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# Image phase shift invariance based cloud motion displacement vector calculation method for ultra-short-term solar PV power forecasting

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## ABSTRACT

Irradiance received on the earth's surface is the main factor that affects the output power of solar PV plants, and is chiefly determined by the cloud distribution seen in a ground-based sky image at the corresponding moment in time. It is the foundation for those linear extrapolation-based ultra-short-term solar PV power forecasting approaches to obtain the cloud distribution in future sky images from the accurate calculation of cloud motion displacement vectors (CMDVs) by using historical sky images. Theoretically, the CMDV can be obtained from the coordinate of the peak pulse calculated from a Fourier phase correlation theory (FPCT) method through the frequency domain information of sky images. The peak pulse is significant and unique only when the cloud deformation between two consecutive sky images is slight enough, which is likely possible for a very short time interval (such as 1 min or shorter) with common changes in the speed of cloud. Sometimes, there will be more than one pulse with similar values when the deformation of the clouds between two consecutive sky images is comparatively obvious under fast changing cloud speeds. This would probably lead to significant errors if the CMDVs were still only obtained from the single coordinate of the peak value pulse. However, the deformation estimation of clouds between two images and its influence on FPCT-based CMDV calculations are terrifically complex and difficult because the motion of clouds is complicated to describe and model. Therefore, to improve the accuracy and reliability under these circumstances in a simple manner, an image-phase-shift-invariance (IPSI) based CMDV calculation method using FPCT is proposed for minute time scale solar power forecasting. First, multiple different CMDVs are calculated from the corresponding consecutive images pairs obtained through different synchronous rotation angles compared to the original images by using the FPCT method. Second, the final CMDV is generated from all of the calculated CMDVs through a centroid iteration strategy based on its density and distance distribution. Third, the influence of different rotation angle resolution on the final CMDV is analyzed as a means of parameter estimation. Simulations under various scenarios including both thick and thin clouds conditions indicated that the proposed IPSI-based CMDV calculation method using FPCT is more accurate and reliable than the original FPCT method, optimal flow (OF) method, and particle image velocimetry (PIV) method.

## 1. Introduction

### 1.1. Background and literature review

In recent years, global renewable energy has grown rapidly against the background of increasing global energy consumption, especially in developing countries. In 2015 renewables accounted for an estimated more than 60% of net additions to global power generating capacity [1], among which the solar photovoltaics (PV), wind, and hydropower contributed the majority of installations. By the end of 2015,

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**Nomenclature**

*Acronyms*

| | |
|---|---|
| CMDV | cloud motion displacement vector |
| FPCT | Fourier phase correlation theory |
| UST-SPPF | ultra-short-term solar PV power forecasting |
| IPSI | image phase shift invariance |
| PIV | particle image velocimetry |
| OF | optical flow |
| DFT | discrete Fourier transform |
| CPS | cross-power spectrum |
| DRM | displacement response matrix |

*Symbols*

| | |
|---|---|
| $f(x,y)$ | the grayscale matrix of sky image |
| $\boldsymbol{F}(\boldsymbol{u},\boldsymbol{v})$ | the 2-D Discrete Fourier transform of sky image grayscale matrix |
| $\Delta\varnothing(u,v)$ | the phase difference spectrum |
| $\boldsymbol{C}(\boldsymbol{u},\boldsymbol{v})$ | the cross-power spectrum |
| $\boldsymbol{f}_R(\boldsymbol{x},\boldsymbol{y})$ | the displacement response matrix |
| $\delta(x-x_0,y-y_0)$ | the pulse matrix |
| $\theta$ | rotation angle degree |

renewables produced an estimated 27.7% of the world's power-generating capacity and are sufficient to supply about 22.8% of global electricity demand [2]. However, the rapid development of solar power generation also brings a number of challenges. The nonlinear, stochastic nature of solar radiation translates directly into the power generated by solar PV installations. The resulting fluctuations in power output from grid-connected PV system lead to the possibilities of reducing grid reliability and the difficulties in the control of load-generation balancing. The optimal operation of power systems with high penetrations of solar PV has become an important challenge which needs to be addressed through a number of means, including unit commitment, economic dispatch and scenarios with flexible loads like demand response. [3–6].

As the key factor impacting the output power of solar PV plants, solar irradiance forecasting is an important technology for reducing the uncertainty in PV power generations. [7–10]. Especially in cloudy weather conditions, the solar irradiance on the ground can be fluctuant significantly at the minute level, which brings a great many difficulties for solar irradiance forecasting in intra-hour [11,12] instead of hourly [13] or daily [14] time scales. One approach for producing better forecasts is to observe the local cloud distributions through direct observation of the sky above the solar PV station with high spatial and temporal resolution [15,16]. For most ultra-short-term solar PV power forecasting (UST-SPPF) approaches at minute time scale, sky images are important data sources to provide clouds locations at different times. In previous studies, different kinds of digital image processing techniques were utilized to track cloud motion and calculate the displacement of clouds in sky images [17,18]. Then the cloud distribution in a future sky image is predicted based on linear extrapolation. Subsequently, the ground solar irradiance can be calculated according to the predicted cloud distribution in sky images and converted to solar PV output power [19,20].

The current techniques using digital image process for cloud tracking and displacement calculation can be divided into two categories: the gray scale information based methods and the Fourier translation based methods. The former methods calculate the object displacement in image according to the correlation or similarity of gray scale distribution. The latter method is based on the principle that the frequency spectrum of the image in the Fourier domain will also change correspondingly when the clouds in a sky image moved. The detailed introduction and literature review on the above two categories methods are as follows.

Generally, there are four popular gray scale information based methods to derivate cloud velocity: scale invariant feature transform (SIFT), optical flow (OF), X-correlation (X-corr), and particle image velocimetry (PIV). The SIFT method extracts key points of cloud image according to scale invariant feature transform and then tracks these key points to derivate cloud velocity [21,22]. In the tracking process proposed in [23], merging and splitting of clouds are handled via checking matched pairs of feature points among different clusters. Afterwards, the tracking information of feature points is utilized to predict if the sun will be covered or obscured by clouds within the prediction horizon. The OF method calculates cloud pixel displacement based on the assumption that the gray scale value of an image pixel remains constant during the cloud motion [24,25], which is recently introduced in the research of solar forecasts for cloud velocity derivation [26,27]. In [28], a variational optical flow (VOF) technique was utilized to determine the sub-pixel accuracy of cloud motion for every pixel, then cloud locations up to 15 min ahead can be forecasted by inverse mapping of the cloud map. The X-corr and PIV method all calculate the cloud velocity based on the matching correlation between two images, but the former focuses on the whole image while the latter one needs to segment the image first [29]. In [11,15,30], PIV method is applied to calculate the cloud velocity based on image segmentation and matching, then the future position of cloud is obtained by linear extrapolation. The above methods are analyzed and quantitatively evaluated in recent research [31], which indicates that PIV method shows higher accuracy than the other methods in CMDV calculation. However, the performance of PIV method is usually inconsistent when dealing with sky images in which the brightness and shape of cloud changing rapidly [32].

Unlike the gray scale information based methods, Fourier translation based methods use unified technical proposal of Fourier phase correlation theory (FPCT) and it can describe the image discrepancy more thoroughly mathematical [33]. The changes of some abstract features, such as object contour, will be reflected in the frequency domain and can be analyzed through calculation. In practical application, Fourier translation based methods also require less computation and thus less processing time [34]. For example, the displacement of clouds in sky images is calculated based on the analysis of the phase shifting between the spectrums of two consecutive images in early researches such as [35–37]. Despite these advantages, the Fourier translation based methods require us to analyze and compute images in the frequency domain, therefore, the influence of cloud deformation and interferences from the sun and sky background in actual sky images will be different with it appeared in time domain when using Fourier translation based methods to estimate cloud displacement [28,38].

### 1.2. Motivation and contribution

The differences in algorithm principle of the gray scale information based methods and the Fourier translation based methods lead to different performance characteristics. For example, PIV method calculates image displacement according to the similarity of object shape and color in the images, while cloud deformation and other interferences will affect the similarity index value. Fourier translation based FPCT method focuses on the global characteristics of the images, through which not only is the image displacement transformed into phase shift in frequency domain, but also the cloud deformation and other interferences are transformed into random noise signals in frequency domain. Therefore, in the cases with cloud deformation and other image interferences, the PIV method is more reliable than FPCT method since it can always provide an available result although it may be not that