UNCERTAINTY IN CALIBRATION AND CHARACTERISATION OF PYRANOMETERS

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ABSTRACT

This work quantifies the uncertainties of thermoelectric pyranometer measurements made with different calibration methods. Measurement campaigns supported both the evaluation of pyranometer calibrations and newly proposed approaches to characterise the pyranometers in indoor and outdoor conditions. Estimated uncertainties were then applied to a year-long irradiance dataset to evaluate the impact on the assessment of the annual solar irradiation.

This study highlights the differences seen when calibrating pyranometers under different conditions and procedures. Such deeper insight of pyranometers response aims ultimately to assist the integration of short-term (pyranometers) and long-term (satellite-based) data to a more accurate evaluation of PV energy yield.

INTRODUCTION

As the competition over financing of sustainable energy increases, more accurate methods to assess the solar energy resource are required for photovoltaics to successfully compete with other energy sources. The importance of high-quality ground-based measurements of solar irradiance was again highlighted by the updated 9060:2018 standard.

The achievable expanded uncertainty of pyranometer measurements is often taken to be around 3% and 2% for hourly totals and daily totals, respectively [1]. However uncertainty may be twice the recommended values [2] and identified measurement quality issues often depend on issues related to calibration and maintenance [3].

Among the different sources of irradiance measurement uncertainty, calibration plays the biggest role, along with temperature and directional response [4]. Calibration conditions may not adequately represent or adapted to the scope of the desired application. For many institutes, outdoor calibration may be prevented by unsuitable meteorological conditions, while indoor calibration can be a time-intensive activity.

This study extends a previous work [5] by evaluating the difference of uncertainty in irradiance measurements among different outdoor and indoor calibration procedures.

COMPARISON OF OUTDOOR CALIBRATIONS: METHODOLOGY

Outdoor ground-based irradiance measurements performed at EURAC were used to estimate outdoor calibration factors according to different data handling procedures. Pyranometers were from two established manufacturers. The three pyranometers from the first manufacturer (m1) were Secondary Standard (SS), and the one from the second manufacturer (m2) was a Second Class (2C) [6].

The reference device was from the first manufacturer and it includes a temperature-compensation system [7]. The thermoelectric pyranometers were mounted on a thermally isolated structure. All pyranometers were installed in the horizontal plane ±1 degree. Data were acquired every ten seconds and later averaged over one-minute intervals for analysis during almost clear-sky days. Changes in resulting calibration values were evaluated by varying data filters and series selection.

Short description	BI min [W/m^2]	DI max [W/m^2]	DF max [%]	N. of series
All clear-sky series	700	150	15	32
15 clear-sky series	700	150	15	15
All series	0	1000	100	15

Legend: beam irradiance (BI), diffuse irradiance (DI), diffuse fraction (DF)

Table 1. Weather filters and number of series considered for the different approaches.

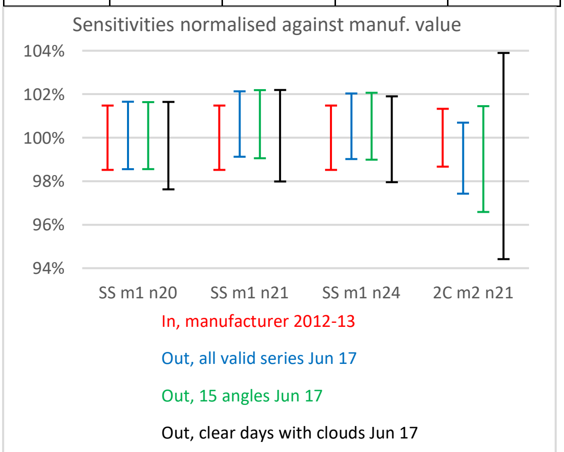
Outdoor calibration uncertainty Equation (1) accounted for standard uncertainty from series (s), data logger uncertainty (l), reference calibration (r) and directional response (d), calibration transfer (c) and coverage factor (k).

$$u_{p,k} = \sqrt{(s_p \times k)^2 + (l \times k)^2 + (r^2 + d^2 + c^2)} \qquad (1)$$

COMPARISON OF OUTDOOR CALIBRATIONS: RESULTS

For all the procedures, deviation of calibration values from the one declared by the manufacturer were smaller than 1%. For clear sky series the percentage deviations from the manufacturer values were around 0.1%, 0.6% and 0.5% respectively for the sensor SS_m1 _n20 (Secondary Standard, first manufacturer, identifier 20), SS_m1_n21 and SS_m1_n24. In conditions of higher diffuse fraction, the uncertainty of the secondary standard sensors increased from 1.4% (manufacturer) to around 2%. For the pyranometer from the second manufacturer, uncertainty increased up to 4.73%.

Pyran.	**In, manuf.**	**Out, all clear sky series**	**Out, 15 clear sky series**	**Out, all series**
m1 n24	8.39 µV/W/m² ± 1.48%	8.43 µV/W/m² ± 1.47%	8.43 µV/W/m² ± 1.51%	8.38 µV/W/m² ± 1.97%
m1 n21	8.12 µV/W/m² ± 1.48%	8.17 µV/W/m² ± 1.47%	8.16 µV/W/m² ±1.50%	8.13 µV/W/m² ±2.10%
m1 n20	8.64 µV/W/m² ± 1.48%	8.65 µV/W/m² ± 1.52%	8.66 µV/W/m² ± 1.55%	8.61 µV/W/m² ± 1.97%
m2 n21	18.80 µV/W/m² ±1.33%	18.62 µV/W/m² ± 1.60%	18.63 µV/W/m² ± 2.43%	18.64 µV/W/m² ± 4.74%



Comparison of absolute sensitivities (top Table 2) and normalised sensitivities (bottom Figure 1) calculated through different data handling approaches. Sensitivity extremes based on an assumed symmetrical uncertainty.

The percentage deviation of each series calibration from the final calibration factor was analysed also for sensor SS_m1_n21 and 2C_m2_n21. For SS_m1_n21, higher and lower deviations occurred respectively for (median) angles of incidence of 70 and 50. For 2C_m2_n21, higher and lower deviations occurred respectively for angles of incidence of 70 and 23.

Pyranometer	**Angle**	**Diffuse fraction [%]**	**Deviation [%]**
SS_m1_n21	70	99	1.18%
	50	99	-1.57%
2C_m2_n21	70	99	3.98
	63	31	2.85
	56	20	1.72
	23	99	-5.50

Table 3. Sample of series calibration factor deviations from the overall calibration. All series but the last one refers to the first half of the day.

COMPARISON OF INDOOR CALIBRATIONS: METHODOLOGY

Indoor calibration values provided by one manufacturer were compared with calibration values obtained through a single indoor direct beam calibration procedure performing alternate readings based on the MetObs procedure [8] and a newly developed procedure of sequential calibration performing simultaneous readings.

The single calibration of a pyranometer in horizontal position relies on a class AAA solar simulator using a xenon lamp, a halogen lamp and spectral filters to well approximate the AM 1.5G solar spectrum. The single indoor calibration through direct beam response records five series of measurements, both for the reference and test devices. For each series, dark measurements are recorded first with the light obscured by a shutter. The shutter is then removed and, after 60 seconds, five measurements are taken with steps of approximately 2 seconds. The overall response is estimated as average of the five series response measurements (average light measurements minus average dark measurements) to compensate for the effects of light instability.

For the sequential calibration procedure, test pyranometers of type 1 (t1) and 2 (t2, higher quality) from the first manufacturer were located in a vertical position inside a ventilated thermal chamber with a glass surface facing the artificial light source, an ARRIMAX 18/12 lamp unit [9]. Unshaded measurements were taken between series of shaded measurements before swapping the position of the reference pyranometer with the next test pyranometer. Based on standard prescriptions and previous calibration experience, a stabilisation period of 30 seconds was used. 21 measurements were obtained with a timestep of two seconds between consecutive measurements. After each second shading phase, the reference pyranometer was swapped with the next pyranometer to reduce bias due to light inhomogeneity.

Series	position one	position two	position three	position four
Shade Unsh. Shade	t1 refer.	t2 n18	t1 n13	t1 n12
Shade Unsh. Shade	t2 n18	t1 refer.	t1 n13	t1 n12
Shade Unsh. Shade	t2 n18	t1 n13	t1 refer.	t1 n12
Shade Unsh. Shade	t2 n18	t1 n13	t1 n12	t1 refer.

Sensors positions from one to four (top Figure 2) and setup of the different groups of measurements (bottom Table 4).

The average irradiance was estimated through Equation (2) for each position p according to the measured voltage V_{pm} referring to a series of M measurements through sensors, with calibration factors f_m, located in that position during one of the measurements sessions.

$$\bar{\iota}_p = \frac{\sum_{m=1}^{M} f_m \times V_{pm}}{M} \quad (2)$$

Calibration factor Equation (3) for simultaneous readings [8] used the calculated voltages (unshaded measurements minus average of shaded measurements) when the reference and test sensor swapped their position p and p+1 during two consecutive series of measurements m and m+1.

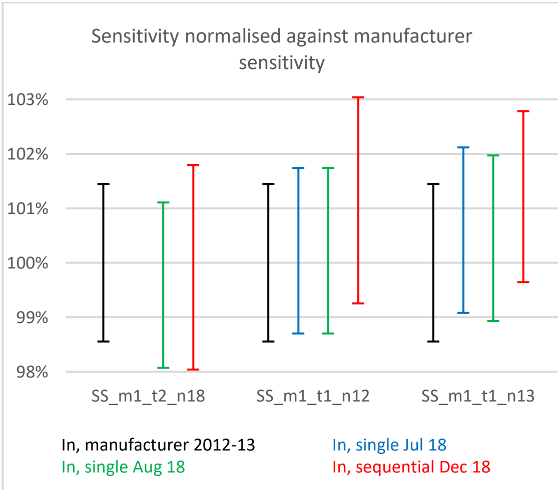
$$f_T = F_R \times \frac{\left(V_{R(p,m)} + V_{R(p+1,m+1)}\right)}{\left(V_{T(p+1,m)} + V_{T(p,m+1)}\right)} \quad (3)$$

Uncertainty assessment for the sequential procedures accounted for the reference sensor, maximum uncertainty due to steady temperature, tilt difference (up to two degrees) and irradiance variability within the series.

COMPARISON OF INDOOR CALIBRATIONS: RESULTS

For the sensors m1_t1_n12 (first manufacturer, type 1 sensor, identifier 12) and m1_t1_n13, the deviations of calibration factors from the values provided by the manufacturer increased from 0.22% to 1.15% and 0.45% to 1.21%, respectively. For the pyranometer m1_t2_n18 the calibration value was closer (99.92%) to the manufacturer value compared to the previous calibration value (99.59%) determined a few months prior, although the uncertainty was higher.

Pyra.	In, man. 2012-13	In, single calibr. 20/7/18	In, single calibr. Aug 18	In, seq. calibr. 12/12/18
t2 n18	9.47 μV/W/m^2 ± 1.44%		9.43 μV/W/m^2 ±1.52%	9.46 μV/W/m^2 ±1.88%
t1 n12	9.31 μV/W/m^2 ± 1.44%	9.33 μV/W/m^2 ±1.52%	9.33 μV/W/m^2 ±1.52%	9.42 μV/W/m^2 ±1.89%
t1 n13	8.79 μV/W/m^2 ± 1.44%	8.84 μV/W/m^2 ±1.52%	8.83 μV/W/m^2 ±1.52%	8.90 μV/W/m^2 ±1.57%



Comparison of absolute sensitivities (top Table 5) and normalised sensitivities (bottom Figure 3) from different indoor calibrations. Sensitivity extremes were determined assuming a symmetrical uncertainty.

IMPACT OF CALIBRATION UNCERTAINTY ON THE EVALUATION OF PV PERFORMANCE

The newly found values of pyranometer uncertainty were applied to a solar farm of 7.4 MW peak [5] to assess the impact on yield assessment from August 2015 to August 2016. Uncertainty was calculated assuming all sources as independent and random , through a first-order Taylor polynomial with a coverage factor k equal to 1.96 [10].

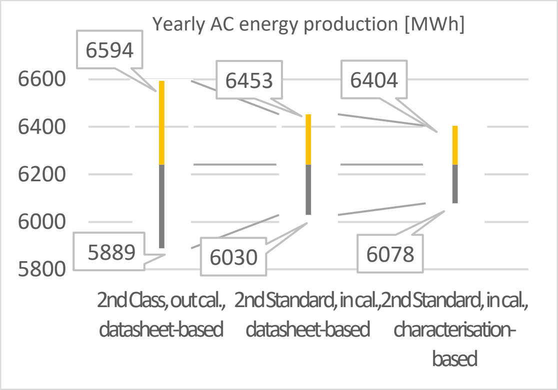


Figure 4. Effects of calibration and characterisation uncertainty, based on hourly averaged values, in a PV solar farm of 7.4 MW peak

In the most favourable scenario (Secondary Standard sensor, indoor calibration and characterisation-based uncertainty), the expanded (k=1.96) production uncertainty was equal to ±157 MWh (2.6% of the production). In the worst scenario (Second Class sensor, outdoor calibration in not perfectly sky condition through a different type of sensor as reference, and datasheet-based uncertainty), the uncertainty increased to ±350 MWh (5.9% of the production).

CONCLUSIONS

Calibration factors of thermoelectric pyranometers provided by the manufacturers were compared with those calculated by applying different outdoor and indoor calibration procedures at CREST and EURAC.

Outdoor calibration uncertainty increased up to around 2% under conditions of higher diffuse fraction and up to 4.73% when the reference sensor is of a different type to the test sensor. In the latter case, it is not clear if such increase of uncertainty is mainly due to the different manufacturing process (e.g. dome symmetry) or the lower quality of the pyranometer (Second Class).

Results of indoor calibration procedures agreed within 1.21% even when calibrating multiple sensors at the same time. Calculated uncertainty of the simultaneous calibration procedure was lower than 2% (against 1.44% provided by the manufacturer) but it could be reduced further by using more stable light sources.

When comparing different scenarios for the annual yield assessment, expanded uncertainty was equivalent to about 5.9% of the energy production in the worst case. By using more accurate sensors, a more precise calibration procedure and characterisation information, such value could be at least halved.

Additional measurement campaigns will contribute to a better understanding of the pyranometer response to variations in angle of incidence and temperature, which should allow further reduction in solar resource and PV system performance uncertainty.

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