RaZON$^+$, a novel solar monitoring system

Marc Korevaar[1], **Ilja Staupe**[1], **Clive Lee**[1], **and Joop Mes**[1]

[1]Kipp & Zonen B.V. Delft, the Netherlands

Email: marc.korevaar@kippzonen.com

Abstract

We present RaZON$^+$, the new Kipp & Zonen solar monitoring system for accurate and cost effective solar radiation measurements. The system uses a novel concept pyrheliometer to measure direct normal irradiance (DNI) and a new shaded pyranometer for diffuse horizontal irradiance (DHI).

Both are smart instruments designed to have inherently low sensitivity to fouling of the window and dome.

From these measurements, and the sun position from GPS data, RaZON$^+$ calculates the global horizontal irradiance (GHI). Calculation of the GHI and measurement of the DHI instead of the other way around minimizes the uncertainty due to the directional response of the pyranometer.

Sunshine duration is accurately calculated from the DNI measurement instead of being derived from GHI and DHI.

The RaZON$^+$ system performance has been evaluated by comparison with a high-end Kipp & Zonen solar monitoring station consisting of a CHP1 pyrheliometer, a CMP11 and CMP21 pyranometer mounted on a 2AP automatic sun tracker.

Performance was also compared with leading alternative products on the market; a SPN1 Sunshine Pyranometer from Delta-T Devices Ltd. of the UK and a RSR2 Rotating Shadowband Radiometer from Irradiance Inc. of the USA. The comparison took place at a rooftop location in Almere, the Netherlands.

An overview of these measurements and comparison will be presented. Preliminary results of the RMSE have already shown a benefit of the RaZON$^+$ for DNI and GHI compared to the RSR2 and SPN1. The pointing accuracy of the RaZON$^+$ has been established using a specially designed test apparatus.

The Smart instruments communicate through a Modbus® protocol with the on-board microprocessor system in the housing of the maintenance-free gear drive sun tracker. This also allows for connecting Modbus® enabled sensors from Kipp & Zonen and other manufacturers, such as for tilted global irradiance, PV panel temperature or an 'all-in-one' automatic weather station.

All the measured data is recorded by an internal data logger. The RaZON$^+$ has connectivity through a wired connection, either Ethernet or two wire RS-485, or by optional Wi-Fi. Monitoring data can be accessed in real-time on an interactive and on-board webpage as well as by download of data files.

1. Introduction

For measuring the solar irradiance accurately, the measurement system of choice is a high quality automatic sun tracker fitted with a pyrheliometer for direct normal irradiance (DNI), an unshaded pyranometer for global horizontal irradiance (GHI) and a shaded pyranometer for diffuse horizontal irradiance (DHI) [10]. However, recently also other systems using different approaches to measuring these components of solar radiation have come on the market. Two of the best known are the SPN1 Sunshine Pyranometer from Delta-T Devices Ltd. of the UK [4] and the RSR2 from Irradiance Inc. of the USA [1],[3],[5]. What these systems lack in accuracy of measurement they make up for in price, which is attractive for certain applications; particularly in solar energy.

At Kipp & Zonen the goal was to develop an all-in-one solar monitoring system that is cost effective compared to SPN1 and RSR2, whilst at the same time offering improved performance.

Here we present our solution, the new RaZON$^+$.

The radiometers consist of the novel design PH1 Smart pyrheliometer to measure DNI, which has inherently low sensitivity to fouling, and the new PR1 Smart pyranometer that has been designed specifically for the shaded measurement of DHI. These devices communicate by Modbus® RTU protocol to the Smart sun tracker, which aggregates the measurement results for DNI and DHI and calculates GHI and sunshine duration. The tracker has a gear drive system that requires no maintenance and a GPS receiver enables calculation of the sun position and accurate time synchronisation of the on-board data logger. We evaluated the pointing accuracy performance of the RaZON$^+$.
There have been comparisons in the past for solar measurement systems such as the SPN1, RSR2 and others [2], [6],[7],[8].
Here we performed a similar comparison of the DNI, GHI and DHI from the SPN1, RSR2 and RaZON$^+$ with a Kipp & Zonen reference system and evaluate amongst others the root mean square error (RMSE).

2. RaZON$^+$ system

The RaZON$^+$ shown in figure 1 (a) is an all in one measurement system which measures DHI and DNI and from these and the sun position calculates the GHI.
DHI is measured with a new design of pyranometer, shown in figure 1 (b), and DNI is measured with a novel pyrheliometer, shown in figure 1 (c) and (d).
The thermopile type detector and Smart digital electronics are common to both radiometers and incorporate accurate correction for the change of detector sensitivity with temperature. The individual detector sensitivity and other data are stored in flash memory so that the output is directly in W/m^2 and instruments are interchangeable. The 95% response time is less than 0.2 seconds and the calibration history, power supply voltage and internal temperature are available in the data stream.
The Smart electronics in the RaZON$^+$ sun tracker act as a data hub for the pyrheliometer and pyranometer and additional Modbus® enabled external sensors and as a data processing and storage system. The microprocessor uses data from the on-board GPS receiver to calculate the sun position (which is also available as a data output) and thus calculate GHI from DHI and DNI values. It also accurately calculates sunshine duration from DNI using the World Meteorological Organisation (WMO) defined sunny/not sunny threshold of 120 W/m^2 of direct solar radiation.
The system can be installed, aligned and monitored in real-time via a smartphone, tablet or laptop using the optional Wi-Fi. Other connection options are via Ethernet with a web browser or two-wire RS-485 (Modbus® RTU or ASCII serial) for viewing real-time measurement or the download of stored data files.

(a) (b) (c) (d)

Figure 1 (a) The RaZON$^+$ at the measurement location, (b) the RaZON$^+$ PR1 pyranometer, (c) PH1 pyrheliometer, and (d) PH1 collimation tube separate from detector unit.

Novel pyrheliometer and new pyranometer concept

The novel PH1 pyrheliometer has an open collimation tube, without front window (figure 1 (c)). This provides the required 5° field of view and 1° slope angle and a series of holes along the lower side allow rain water to exit the tube. At the rear of the tube is a removable detector unit with a diffuser for the detection of irradiance (figure 1 (d)). This concept is inherently insensitive to soiling mainly for two main reasons.
Firstly, the amount of soiling particles that reach the diffuser is lower than for the front window of a conventional pyrheliometer. This is because the particles that normally deposit on the window are now distributed over the entire internal area of the collimation tube. This much larger area ensures that the density of the soiling particles on the actual diffusor is much lower than on the window in a classical pyrheliometer design.
Secondly, if soiling particles reach the diffuser the detector is less sensitive to them. This is because the detector is already scattering the light in a similar way to the soiling particles and the additional scattering due to soiling has a relatively small effect. The detector unit is easily removed without tools to clean the diffuser if required and the collimation tube can also be easily washed to remove soiling.

Because the direct solar beam is blocked by the tracker shading disk (figure 1 (a)) the PR1 pyranometer only sees the diffuse radiation from the sky and atmosphere, so it is already less sensitive to the effects of soiling on the precision machined an polished glass dome than a GHI pyranometer. The PR1 has a similar detector unit to the PH1 with a diffuser (figure 1 (b)) that further reduces the effects of dome soiling.

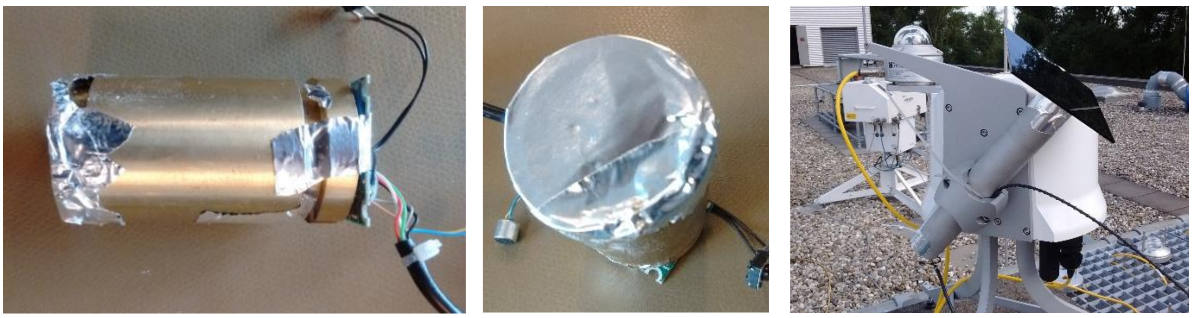
Future developments

Possible future developments for the RaZON$^+$ solar monitoring system include the use of a Kipp & Zonen pyranometer to measure plane of array (POA) tilted global radiation, a PV panel temperature sensor and an all-in-one automatic weather station. This would provide a complete station for solar energy prospecting. Furthermore, the system is to be extended with the possibility for on-site automated comparison as well as calibration of Kipp & Zonen Smart pyranometers.

3. Methods

Pointing accuracy measurement RaZON$^+$

For evaluation of the capabilities of the RaZON$^+$ system the pointing accuracy has been determined. For this a pointing accuracy apparatus was developed, shown in figure 2. It consists of a small brass tube (figure 2 (a)) with an aluminium foil covering at one end that has a pinhole of approximately 250 µm diameter. The pinhole was made using a small drill into aluminium tape (shown in figure 2 (b)). An off-the-shelf CMOS camera (without the lens) is mounted at the other end of the tube. This brass tube is placed inside a larger tube that can be mounted on a solar tracker such as here on the RaZON$^+$ (shown in figure 2 (c)).



(a) (b) (c)

Figure 2 (a) Pointing accuracy apparatus consisting of a brass tube with a pinhole in aluminium at the left and a CMOS camera at the right end, (b) aluminium foil with pinhole, and (c) the pointing accuracy apparatus on the RaZON$^+$.

The image of the sun through the pinhole is projected onto the CMOS camera and the pointing of the solar tracker can be evaluated by movement of the projection of the sun over the camera detector array. In order not to saturate the camera, welding glass is mounted at the front of the outer tube to block most of the solar irradiance.

Images of the projection of the sun were acquired by connecting the camera through USB to a laptop. In order to determine the centre of the projection a data analysis of these images was done using a Gaussian smoothing algorithm and subsequent maximum search algorithm [9].

Comparison of RaZON+, SPN1 and RSR2

We evaluated different solar monitoring systems, the RaZON+ from Kipp & Zonen, the SPN1 Sunshine Pyranometer from Delta-T Devices Ltd. and the RSR2 Rotating Shadowband from Irradiance Inc. As a reference we used a Kipp & Zonen solar monitoring station consisting of a 2AP automatic sun tracker fitted with a CHP1 pyrheliometer, CMP11 and CMP21 pyranometers, one shaded and the other unshaded. The location for the comparison is on a private rooftop at Almere, the Netherlands. The roof setup of all instruments together and individually are shown in figure 3. For the SPN1 the DNI was calculated using the SPN1 DHI and GHI, and the solar zenith angle calculated by the RaZON+.

We analysed the DNI, GHI and DHI over a period from 18th to 29th of July containing both cloudy and clear days. The differences between the 3 evaluated systems and the reference system were evaluated. For this we calculated the bias, the RMSE due to variability and performed a "box and whisker" analysis similar in approach to previous comparisons [8]. The "box and whisker" analysis consists of calculation of the minimum and maximum difference, 1st quartile, median and 3rd quartile. The RMSE due to variability is without the contribution of the bias to the total RMSE.

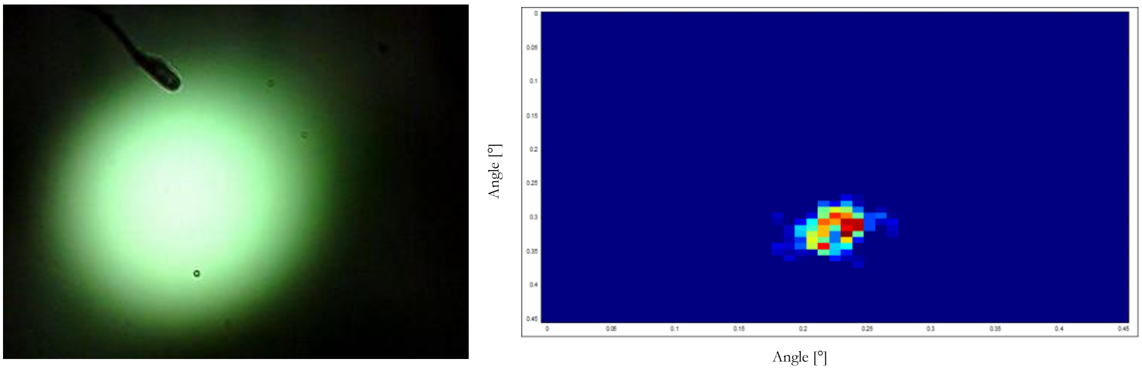
(a) (b) (c) (d)

Figure 3 rooftop setup (a) all the solar monitoring systems (b) SPN1 Sunshine Pyranometer, (c) RSR2 Rotating Shadowband Radiometer, and (d) Kipp & Zonen reference station.

4. Results

Pointing accuracy measurement RaZON+

The pointing accuracy apparatus was mounted on the RaZON+ and images of a clear sun were acquired for several minutes. A captured image of the solar projection on the CMOS camera is shown in figure 3 (a). In these images the motor movements of the RaZON+ are visible by slight movements of the projected sun. After data analysis the centre of each sun projection are determined and are plotted in a density plot in figure 3 (b).



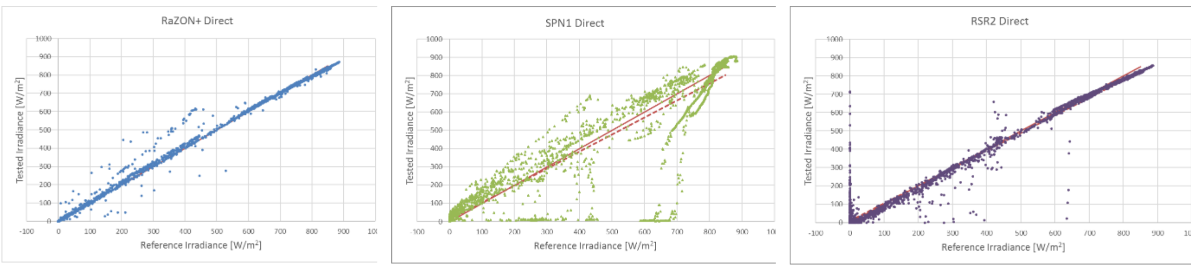
(a) (b)

Figure 3 (a) the image of the sun on the camera in the pointing accuracy apparatus, and (b) a pointing angle density plot over 2200 image frames of the sun projection centre. The pointing angle density plot has the angle on the x and y axis; The colour map from red to yellow to light blue and dark blue denotes a high frequency to a low frequency of the pointed angle.

The pointed angles fall within a somewhat circular area with a diameter of approximately 0.1°.

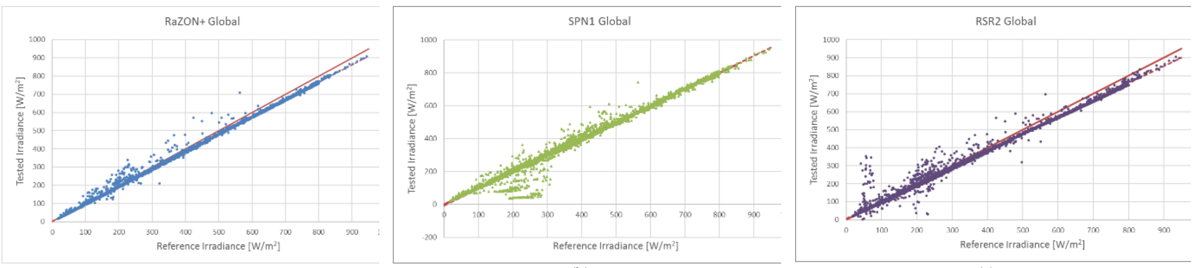
Comparison of RaZON⁺, SPN1 and RSR2

The solar monitoring systems were evaluated over a period from 18th to 29th of July. Due to an issue with mechanical levelling of the 2AP tracker the quality of the reference data was not sufficient in the afternoon. For the comparison we therefore used only data from the mornings. The data for the 3 systems for DNI are plotted in figure 4, for GHI in figure 5 and for DHI in figure 6.



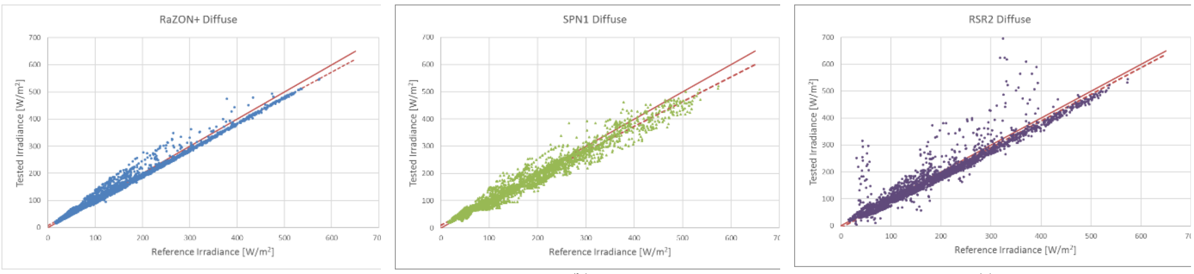
(a) (b) (c)

Figure 4 DNI measurements plotted with on the x-axis the reference irradiance and on the y-axis the (a) RaZON⁺, (b) SPN1, and (c) RSR2 data. The solid red line is y=x and the dashed red line is the fit of the measurement points.



(a) (b) (c)

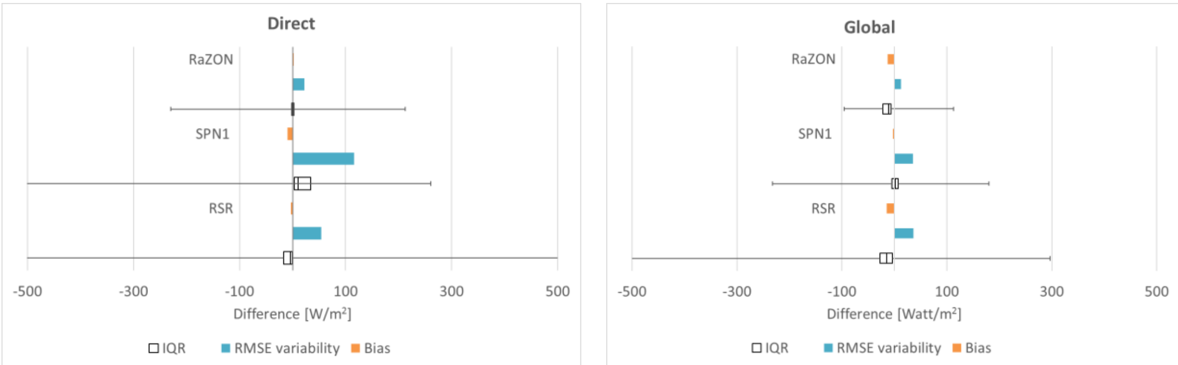
Figure 5 GHI measurements plotted with on the x-axis the reference irradiance and on the y-axis the (a) RaZON⁺, (b) SPN1, and (c) RSR2 data. The solid red line is y=x and the dashed red line is the fit of the measurement points.



(a) (b) (c)

Figure 6 DHI measurements plotted with on the x-axis the reference irradiance and on the y-axis the (a) RaZON⁺, (b) SPN1, and (c) RSR2 data. The solid red line is y=x and the dashed red line is the fit of the measurement points.

As a general remark one can say the RaZON⁺ has the least scatter of data, followed by the RSR2 and the most scatter is seen for the SPN1. Especially for the DNI this is very clear. For the RaZON⁺ and RSR2 the fit shows a slight deviation from the y=x line for the GHI and DHI whereas the DNI shows a very good match between fitted line and y=x. The SPN1 shows a good match between fit and y=x for GHI but for DHI and DNI it is off.



(a) (b)

Figure 7 For the difference of the RaZON⁺, SPN1 and RSR2 and the reference the bias, RMSE due to variability and box and whisker analysis showing the maximum and minimum (whiskers) and the 2 quartiles around the median (box) are shown. For (a) the DNI and (b) the GHI.

The analysis of the differences of the 3 solar monitoring systems with the reference system is shown in figure 7 for DNI and GHI and in figure 8 for DHI. From this analysis it is clear that the RMSE due to variability is the smallest for RaZON⁺ compared to the other systems. The SPN1 has a significantly larger RMSE due to variability, especially for the DNI. The bias of the measurement results is somewhat larger for the GHI for the RaZON⁺ and RSR2 than for the SPN1.

The box and whisker analysis shows that the maximum and minimum differences between the test systems and the reference system and are smallest for the RaZON⁺ and bigger for the SPN1 and RSR2. The 50% of the data is clustered closely around the median for DNI and DHI for the RaZON⁺. However, for the GHI with the SPN1 the 50% data is clustered more closely around the median. This is caused partially by the smaller bias of the SPN1 for the GHI.

We think that the remaining bias between the RaZON⁺ and the reference system can be because the pyranometer was not calibrated according to the regular procedure. With the regular procedure in place the bias is expected to reduce.

A summary of the RMSE and bias is given in table 1.

Table 1 RMSE due to variability and bias for the 3 systems for DNI, GHI and DHI.

Scope	System	DNI	GHI	DHI
RMSE due to variability	RaZON⁺	22.3	12.9	13.1
[Watt/m²]	SPN1	115.9	35..5	20.4
	RSR2	54.4	36.7	45.1
Bias	RaZON⁺	2.5	-12.7	-4.6
[Watt/m²]	SPN1	-9.2	-2.9	-10.4
	RSR2	-3.2	-14.5	-9.6

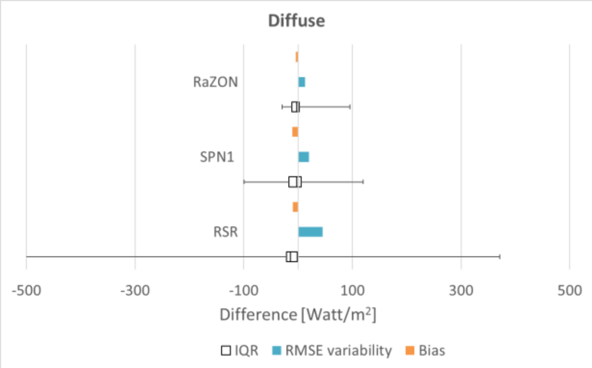


Figure 8 The same analysis as in figure 7 for the DHI.

5. Discussion

A method to measure the pointing accuracy of a solar monitoring system using a pinhole and a CMOS camera has been presented. The RaZON$^+$ showed good results for the measurement over a short time period of pointing within a circle of a diameter of 0.1°.

This indicates that a RaZON$^+$ equipped with a SHP1 and SMP11 would achieve similar performance to the reference system with CHP1, CMP11 and CMP21. The only difference being that the GHI is calculated instead of measured. However, we believe its favourable to calculate the GHI because the directional response of the GHI pyranometer does no longer play a role.

We see that the RMSE due to variability is significantly smaller for the RaZON$^+$ than for the RSR2 and the SPN1. Furthermore, we saw that the bias of the DNI and DHI is the smallest for the RaZON$^+$, for the GHI the SPN1 has the smallest bias.

The RaZON$^+$ with the PH1 and PR1 radiometers can produce a calculated measurement of GHI with a low uncertainty. The accurate method with which the DNI is measured allows for high quality sunshine duration calculation internally under all sky conditions. In addition, DNI, DHI, GPS and sun position data products are available; it has built-in data logging and greatly reduced sensitivity to soiling.

6. Conclusion

The pointing accuracy of the RaZON$^+$ was evaluated to be within a circle of 0.1°, for short time periods.

Comparison of the 3 solar monitoring systems to a reference solar monitoring station shows the best performance of the three to be for this pre-production unit RaZON$^+$. The RMSE due to variability for the RaZON$^+$ is significantly smaller than for the RSR2 and the SPN1, more than a factor 2 for DNI and GHI. The bias is smallest for the RaZON$^+$ for DNI and DHI but for GHI the SPN1 has the smallest bias.

Acknowledgements

We would like to thank A. Staupe and the Staupe family for providing the rooftop measurement facility and A. Partosoebroto for valuable comments.

References

[1] W. Jessen, S. Wilbert, B. Nouri, N. Geuder, and H. Fritz, "Calibration methods for rotating shadowband irradiometers and evaluation of calibration duration", Atmos. Meas. Tech. Discuss., 8, 10249–10282, 2015

[2] D.R. Myers, "Comparison of direct normal irradiance derived from silicon and thermopile global hemispherical radiation detectors", NREL.

[3] C.A. Gueymard, "Direct Normal Irradiance for CSP/CPV: Modeling Challenges", presentation.

[4] J. Badosa, J. Wood, P. Blanc, C.N. Long, L. Vuilleumier, D. Demengel, and M. Haeffelin, "Solar irradiances measured using SPN1 radiometers: uncertainties and clues for development", Atmos. Meas. Tech., 7, 4267-4283, 2014.

[5] N. Geuder, M. Hanussek, J. Haller, R. Affolter, and S. Wilbert, "Comparison of Corrections and Calibration Procedures for Rotating Shadowband Irradiance Sensors", Solar PACES Granada Spain, 2011.

[6] A. Habte, S. Wilcox, and T. Stoffel, "Evaluation of Radiometers Deployed at the National Renewable Energy Laboratory's Solar Radiation Research Laboratory", NREL.

[7] N. Geuder, F. Trieb, C. Schillings, R. Meyer, and V. Quaschning, "Comparison of different methods for measuring solar irradiation data", 3rd International Conference on Experiences with Automatic Weather Stations Torremolinos Spain, 2003.

[8] L. Vuilleumier, M. Hauser, C. Félix, N. Sommer, D. Ruffieux and B. Calpini, "Performance Evaluation of Radiation Sensors for the Solar Energy Sector", MACC-II Open Science Conference Brussels Belgium, 2014.

[9] M. Korevaar, J. Heemskerk, M. Goorden, and F. Beekman, "Multi-scale algorithm for improved scintillation detection in a CCD-based gamma camera", Physics in Medicine and Biology 54, 2009.

[10] L.J.B. McArthur, "BSRN operators manual", version 2.1, 2005, https://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/WCRP/WCRP21_TD1274_BSRN.pdf