V. Fung, J.L. Bosch, S.W. Roberts, J. Kleissl

We would like to thank the anonymous referee for providing comments and suggestions to improve our manuscript.

Overall Comment:

This is a technical paper describing a simple sensor to determine speed of cloud pattern in order to provide adequate information to solar power plant. While technically paper is well written, the efforts to characterize the senor performance are too limited. The principle of sensor operation assumes a single layer of relatively shallow clouds, which speed (or more accurate: vector of cloud shadow speed on ground) is well defined and can be detected with use of correlation technique. How does the sensor perform in a case of multiple cloud layers and presence of directional wind shear in the atmosphere? How does the sensor perform in situations with developing convective clouds which move towards or against the sun at relatively low elevations? These questions should be addressed to characterize the sensor performance and applicability. I do understand that collection of such data in natural conditions can be difficult and takes time. Can additional experiments/validations with artificial shadows help? I highly recommend at least discussion of the mentioned effects in the revised version of the paper.

Response: We agree with the reviewer that the measurement of the CSS was not accurately defined. The CSS determines CMVs based on the cloud projection by capturing ambient light at 9 points across the sensor footprint. Therefore, the CSS will detect 2D cloud shadow motion (x-y plane) in scenarios with 3D cloud movement. We have changed the title of the paper to 'Cloud Shadow Speed Sensor', replaced "cloud speed" with "cloud shadow speed" throughout the abstract and added the following discussion in the introduction:

"Ground measurements can be used to yield cloud shadow speed. Cloud shadow motion vectors are typically equivalent to cloud motion vectors as measured from satellites or simulated through numerical weather prediction (since sun-earth distance >> cloud-earth distance), but large solar zenith angles or large cloud vertical development relative to horizontal translation can introduce differences. While cloud shadow speed measurements may not be as useful as horizontal cloud speed for meteorological models, cloud shadow motion vectors are more relevant for solar variability and forecasting applications. For the remainder of the paper we will refer to 'cloud speed' or 'cloud motion vector' measurements for conciseness although strictly it is the cloud shadow motion vector that is measured."

While the data processing in the paper assumes a single cloud layer, prior research on CMV determination from ground data demonstrated that multilayer cloud movement (even in conditions of wind shear) can be detected using a histogram peak finding technique as shown in Figs. R1 and R2. By plotting cloud direction versus cloud speed, multiple regions with high concentration of QC CMVs (one region is -90^0 at 18 m s^{-1} and another is -45^0 at 10 m s^{-1}) can be found in the presence of multilayer clouds. This method requires further analysis and code development, but should be feasible to implement on the CSS algorithm for identifying multilayer CMVs.

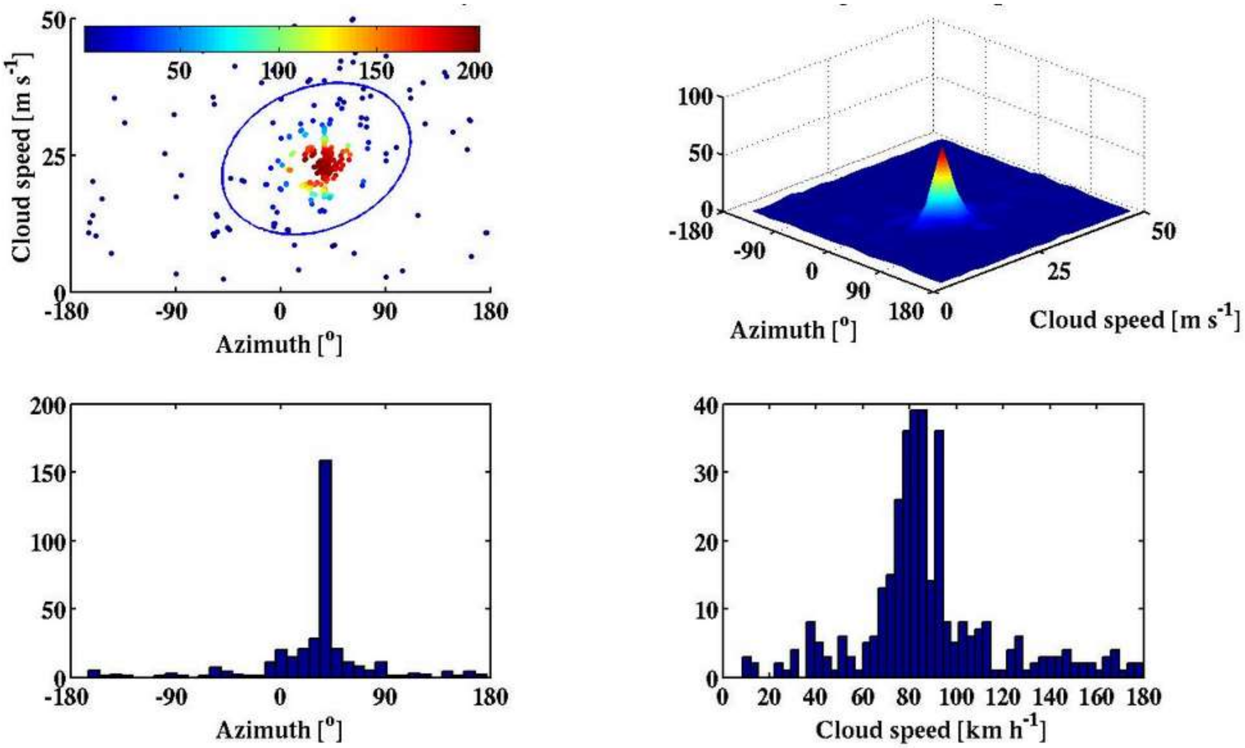

Fig. R1. Histogram peak finding method to distinguish different cloud layers in CSS measurements. Instead of considering just cloud speed or just azimuth histograms (bottom row) or medians, the joint distribution of azimuth and cloud speed is considered (top right). A single region with a high concentration of points indicates one layer of cloud movement.

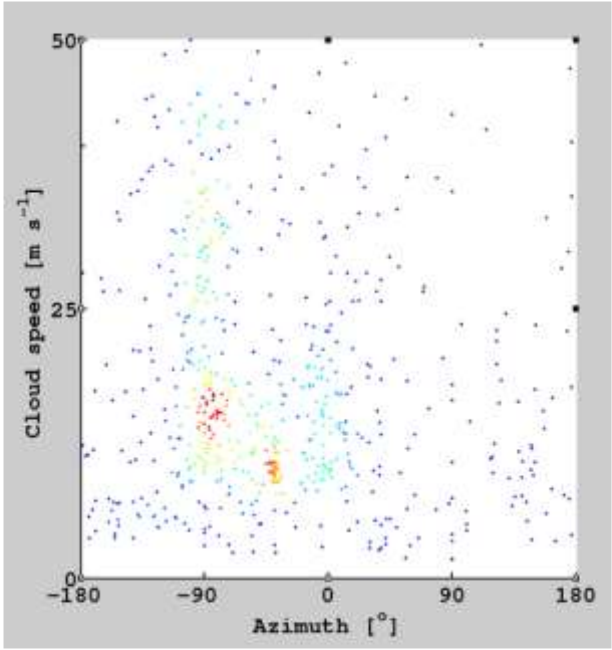

Fig. R2. In this example from data used in Bosch and Kleissl (2013) two layers of clouds were successfully detected (one motion is -90^0 at 18 m s^{-1} and the second is -45^0 at 10 m s^{-1}). A hotter (more red) color represents higher concentration of CMVs.

We have added the following to section 4:
"The post–analysis conducted on the days presented in Tables 2 and 3 assumes a single layer of cloud movement. In the presence of multilayer clouds, a histogram peak finding technique could be used to determine multilayer cloud movement (see reviewer response for details)"

Secondary Comments:

Comment 1: *It seems that the instrument suffers a bit from performance of the electronics. Can you comment on a particular choice of the platform?*

Response: One limiting factor is the 10-bit ADC resolution of the microprocessor in measuring voltages that resemble the full range of solar flux. To avoid poorly resolved irradiance trends during cloudy periods, a compromise had to be made between measurement resolution/precision and expected detectable voltage range. Hence, we specifically design the TEPT4400 sensor circuit to report voltages that exceed the measurement range of the microcontroller near noon on clear days. In specific, the detected solar irradiance saturates at 880 W m^{-2} but higher irradiance can be neglected since clear-sky periods are mostly rejected for CSS post-processing due to small variance. Irradiance measurements under 880 W m^{-2} representing cloudy conditions are therefore better resolved and are more appropriate for CSS applications.

The Arduino Mega 2560 was the initial platform of choice for the first CSS prototype. Further analysis revealed that the limited 8KB SRAM was not sufficient to capture time scales of variability in solar irradiance while maintaining a high sampling frequency. Consequently, most CMVs were not retained and only cloud speeds up to 10 m s^{-1} with at least 1 m s^{-1} resolution were detectable. The low clock speed also required excessive computational time for data processing. Hence, these limitations were the primary motivations to choose the Digilent ChipKit Max32 microcontroller that has greater capabilities but similar features (Table R1). The microcontroller could be replaced with a Digital Signal Processor (DSP) in the future for further reduction in computational time.

Table R1: Comparison of microprocessor specs. The Digilent Max32 platform is the same form factor as the Arduino Mega.

	Arduino Mega 2560	**Digilent Max32**
Clock Speed	16 MHz	80 MHz
Operating Voltage	5V	3.3V
AD Converter	10-bit	10-bit
Analog Inputs	16	16
Max Sampling Freq (for 9 TEPT4400 sensors)	1.1 kHz	15.4 kHz
Cost	$52	$50

A discussion on limitations of the Max32 platform were added in section 3.3.
"A compromise had to be made between measurement precision and detectable irradiance range due to the limited 10-bit ADC of the microprocessor. Hence, the TEPT4400 sensor circuit was deliberately designed to report voltages that exceed the measurement range of the microcontroller near noon on clear days. In particular, the detected solar irradiance saturates at 880 W m^{-2} but higher irradiance can be neglected since clear-sky periods are mostly rejected for CSS post-processing due to small variance. Irradiance measurements under 880 W m^{-2} representing cloudy conditions are therefore better resolved and are more appropriate for CSS applications."

Comment 2: *It seems that after calibration/adjustments the sensor would provide information about the variability of solar flux, not only about the cloud speed and direction. How valuable is such information?*

Response: Indeed variability in solar irradiance can be detected by the CSS and could be used by grid operators to inform control schemes for energy storage system or rampable generation throughout the day. The CSS could operate as a pyranometer with added value of CMV detection. The advantage of detecting GHI as well as CMV has been included at the end of Section 3.3.

Comment 3: *Wind direction scale in Figs. 5 and 6 covers the full circle. Can you expand it? Do you have any idea what is the reason of large jumps in detections from LCE?*

Response: The cloud direction and speed from Figs. 5 and 6 are expanded in Figs. R3 and R4. The LCE directions from both figures are consistent with USI images showing incoming clouds from the N (0^0) direction in the morning and the W (270^0) direction in the afternoon (and persisted throughout the day). The LCE algorithm uses a moving mode filter as quality control and can experience abrupt changes during cloud direction transitions. Bosch et al. (2013)[1] explain the LCE algorithm and quality control procedures in greater detail. A moving median filter is applied to both USI and CSS post-analysis algorithm and can detect a gradual change in cloud direction.

The new direction plots have replaced the direction subplots in Figs. 5 and 6 in the manuscript.

[1] Bosch, J. L., Zheng, Y., and Kleissl, J.: Cloud velocity estimation from an array of solar radiation measurements, Sol. Energy, 87, 196–203, doi:10.1016/j.solener.2012.10.020, 2013.

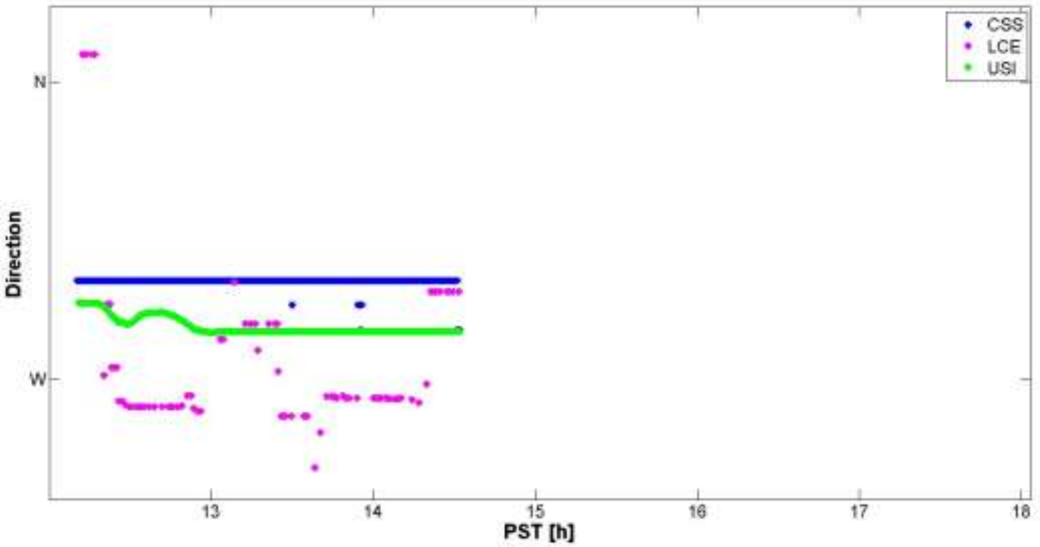

Fig. R3. Cloud directions expanded from Fig. 5.

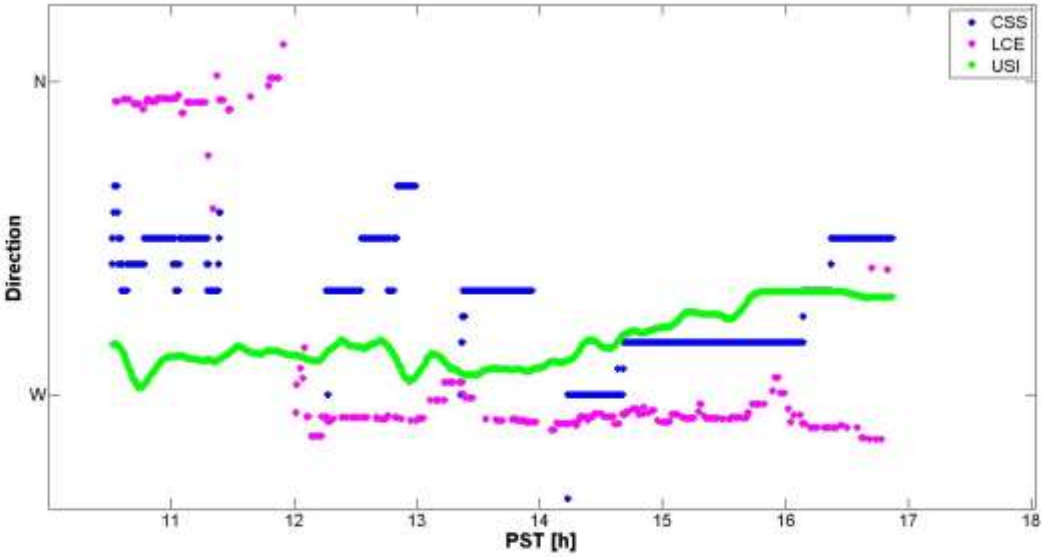

Fig. R4. Cloud directions expanded from Fig. 6.

Additional changes not specifically requested by the reviewer:

In addition to the manuscript changes mentioned above and minor edits for clarity and readability, page 9043, lines 17 – 21 were removed from the revised manuscript. In the original paper, calibration between TEPT4400 sensors was indicated as a necessary procedure in finding accurate maximum cross correlation. Although the cross correlation cannot distinguish between horizontal or vertical displacement of two un-calibrated signals, further analysis revealed that sensor calibration had no overall effect on CMV results. We speculate that this is because the signal trends and features predominantly determine the cross correlation.