuring the different components of solar radiation is therefore an expensive and restrictive process.

The present invention aims to remedy these drawbacks.

The invention proposes a system making it possible to measure the components of solar radiation more easily and at lower cost.

This goal is achieved thanks to the fact that the system includes a camera equipped with a hemispherical objective and a sensor capable of capturing light to generate an image, and a processor capable of:

- Performing a geometric calibration of the camera in order to obtain correspondence between the coordinate system of the image pixels and the coordinate system of the camera.

- Calculating the solid angle subtended by each pixel of the image, which will make it possible to weight the value of the luminance in the subsequent calculations.

- Performing a camera calibration giving the position of the Sun in the sky to obtain correspondence between the camera's coordinate system and the cardinal points.

- Calculating the angle between each pixel and the zenith (PZA), the angle between each pixel and the azimuth (PAA), the angle between the Sun and the zenith (SZA), and the angle between the Sun and the azimuth (SAA), then the angle between each pixel and the Sun (SPA), using the relation:

$$\cos(SPA) = \cos(SZA) \cdot \cos(PZA) + \sin(SZA) \cdot \sin(PZA) \cdot \cos(|SAA - PAA|)$$

- Obtaining a High Dynamic Range (HDR) image of the sky.

- Calculating the overall horizontal illuminance index (σ_{GHI}), the direct normal illuminance index (σ_{DNI}), and the horizontal diffuse illuminance index (σ_{DHI}), defined as the

Advantageously, the measurement system includes a waterproof and dustproof protective box in which the camera is housed, and which includes a transparent window located in front of the camera objective.

Thus, the camera is protected from bad weather (rain and wind) and foreign bodies.

Advantageously, the protective box is equipped with a temperature regulator capable of regulating the temperature inside the box.

Thus, the system is able to operate in a hostile environment, for example on the site of implantation of a solar power station, where the temperatures are sometimes very high.

Advantageously, the system comprises at least one filter which is capable of attenuating or modulating the light entering through the objective into the camera.

The invention also relates to a method for measuring solar radiation.

According to the invention, this method of measuring solar radiation uses a camera provided with a hemispherical objective and comprising a sensor capable of capturing light to generate an image, and a processor, while this method comprises the steps:

(a) The camera is geometrically calibrated in order to obtain correspondence between the pixel coordinate system of the image supplied by the camera and the coordinate system of the camera.

(b) The solid angle subtended by each pixel of the image is calculated in order to weight the value of the luminance in the subsequent calculations.

(c) The camera is calibrated a second time by comparing the theoretical position of the Sun with its position on the image obtained. In this way, the correspondence between the coordinate system of the camera and the cardinal points is obtained.

(d) We calculate the angle between each pixel and the zenith (PZA), the angle between each pixel and the azimuth (PAA), the angle between the Sun and the zenith (SZA), and the angle between the Sun and the azimuth (SAA), then the angle between each pixel and the Sun (SPA), thanks to the relationship:

$$\cos(SPA) = \cos(SZA) \cdot \cos(PZA) + \sin(SZA) \cdot \sin(PZA) \cdot \cos(|SAA - PAA|)$$

(e) A High Dynamic Range (HDR) image of the sky is obtained.

(f) We calculate the Global Horizontal Irradiance (σ_{GHI}) index, the Direct Normal Irradiance (σ_{DNI}) index, and the Diffuse Horizontal Irradiance (σ_{DHI}) index, where Ωp, Lp and PZA are the solid angle subtended by a pixel p, the luminance measured by this pixel and the angle between this pixel and the zenith, respectively:

$$\sigma_{GHI} = \frac{\sum_{p \in \Lambda_1} L_p \Omega_p \cos(PZA)}{\sum_{p \in \Lambda_1} \Omega_p}$$

$$\sigma_{DNI} = \frac{\sum_{p \in \Lambda_2} L_p \Omega_p}{\sum_{p \in \Lambda_2} \Omega_p}$$

$$\sigma_{DHI} = \frac{\sum_{p \in \Lambda_3} L_p \Omega_p}{\sum_{p \in \Lambda_3} \Omega_p}$$

(g) A conversion is carried out between the Global Horizontal Irradiance (σ_{GHI}) index, the Direct Normal Irradiance (σ_{DNI}) index, and the Diffuse Horizontal Irradiance (σ_{DHI}) index, and the Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI), respectively.

Advantageously, the method according to the invention further comprises the following step:

(h) The solar profile is calculated by measuring the Direct Normal Irradiance (DNI) along a line of pixels passing through the center of the Sun on the image, then this measurement is repeated for a plurality of angles, in order to obtain the radial distribution of the luminance around the Sun.

Thus, the use of expensive additional equipment is avoided, and a measurement of the solar profile is obtained that is more precise, since this measurement takes into account the anisotropy of the luminance around the Sun.

The invention will be better understood and its advantages will become more apparent upon reading the detailed description which follows, of an embodiment shown by way of non-limiting example. The description refers to the accompanying drawings in which:

- Figure 1 is a schematic view of a measurement system according to the invention;
- Figure 2 is a diagram illustrating the correspondence between a camera sensor of the pixel of the system according to the invention and a solid angle;
- Figure 3 is a diagram showing the different angles used to define the position of the Sun and of a pixel of the camera of the system according to the invention with respect to a reference.

The system according to the invention comprises a camera 10, equipped with a hemispherical objective 20 (also called a “fisheye” objective), i.e., a lens with a large angle of field, with a field of vision greater than 180°. The camera 10 includes a sensor 12 capable of capturing light to generate an image, for example a CMOS (Complementary Metal Oxide Semiconductor) sensor or a CCD (Charge Coupled Device) sensor. The

CLAIMS

1. System of measurement of the solar radiation characterized in that it comprises a camera (10) provided with a hemispherical objective (20) and comprising a sensor (12) adapted to receive light to generate an image and a processor (30) able to:

- Perform a calibration geometry of the camera (10) in order to obtain a correspondence between a system of coordinates of pixels (125) of the image and a system of coordinates of said camera (10),
- Calculate a solid angle subtended by each pixel (125, p) of said image, in order to weight a value of a luminance in subsequent calculations,
- Carry out a second calibration of the camera (10) by comparing a theoretical position of the Sun and its position on the image, of how to obtain the correspondence between the system of coordinates of said camera (10) and the cardinal points,
- Calculate an angle between each pixel (125) and a zenith (PZA), an angle between each pixel (125) and an azimuth (PAA), an angle between the Sun and a zenith (SZA), and an angle between the Sun and an azimuth (SAA), then an angle between each pixel (125) and the Sun (SPA), by the relationship:

$$\cos(SPA) = \cos(SZA) \cdot \cos(PZA) + \sin(SZA) \cdot \sin(PZA) \cdot \cos(|SAA - PAA|)$$

- Obtain a high dynamic image (HDR) of the sky,
- Calculate a Global Horizontal Irradiance (σ_{GHI}) index, a Direct Normal Irradiance (σ_{DNI}) index, and a Diffuse Horizontal Irradiance (σ_{DHI}) index, defined as the sum of the luminances measured by the pixels (125) of said image belonging to a first region of interest (Λ_1), to a second region of interest (Λ_2) and to a third region of interest (Λ_3), respectively, where Ω_p, L_p and PZA are a solid angle subtended by a pixel p, the luminance measured by this pixel and the angle between this pixel and the zenith, respectively:

$$\sigma_{GHI} = \frac{\sum_{p \in \Lambda_1} L_p \Omega_p \cos(PZA)}{\sum_{p \in \Lambda_1} \Omega_p}$$

$$\sigma_{DNI} = \frac{\sum_{p \in \Lambda_2} L_p \Omega_p}{\sum_{p \in \Lambda_2} \Omega_p}$$

$$\sigma_{DHI} = \frac{\sum_{p \in \Lambda_3} L_p \Omega_p}{\sum_{p \in \Lambda_3} \Omega_p}$$

- Convert the Global Horizontal Irradiance (σ_{GHI}) index, the Direct Normal Irradiance (σ_{DNI}) index, and the Diffuse Horizontal Irradiance (σ_{DHI}) index to Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI), respectively.

2. Solar radiation measurement system according to claim 1, wherein the said high dynamic range image is obtained by an acquisition of several low dynamic range images taken with different exposure times and then a combination of these images in one high dynamic range image, all while maintaining the linearity of the sensor's camera.

3. System of measurement of the solar radiation according to claim 1 or 2, characterized in that said first region of interest (Λ_1) is a set of pixels (125) of the image verifying PZA < 90°, said second region of interest (Λ_2) is a set of pixels (125) of the image verifying SPA < β, β being the angle defined as the limit between the circumsolar zone and the rest of the sky, and said third region of interest (Λ_3) is a set of pixels (125) of the image verifying {SPA < β} ∩ {PZA <90°}.

4. Solar radiation measuring system according to any one of claims 1 to 3, characterized in that it comprises a waterproof and dustproof protective box (40) in which is housed said camera (10) and which comprises a transparent window (42) located in front of the objective (20) of said camera (10).

5. Solar radiation measurement system according to claim 4, characterized in that said box (40) is equipped with a temperature controller (50) capable of regulating the temperature inside said box (40).

6. Solar radiation measurement system according to any one of claims 1 to 5, characterized in that it comprises at least one filter (60) which is adapted to mitigate or modulate the light entering through the objective (20) of said camera (10).

7. Method of measuring the solar radiation characterized in that it uses a camera (10) provided with a hemispherical objective (20) and having a sensor (12) adapted to receive light to generate an image and a processor (30), and in that it comprises the following stages:
(a) The camera (10) is geometrically calibrated in order to obtain a correspondence between a pixel coordinate system (125) of the image supplied by said camera (10) and a coordinate system of the camera (10),

(b) A solid angle subtended by each pixel (125, p) of said image is calculated, in order to weight a value of a luminance in the subsequent calculations,

Calibration of said camera (10) a second time by comparing a theoretical position of the Sun and its position obtained on the image, in order to obtain the correspondence between the coordinates of said camera system (10) and the cardinal points,

(d) Calculating an angle between each pixel (125, p) and a zenith (PZA), an angle between each pixel (125, p) and an azimuth (PAA), an angle between the Sun and a zenith (SZA), and an angle between the Sun and a azimuth (SAA), then an angle between each pixel (125, p) and the Sun (SPA), thanks to the relationship:

$$\cos(SPA) = \cos(SZA) \cdot \cos(PZA) + \sin(SZA) \cdot \sin(PZA) \cdot \cos(|SAA - PAA|)$$

(e) A High Dynamic Range (HDR) image of the sky is obtained,

(f) Calculating a value of a Global Horizontal Irradiance (σ_{GHI}) index, a value of a Direct Normal Irradiance (σ_{DNI}) index, and a value of a Diffuse Horizontal Irradiance (σ_{DHI}) index, defined as the sum of the luminances measured by the pixels (125) of said image belonging to a first region of interest (Λ_1), to a second region of interest (Λ_2), and to a third region of interest (Λ_3), respectively, where Ω_p, L_p and PZA are a solid angle subtended by a pixel p, the luminance measured by this pixel and the angle between this pixel and the zenith, respectively:

$$\sigma_{GHI} = \frac{\sum_{p \in \Lambda_1} L_p \Omega_p \cos(PZA)}{\sum_{p \in \Lambda_1} \Omega_p}$$

$$\sigma_{DNI} = \frac{\sum_{p \in \Lambda_2} L_p \Omega_p}{\sum_{p \in \Lambda_2} \Omega_p}$$

$$\sigma_{DHI} = \frac{\sum_{p \in \Lambda_3} L_p \Omega_p}{\sum_{p \in \Lambda_3} \Omega_p}$$

(g) A conversion is carried out between the Global Horizontal Irradiance (σ_{GHI}) index, the Direct Normal Irradiance (σ_{DNI}) index, and the Diffuse Horizontal Irradiance (σ_{DHI}) index, and the Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI), respectively.

8. Method for measuring solar radiation according to the preceding claim, characterized in that it also comprises the following step:

(h) Calculating a solar profile by measuring the Direct Normal Irradiance (DNI) along a row of pixels passing through the center of the Sun in the image, then this measurement is

repeated for a plurality of angles, in order to obtain a radial distribution of the luminance around the Sun.