Response to Reviewers' Comments
amt-2019-141: Estimating Solar Irradiance Using Sky Imagers

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We would like to thank the Associate Editor and the anonymous reviewers for your valuable comments and suggestions. Based on your inputs, we have thoroughly revised the manuscript. All the comments and suggestions have been addressed and implemented in this revised manuscript.

Responses to the individual comments can be found below. Unless otherwise specified, the references, equations, figures and tables cited in the answers are numbered as per the revised manuscript.

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>> REVIEWER 1<<
This paper proposes a new model for estimating the solar irradiance using pictures. This
     method has some new ideas. In particular, this method may play an important role in
     the prediction of solar radiation. But, It seems to me that this research shows a
     kind of preliminary results, so more details and data are required to extract robust
     conclusions. Therefore, this version of the manuscript is not ready for a regular
     article.
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Thanks for the comment. The core idea of this manuscript is to establish the fact that images obtained from ground-based sky cameras can assist us in accurately estimating the rapid fluctuations of measured solar irradiance. This is the first step, for a robust and reliable short-term solar forecasting. In this manuscript, we restrict our discussions to mainly solar irradiance estimation, and do not delve into solar irradiance prediction.

We have incorporated several major changes in the current version of the manuscript. Some of the major changes include:

- We have provided a detailed discussion of the calibration techniques – white balancing, geometric calibration and vignetting correction, used in our ground-based sky camera;
- We have provided an extensive evaluation of several other non-linear models (or empirical fits) between solar irradiance and image luminance. Instead of a linear model, we have investigated the use of a higher-order polynomial fit to model the irradiance based on image-based luminance. More discussions of these models are provided in Section 3.3 of the revised manuscript; and
- We have also added useful insights on the use of optical flow techniques to forecast the future sky/cloud image. We provided our initial results on estimating the image forecasts with a lead time of upto 15 minutes. We discussed this in Section 5 of the revised manuscript.

In the revised manuscript, these changes are incorporated throughout the manuscript.

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General comments.
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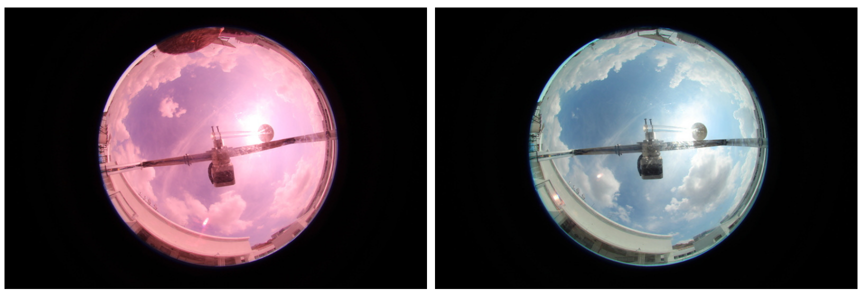
1.The most important problem to be explained is the calibration. Because the parameters of each WSIs are different, the new WSIs must be calibrated for six months to one year to achieve solar radiation estimation. This is very limited in practical application. Even so, what is the uncertainty of estimation result?

Thanks for the comment. We agree that the calibration of the ground-based cameras is an important step. Our ground-based camera WAHRSIS is calibrated with respect to – white balancing, geometric calibration and vignetting correction.

The imaging system in WAHRSIS is modified so that it captures the near-infrared region of the spectrum. Hence, the red channel of the captured image is more prone to saturation. It renders the captured image reddish in nature. Therefore, we employ custom white balancing in the camera, such that it compensates the alteration owing to the near-infrared capture. Figure 1 depicts the captured images obtained from automatic and custom white balancing.



(a) With auto white-balancing (b) With custom white-balancing

Figure 1: We use custom white-balancing for correcting the white balance.

We use the popular toolbox by Scaramuzza *et al.* [1] for the geometric calibration of WAHRSIS. This process involves the computation of the intrinsic parameters of the camera. We use a black-and-white regular checkerboard pattern, and position it at various positions around the sky camera. Figure 2 illustrates a few sample positions of the checkerboard. Using user interaction to identify the corner points and the known 3D co-ordinates, we estimate the intrinsic parameters of the camera.

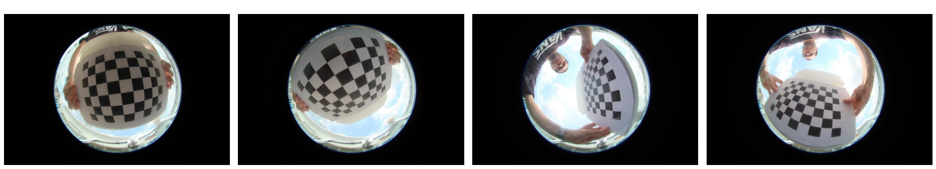


Figure 2: We position the checkerboard at various locations for the geometric calibration.

Finally, we also employ vignetting correction to the images captured by our sky camera. Owing to the fish-eye nature of the lens, the area around the centre of the lens is brighter, as compared to the sides. We use an integrating sphere to correct this variation of illumination. Figure 3 depicts an image captured inside an integrating sphere that provides an uniform illumination distribution in all directions. We use this reference image to correct the illumination of all captured sky/cloud images by our sky camera.

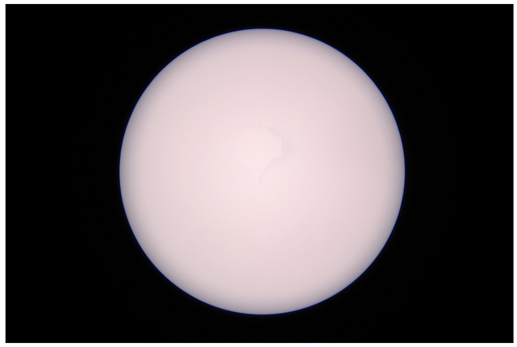


Figure 3: We captured a reference image inside the uniformly-illuminated integrating sphere.

Of course, these calibration techniques are fundamental, and needs to be completed for subsequent analytics using sky cameras. In the revised manuscript, we have mentioned that a prior calibration of the imaging systems is required for estimating solar irradiance from sky cameras.

In the revised manuscript, we have added this discussion in Section 2.1 of the manuscript.

2. The method of determining the sampling points around the sun proposed in this paper is not the core issue in my opinion. In fact, with the sun as the center, the result of determining the sampling point by any method based on distance weighting will not be very different from the result in this paper. Or, the results of these methods should be compared in the paper.

Thanks for the comment in investigating an alternate strategy of sampling. In our previous work [2], we used a cropped version of the image with the sun as the centre. However, we realised that there are several disadvantages to this approach.

- We need to find the position of the sun in the image, in order to crop a square image with the sun as centre. However, this identification becomes difficult during overcast, wherein the sun is completely covered by clouds;
- We also need to ascertain the optimal crop size dimension to obtain the best accuracy. We compute the correlation value between solar irradiance value and image luminance value for various crop size dimensions. Figure 4 shows the impact of crop size on the obtained correlation.

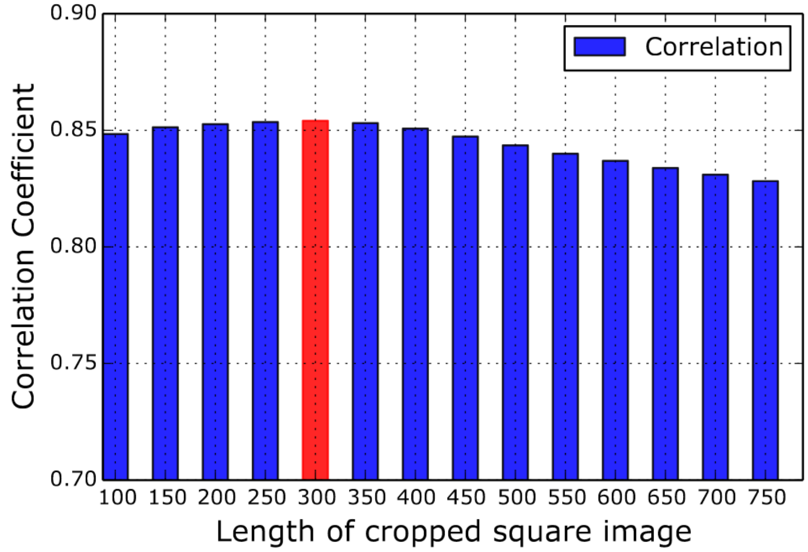


Figure 4: We observe that the best performance is obtained for a crop size of 300×300 (red bar).

Therefore, in order to avoid these demerits, we sample the pixels around the hemispherical dome to estimate the solar irradiance values. Our obtained results (cf. Section 4) establish that such sampling strategy work well in estimating solar irradiance.

In the revised manuscript, we have added this discussion in Section 3.1 of the manuscript.

3.Based on the current research, the paper hopes to further realize the prediction of solar radiation based on pictures obtained by WSIs. That's really a good idea. However, the predicted results should also be given in the article. Because if there is no next step to predict radiation, this paper has no practical application value. (Solar pyranometers are cheaper and more accurate than WSIs)

Thanks for the feedback. We absolutely agree that the full potential of using ground-based sky cameras will be realised in the solar energy *prediction* stage, in addition to the current solar irradiance *estimation*. The main focus of this manuscript is to establish to our community that ground-based imaging systems can provide us useful insights in understanding and estimating the rapid fluctuations of solar irradiance over the different hours of the day. In this paper, we restricted our message to convey this key idea of solar irradiance estimation, and did not delve into solar irradiance forecasting.

However, in this response letter, we provide our initial result on solar irradiance forecasting. We borrow techniques from time series modelling, to forecast future solar irradiance values. In our recent work [3], we modelled the solar irradiance values using triple exponential smoothing (TES). Figure 5 illustrates the performance of TES model for a short lead time. These solar irradiance recordings are measured in the interval of 1 minute. We use a historical data of 1000 observations, to estimate the next 50 observations. We set the seasonal period in TES model as 288. We observe that the predicted solar irradiance values (represented in green color) closely follows the actual solar irradiance values.

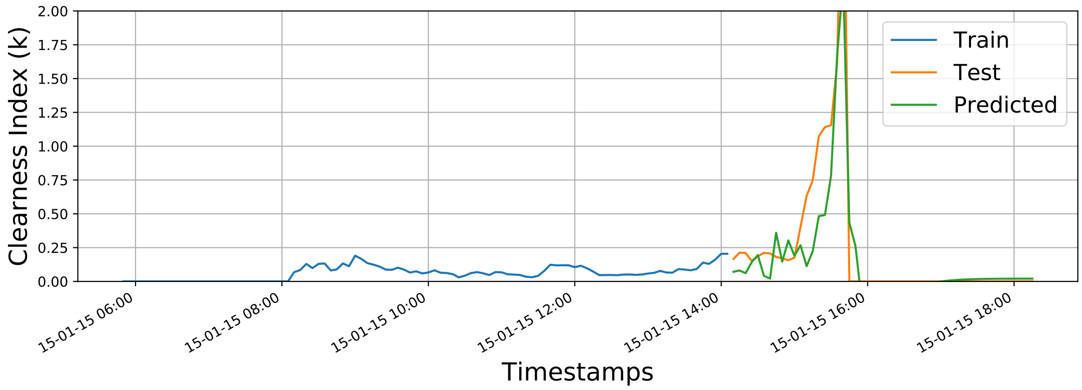


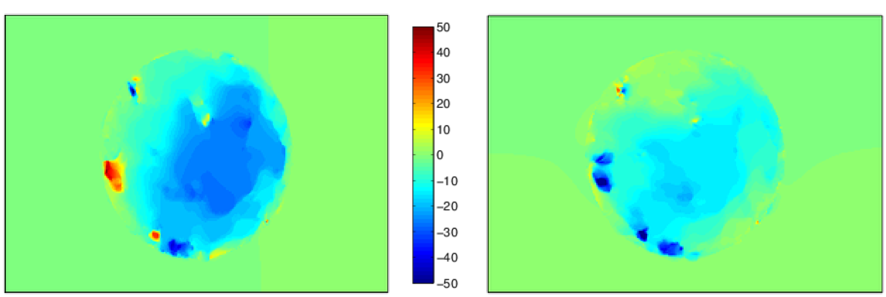
Figure 5: We illustrate the clearness index (k) values in the time series. This clearness index is defined as the ratio of observed solar irradiance and measured solar irradiance. We observe that the predicted solar irradiance values closely matches the actual solar irradiance.

In our upcoming work, we are currently incorporating the TES modelling technique directly on the sky camera image, instead of applying onto solar irradiance point measurements. We hope this will provide a better solar estimation technique than the current state-of-the-art methodologies.

In the revised manuscript, we have added this discussion in Section 6 of the manuscript.

`4.The author should pay attention to the prediction of solar radiation, Especially in the first step, cloud motion prediction. There are many problems in cloud motion prediction based on distorted images. How accurate the radiation prediction can be obtained from the predicted image should be explained together.`

Thanks for the feedback. We agree that the prediction of cloud motion vectors [4] is the first step in the realm of solar radiation forecasting. We have exploited optical flow techniques to estimate the direction and flow of cloud motion vectors between two successive image frames. We use the $(B - R)/(B + R)$ ratio channel of the sky/cloud image, where B and R are the blue and red channels respectively. We use an implementation [1] of optical flow technique that uses a simpler conjugate gradient solver to obtain the flow field. Figure 6 illustrates the estimated flow field.



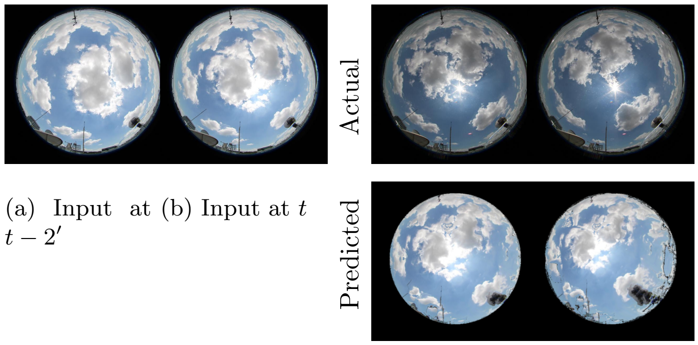
(a) Horizontal translation (b) Vertical translation

Figure 6: We visualize the horizontal and vertical translation of pixels between two successive frames, using optical flow technique.

Using the images captured at t and $t - 2$ minutes, we estimate the horizontal and vertical translation of the pixels. Under the assumption that the flow of cloud motion vectors for the successive $t + 2$ minutes is similar to that of previous frames, we estimate the future $t + 2$ minutes frame, and subsequently the $t + 4$ minutes frame. Figure 7 illustrates this. We obtain a forecast

[1] Available at `https://people.csail.mit.edu/celiu/OpticalFlow/`

accuracy of 70% for a prediction lead time upto 6 minutes. However, the accuracy decreases for a longer lead time. In our future work, we will estimate the solar irradiance value on the predicted sky/cloud image, using the empirical model proposed in this manuscript.



(a) Input at $t-2'$ (b) Input at t

(c) $t+2'$ (d) $t+4'$

Figure 7: Prediction of sky/cloud image using optical flow technique.

In the revised manuscript, this discussion is added to Section 5.1 of the manuscript.

`Specific comments`

`5.The references cited in this paper are incorrect.`

Thank you for pointing out. In the revised manuscript, we have ensured that all the references are cited in the AMT style.

In the revised manuscript, these changes are incorporated throughout the manuscript.

`6.Some abbreviations need to be given in full English and even explained. For example, DSLR (P3L29);`

Thanks for the comment. In the revised manuscript, we have provided the full form of digital single-lens reflex (DSLR). We have also provided detailed explanations of DSLR camera.

In the revised manuscript, we have provided the changes in Section 2.1 of the manuscript.

`7.P4L4: Davis Instruments 7440 Weather Vantage Pro, References or detailed explanations are required.`

Thanks for the feedback. We have now added more discussion in the revised manuscript. The solar pyranometer is included in *Davis Instruments 7440 Weather Vantage Pro* weather station. It measures the total solar irradiance flux density in Watt/m^2. On a clear day with no occluding clouds, the solar sensor ideally follows a typical cosine response. Figure 8 shows the theoretical response of the solar sensor in the pyranometer, for varying degrees of solar incident angle.

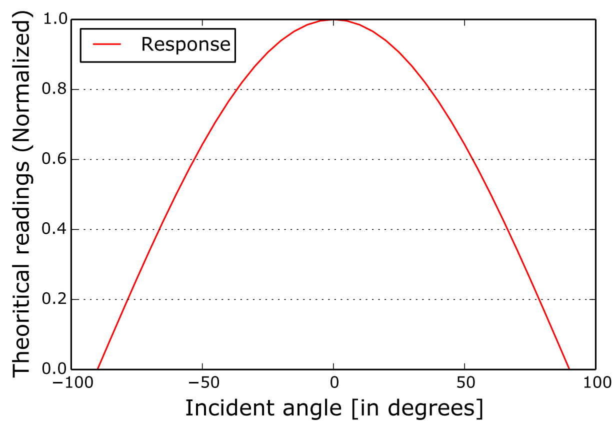


Figure 8: Response of the solar sensor with varying solar incident angle.

In the revised manuscript, the changes are made in Section 2.2 of the manuscript.

`8.How did the P6L9 formula come into being? Is it suitable for use here? Explanation is needed`

Thanks for the comment. The P6L9 formula is used to compute the luminance of an image from the R, G and B values of the RGB image. The formula is proposed in SMPTE Recommended Practice 177 [5].

In the revised manuscript, we added this discussion in Section 3.2 of the manuscript.

`9.P12, Figure 7. Watt/ m2  should be  Watt / m2`

Thanks for pointing it out. The superscript in the y-label of the corresponding figure is now depicted properly.

In the revised manuscript, this update is performed in Section 4.2 of the manuscript.

References

[1] D. Scaramuzza, A. Martinelli, and R. Siegwart, "A toolbox for easily calibrating omnidirectional cameras," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2006, pp. 5695–5701.

[2] S. Dev, F. M. Savoy, Y. H. Lee, and S. Winkler, "Estimation of solar irradiance using ground-based whole sky imagers," in *Proc. IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. IEEE, 2016, pp. 7236–7239.

[3] S. Dev, T. AlSkaif, M. Hossari, R. Godina, A. Louwen, and W. van Sark, "Solar irradiance forecasting using triple exponential smoothing," in *Proc. International Conference on Smart Energy Systems and Technologies (SEST)*. IEEE, 2018, pp. 1–6.

[4] S. Dev, F. M. Savoy, Y. H. Lee, and S. Winkler, "Short-term prediction of localized cloud motion using ground-based sky imagers," in *Proc. IEEE Region 10 Conference (TENCON)*. IEEE, 2016, pp. 2563–2566.

[5] RP SMPTE, "RP 177-1993," *Derivation of Basic Television Color Equations*, 1993.