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# Field validation and benchmarking of a cloud shadow speed sensor

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ABSTRACT

With ramp rate regulations for photovoltaic plants being discussed in many countries, the speed of clouds has gained significant importance lately. Besides, measuring cloud velocities and directions is of interest for validations of numerical weather predictions and solar nowcasting systems. Recently, the Cloud Shadow Speed Sensor (CSS) was developed and validated in San Diego for low cumulus clouds. In this publication, the CSS is studied under different weather and cloud conditions in the desert of Tabernas in southern Spain. Furthermore, a novel shadow camera based low-cost, low-maintenance approach to determine cloud shadow motion vectors is presented and used as a reference to benchmark the CSS. In comparison, the absolute velocities derived from the CSS and the shadow camera on 59 days for ±5 min temporal medians show deviations of RMSD 2.1 m/s (28.0%), MAD 1.2 m/s (15.7%) and a bias of −0.2 m/s (2.8%). Deviations of the cloud shadow direction are RMSD 47.9° (26.6%), MAD 25.3° (14.0%) and bias 3.7° (2.0%). An adaption of the CSS software yields 91% more measurements on 59 days in comparison to the previously used algorithms at the expense of reduced accuracies, both for the measured velocities and for the measured directions.

The CSS and the novel shadow camera based reference system enable long-time, low-maintenance ground measurements of cloud shadow speeds, which were previously not available. The distinct advantages and limitations of the two systems are discussed. In addition to the comparisons between the shadow camera system and the CSS on 59 days, the detection rates of the CSS are classified and measured on 223 days by analyzing CSS radiometer signals. Depending on the shading strength and shading durations, detection rates vary between 3.7% and 21.6%. Furthermore, the basic assumption as well as possible correction approaches of the linear cloud edge – curve fitting method are studied.

The CSS was found to be a robust tool with great potential. However, optically thin clouds with diffuse edges pose a challenge and the detection rate leaves room for improvements. The newly developed shadow camera system provides more measurements which scatter less but needs certain geographical requirements. The shadow camera is found to be a feasible validation tool for cloud (shadow) motion vectors.

## 1. Introduction

Obtaining reference motion vectors of clouds is relevant for the optimization and validation of all-sky imager based nowcasting systems (Kuhn et al., 2017a) as well as numerical weather predictions (NWP) and satellite-based weather forecasts (Molteni et al., 1996; Klein and Jakob, 1999; Tomassini et al., 1999). In addition to that, the rapid growth of solar power generation with its inherent variability calls for solar forecasting tools, which can predict shading events. Recently, ramp rate regulations (Lave et al., 2013; Marcos et al., 2014; Chen et al., 2017) in several countries with high solar grid penetrations have further stressed the need of cloud speed measurements. The Cloud Shadow Speed Sensor (CSS) can be used to derive such cloud motion vectors and can be a part of a camera-based solar nowcasting system (Wang et al., 2016). A singular all-sky imager can measure angular speeds of clouds, but cannot provide absolute speeds in [m/s].

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(a) (b)

**Fig. 1.** The Cloud Shadow Speed Sensor (CSS) at PSA, Spain.

The CSS, pictured in Fig. 1, was developed and presented in Fung et al. (2013). Previous validations, both under laboratory conditions and in-field, have been conducted (Fung et al., 2013). However, the variability of clouds and the complexity of the weather vary for different locations. For instance, in San Diego (USA), where the CSS was previously validated, cloud heights rarely exceed 1000 m (Wang et al., 2016).

In this publication, the CSS is compared to a novel shadow camera reference system on 59 days at the Plataforma Solar de Almería (PSA) in southern Spain. In southern Spain, a wide range of cloud speeds, heights and clouds of various classes is observed (Killius et al., 2015; Kuhn et al., 2017a). Investigating and benchmarking the performance of the CSS in this complex meteorological environment gives insights into its general applicability. In addition to the comparison against a shadow camera on 59 days, the detection rate of the CSS is determined on 223 days by directly investigating the measurements of the CSS sensors.

The shadow camera is a downward-facing camera placed on top of an 87 m high tower (CIEMAT CESA-I), which is part of a shadow camera system providing spatially resolved irradiance maps (Kuhn et al., 2017a,b,c, 2018a). The shadow camera is used to measure reference cloud speeds, which are compared to the CSS.

This publication is structured as follows. After the introduction, the CSS is presented and its software optimization discussed in Section 2. In Section 3, the shadow camera method is explained in detail. Comparing these two systems in Section 4 enables an in-field validation of the CSS. Also, the detection rate is determined in this section by scrutinizing the raw data of the CSS. The advantages and disadvantages of the CSS in comparison with the shadow camera approach are discussed in Section 5. The conclusion is given in Section 6. In the appendix, assumptions and possible corrections of the Linear Cloud Edge method are studied.

## 2. The cloud shadow speed sensor

### 2.1. Working principle

The working principle of the CSS, developed by Fung et al. (2013), is based on methods for determining cloud motion vectors with an array of irradiance sensors (Bosch and Kleissl, 2013; Bosch et al., 2013; Schenk et al., 2015). It consists of nine uncalibrated photodiode pyranometers, which are sampled at a frequency of 667 $s^{-1}$. Eight of these sensors are placed in a circular arc of 105° with a radius of 29.7 cm around the ninth sensor (see Fig. 1). In order to measure the speed and direction of a cloud shadow, the CSS must be directly shaded. If the shadow of a cloud passes the CSS, the sensors detect ramps at slightly different times. This way, both the speed and the direction of the clouds is determined. Due to the high frequency, the distances of the sensors can be small, which enabled a very compact design. Overall material costs are specified to be approximately 400 US-$ (Wang et al., 2016).

The CSS does not need regular cleaning as the working principle is based on relative deviations, not absolute irradiance measurements. As experienced over more than two years of active service, this user-friendly maintenance routine was found to hold even in the harsh conditions of the desert of Tabernas (Almería, Spain). Although not cleaned, the CSS data are checked daily, e.g. to detect constantly shaded sensors due to bird excrements. Luckily, such an event did not occur yet. Based on this differential approach, the CSS is able to determine the motion vectors of cloud shadows, not directly the motion vectors of the clouds. However, these vectors deviate only insignificantly (Fung et al., 2013).

### 2.2. Software adaptions of the CSS

During this comparison campaign, no hardware adjustments were conducted on the CSS. Suggestions for hardware improvements are mentioned in the conclusion. However, the evaluation method of the CSS is scrutinized and adapted. All comparisons to the shadow camera measurements will be conducted on the CSS with and without these adaptations.

*Increasing the detection rate*

In the first step of the evaluation algorithm, the CSS filters its data and it does not provide cloud speed measurements if certain criteria are not met. In any case, however, the raw data is stored. The filtering as implemented in Fung et al. (2013) and Wang et al. (2016) is based on a second order error metric (presented in the following), which results in a low number of calculated cloud motion vectors in relation to the total number of shading events.

The algorithm used for the cloud motion measurements itselves and described in Wang et al. (2016) is the *LCE – curve fitting algorithm*, which determines the maximum cross-correlation coefficient $R_{ij}$ of each pair of signals and records the associated time shift $\Delta t_{i,j}$ for the sensor pair consisting of sensor $i$ and $j$ corresponding to this maximum cross-correlation. Due to the setup of the CSS, there are $\#(i \circ j) = \#\alpha = 12$ sensor pairs. Based on the time shifts of these sensor pairs, the speed is calculated. The method will be briefly described here and is explained in detail in Wang et al. (2016).

In Fig. 2, an example situation is shown. Coming from the bottom-left, a shadow is sequentially shading the sensors. The trigonometric relation visualized in Fig. 2 holds for all cloud edge directions as the cloud speed is assumed to be perpendicular to the cloud edge. Deviations caused by this assumption are studied in Appendix A.

The residuum of the cosine fit $\Gamma$ acts as a filter (Eq. (1)).

$$\Gamma = 1 - \frac{\sum_{\alpha=1}^{12} (t_{\alpha,Fit}(\phi, v) - t_\alpha)^2}{t_{RMS}} \tag{1}$$

It is calculated with $t_{\alpha,Fit}(\phi, v)$ being the time shift according to the calculated cosine fit, $t_\alpha$ being the measured time shift and $t_{RMS}$ being the quadratic scatter of the time shifts according to Eq. (2).