

Analyzing Solar Irradiance Variation From GPS and Cameras

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Abstract—The total amount of solar irradiance falling on the earth’s surface is an important area of study amongst the photovoltaic (PV) engineers and remote sensing analysts. The received solar irradiance impacts the total amount of generated solar energy. However, this generation is often hindered by the high degree of solar irradiance variability. In this paper, we study the main factors behind such variability with the assistance of Global Positioning System (GPS) and ground-based, high-resolution sky cameras. This analysis will also be helpful for understanding cloud phenomenon and other events in the earth’s atmosphere.

I. INTRODUCTION

The total amount of solar irradiance falling on the earth’s surface is an important factor in determining the amount of generated solar energy. However, it suffers from irregular alternation of received energy because of the presence of clouds in the atmosphere. It is important to study this variability, as it directly impacts PV planning and its subsequent integration to power grid. In this context, we explain the term Cloud Radiative Effect (CRE), that is defined as the difference between the actual solar irradiance and theoretical clear-sky irradiance value. A high value of CRE means reduced solar irradiance, indicating the presence of large amount of clouds in the atmosphere. In this paper¹, we study this variability using GPS and sky cameras.

II. METEOROLOGICAL SENSORS

In this section, we briefly describe the various meteorological sensors that are used in analyzing the cloud radiative effect on earth’s surface. Section II-A discusses our methodology in computing the precipitable water vapor (PWV) from GPS. The amount of water vapor in the atmosphere impacts the received solar irradiance. We record the received solar radiance using solar sensors, which is described in Section II-B. Finally, we also compute the cloud coverage ratio using sky cameras in Section II-C.

A. Global Positioning System (GPS)

The PWV values (in mm) are calculated using the zenith wet delay (ZWD), δL_w^o , incurred by the GPS signals as shown in eq.1.

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¹The source code of all simulations in this paper is available online at <https://github.com/Soumyabrata/irradiance-variation>

$$PWV = \frac{PI \cdot \delta L_w^o}{\rho_l} \quad (1)$$

$$PI = [-1 \cdot \text{sgn}(L_a) \cdot 1.7 \cdot 10^{-5} |L_a|^{h_{fac}} - 0.0001] \cdot \cos\left(\frac{(DoY - 28)2\pi}{365.25}\right) + [0.165 - (1.7 \cdot 10^{-5})|L_a|^{1.65}] + f \quad (2)$$

Here, ρ_l is the density of liquid water (1000 kg/m³). PI is the dimensionless factor determined by eq. 2, where, L_a is the latitude, DoY is day-of-year, h_{fac} is 1.48 for stations from northern hemisphere and 1.25 for stations from southern hemisphere. Also, $f = -2.38 \cdot 10^{-6}H$, where H is the station height [3] and factor f can be ignored for stations with height less than 1000 m. In this paper, the ZWD values for a tropical IGS GPS station (IGS GPS station Id: NTUS) located at Nanyang Technological University building (1.3°N, 103.68°E), Singapore are processed using GIPSY OASIS software and recommended scripts [4]. The PWV values are then calculated for NTUS using eq. 1-2; with $L_a = 1.34$, $h_{fac} = 1.48$, $H = 78$ m and DoY values for all days for year 2015. The PWV values calculated has a temporal resolution of 5 minutes.

B. Weather Station (WS)

We perform our experiments in a rooftop of Nanyang Technological University (NTU). In addition to computing PWV values from GPS signals, we also use collocated weather station to measure the various meteorological data. We record the total rainfall, wind speed and its direction, and relative humidity. Our Davis weather station is also equipped with solar sensors that records the total incident solar irradiance on the earth’s surface. All these recordings are measured at a temporal resolution of 1 minute.

The cloud radiative effect is calculated via the difference between total solar irradiance and the theoretical clear sky irradiance. We calculate the clear sky irradiance using Yang et al. clear-sky Global Horizontal Irradiance (GHI) model [5].

C. Whole Sky Imager (WSI)

Recently, with the advancement of photogrammetric techniques, remote sensing analysts have been increasingly using high-resolution, ground-based sky cameras. These cameras are popularly referred as Whole Sky Imagers (WSIs), and captures

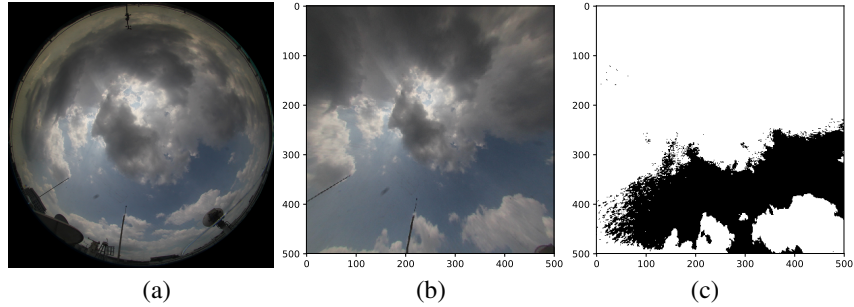


Fig. 1: Demonstration of a sample sky/cloud image captured using our sky camera, along with its cloud coverage computation. (a) Original image captured with our camera, (b) Undistorted image using lens calibration function [1], and (c) Segmented binary image of (b) using our cloud segmentation technique [2].

images of the sky at pre-defined interval of time. We have designed such sky cameras, and installed them collocated with the weather station. These sky cameras capture images at an interval of 2 minutes, and provide us a localized analysis of the cloud formation. Figure 1(a) shows a sample sky/cloud image captured by our sky camera.

We compute the cloud coverage from these captured images. The image captured by our sky camera is distorted owing to the fish-eye lens of its imaging system. We undistort the fish-eye image into a 500×500 image, using the camera calibration function. More details on the calibration function can be found in [1]. The sky/cloud pixels are estimated from the undistorted image using a ratio of *red* and *blue* color channels of the captured image. We employ our segmentation technique in [2], to generate the binary sky/cloud image as shown in Fig. 1. The cloud coverage ratio value is measured by computing the amount of *cloud* pixels in the binary image.

III. RELATION BETWEEN PWV, SOLAR RADIATION AND CLOUD COVERAGE

In our experiment, we consider all the meteorological observations for the entire year of 2015. We consider only the day-time observations of the recordings, as solar radiation recordings are not applicable during night time. The PWV values and cloud coverage percentage are recorded for corresponding observation of cloud radiative effect. We show their relationship amongst each other via a boxplot, shown in Fig. 2. We can clearly observe that the PWV increases with increasing values of CRE. This is because, an increased water content in the atmosphere indicates the presence of large amount of clouds, leading to an increased cloud radiative effect (i.e. large deviation of solar irradiance from clear sky radiation). Figure 2 also indicates that the cloud coverage increases, with increasing values of CRE. This analysis provides us a framework to understand such solar irradiance variability using myriad of meteorological sensors – GPS, sky camera and weather station.

IV. CONCLUSION & FUTURE WORK

In this paper, we studied the variability of solar irradiance using various ground-based sensors. These sensors detect the

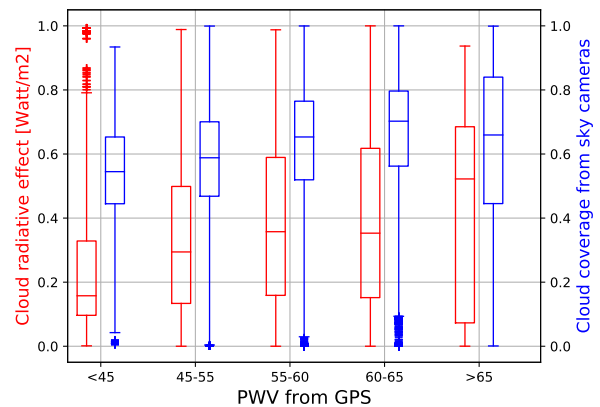


Fig. 2: Relationship amongst normalized solar radiation (obtained from weather station), precipitable water vapor (obtained from GPS), and normalized cloud coverage (obtained from sky cameras). It is clear that with increasing PWV values, both the net cloud radiative effect and cloud coverage increases.

presence of clouds and water vapor in the atmosphere, which in turn, assist us in understanding the variability of solar irradiance. In our future work, we will also consider the seasonal- and diurnal- variations in our analysis.

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