Outdoor solar radiometer calibration under ISO-9847:1992 standard and alternative methods

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***Abstract*—An alternative method for outdoor calibration of horizontal pyranometers, based on ISO-9847:1992, is presented and tested for several different field pyranometers. The new method differs from the standard method in its robust data analysis and in a concrete set of clear-sky filters that are proposed. The proposal is better suited for the automated data acquisition which is commonly used for this task. As a first step towards its validation, results from this method are compared to those resulting from a direct application of the ISO-9847:1992 standard.**

***Index Terms*—calibration, solar radiation, quality assessment**

I. Introduction

An accurate estimate of solar irradiance on a horizontal surface is required for the design of solar energy projects at all scales. Financial risk assessment for these projects is done taking into account the quality, time-period and proximity of the solar irradiance measurements to the specific site of the project. Periodic calibration of pyranometers is essential to reduce uncertainties in ground-based solar irradiance data. On a national scale, it reduces potential inconsistencies between different solar radiation data sets and it is essential for a proper estimation of the underlying uncertainties.

Pyranometers are usually calibrated against a secondary standard pyranometer using the international standard ISO-9847:1992 [1] or its ASTM equivalent [2]. The ISO-9847:1992 standard was introduced more than 25 years ago and was last reviewed and confirmed in 2013. It describes several procedures for the calibration of field pyranometers by comparison to a reference pyranometer, including methods for indoor calibration with artificial light sources. The indoor methods are used by several manufacturers, as they allow independence from climate factors, are considerably faster and are suitable for a predictable work flow. However, this type of calibration may be affected by spectral mismatch errors and the laboratory conditions (temperature, wind, humidity) may not be similar to the realistic conditions under which the test pyranometer will have to operate. On the other hand, outdoor calibration methods usually take more time and are limited by climatic factors. However, they allow all types of pyranometers to be related to a single reference under realistic irradiance and climatic conditions.

The standard ISO-9847:1992 provides methods for outdoor calibration of pyranometers and photovoltaic radiometers on a horizontal surface under either clear-sky, partly cloudy or cloudy sky conditions. In the clear-sky case it also provides methods for calibration on a tilted plane and at normal incidence (with a suitable sun tracker). However, the calibration of radiometers for solar energy applications should be made exclusively using the outdoor clear-sky method [1, Ap. B.2]. This standard needs an urgent update to, among other improvements, give a central role to modern automatic data acquisition and processing methods and to standardize the procedure used to obtain the uncertainty estimates, in agreement with the GUM specifications [3].

In this paper, an alternative method for the data processing for outdoor calibration of solar radiometers on a horizontal surface under clear-sky conditions is presented and its results are compared to those from the standard method, for three different types of radiometers. The alternative method is simpler to implement and allows the calibration procedure to be easily automatized and this paper is a preliminary step towards its validation and refinement. In Section II the requirements and data processing recommended by ISO-9847:1992 are summarized and an uncertainty estimation scheme, in accordance with GUM guidelines, is proposed. In Section II-B the alternative data processing scheme is described and examples of its implementation are provided and compared to those resulting from the standard method. Finally, in Section IV the conclusions are summarized.

II. Outdoor calibration under clear-sky conditions under ISO 9847:1992

The requisites to be satisfied by the reference and the test radiometers, the site and the good practices recommended for recording the data, are described in [1] and implemented at the Solar Energy Laboratory (http:\\les.edu.uy). This research facility is located at Salto, Uruguay (Latitude 31.28 S, Longitude 57.92 W, Altitude 56 m asl) in a subtropical temperate climate and it has on its roof a special installation designed for outdoor calibration of solar radiometers. Daily maintenance (mainly cleaning of the domes and checking the horizontal level of the individual radiometers) is performed early in the morning during a calibration. Simultaneous voltage signals from the standard and test radiometers are recorded every 30 seconds. A Fisher Scientific DT85 data logger with relative error under 0.1% is used for this purpose. The irradiance time-series for all radiometers are displayed in real-time on an indoor screen as a secondary check. The data collection period requires from two to three weeks depending on meteorology. During this period ambient temperature, relative humidity and atmospheric pressure are also recorded. A Kipp & Zonen CMP22 pyranometer calibrated at the World Radiation Center (PMOD) at Davos is used as reference radiometer with trazability to the World Radiometric Reference. This pyranometer model is specially stable and exceeds the specifications required for a Secondary Standard pyranometer [4]. Diffuse irradiance is measured with another CMP22 pyranometer fitted with a shadow ring CM-21 from Kipp & Zonen. A daily correction factor, as recommended by the manufacturer, is applied to the diffuse measurement to account for the portion of sky blocked by the shadow ring from where diffuse irradiance is also arriving. More than a hundred radiometers have been calibrated by comparison to this standard at this laboratory over the last five years.

A. Standard data processing

The data processing scheme, which is the focus of this work, can be separated into three stages:

1) a preliminary filtering stage which preserves daylight clear-sky data and arranges it into candidate series.
2) an outlier rejection stage.
3) the calculation of the new constant and its uncertainty from the filtered series.

1) Filtering stage: The raw data is first filtered according to the following criteria:

F1: Solar altitude, $\alpha_s \geq 20°$
F2: Diffuse fraction, $f_d \leq 0.20$

Filter F1 above is required by ISO-9487:1992. Usually low-sun data is affected by high directional errors (cosine error of the instruments) and other factors. The solar altitude can be calculated from local position (latitude and longitude), time and day of year [5]. This filter selects daytime data for which the sun is at least 20° above the horizon.

Filter F2 places an upper limit on the diffuse fraction f_d (the ratio of diffuse to global irradiance). In Uruguay, under clear-sky conditions, the diffuse fraction is usually lower, between 0.10 and 0.18, depending on the water and aerosol content in the atmosphere. Under a very cloudy sky, the sun is not directly visible and all irradiance is diffuse ($f_d = 1$). The standard ISO-9487:1992 states that *"the calibration of pyranometers to be employed in solar energy applications shall be performed only under conditions in which the sun is unobstructed by clouds throughout the data-taking period, with a minimum direct solar irradiance on a horizontal surface of 80% of the global horizontal irradiance"* and this implies a maximum diffuse fraction of 0.20, as indicated above.

Therefore, F1&F2 (logical AND) selects the data points corresponding to high sun and mostly clear sky conditions. Let N_1 be the number of data records that satisfy these conditions.

Following the ISO-9487:1992 protocol, the N_1 data points are organized into N_s continuous series, each with $N(j)$ data points corresponding to a 10 to 20 minute time interval. Let the index j ($j = 1, 2, \ldots N_s$) refer to a given series and let the index i ($i = 1, 2, \ldots N(j)$) refer to a single measurement within series j. The series must span morning, noon and afternoon periods and must belong to at least two different days, to allow for diversity.

The following restrictions apply to the length and number of the final series,

i. $N(j) \geq 21$
ii. $N_s \geq 15$

That is, at least 15 series of 21 contiguous clear-sky data points are required [1, Sec. 5.2.2.1].

Once the N_1 data records are arranged into N_s candidate series of $N(j)$ contiguous data points, a clear-sky selection filter is applied to each series. Actually the ISO 9847:1992 standard asks for *stable cloudless conditions*, without suggesting a quantitative objective set of criteria to automatically select these conditions in the data. Furthermore, in its Appendix B, the standard states that *no cloud formation shall be within* 30° *of the sun during the data taking period and in the case of automatic data acquisition this criterion can be replaced by a minimum irradiance threshold which indicates interference by clouds* [1, Ap. B.2]. This wording suggests that the standard was intended mainly with a human observer present during the measurements, which was a common way to record solar data at the time.

We use a normalized version of the clearness index [6],

$$k'_t = \frac{k_t}{0.1 + 1.031 \exp\left(\frac{-1.4m}{9.4+0.9m}\right)}, \tag{1}$$

defined in terms of the air mass (calculated from the solar zenith angle θ_z as $m = 1/\cos\theta_z$ for data points which satisfy condition (ii) above) and the clearness index k_t (the horizontal global irradiance normalized by horizontal extraterrestrial irradiance). This is a dimensionless expression of global solar irradiance and for clear-sky conditions in Uruguay typically takes values around 0.85, as even the clearest atmosphere absorbs and disperses some fraction of the extraterrestrial irradiance. See for instance Ref. [5] for details on how to calculate these normalized quantities. The threshold $k'_t > 0.60$ proposed in [7] is used to detect clear-sky conditions. Some authors who use this index to detect clear sky conditions [8] supplement it with other requirements, such as requiring a minimum daily clearness index $K_t > 0.4$. This condition is not used here, as it is very restrictive for our purposes (all series from a day that does not satisfy it would be discarded). We use instead the additional requirement that $k_t > 0.60$. Furthermore, we use an upper limit for the clearness index ($k_t < 0.90$) to exclude overshoot events: when a small cloud covers the sun during a few seconds, the pyranometer responds with a series of short-lived damped oscillations during which it can easily register (spurious) irradiance values larger than the solar constant (the average solar irradiance incident or our planet's external atmosphere, conventionally $1367\,\mathrm{W/m^{-2}}$).

Summarizing, clear-sky records are selected on the basis of two conditions applied to the average values of the clearness index and the modified clearness index,

$$\mathrm{F3}: k_t'(j) \geq 0.60 \qquad \& \qquad \mathrm{F4}: 0.90 > k_t(j) > 0.60. \quad (2)$$

If after these filters are applied a series has less than 21 data points, it is discarded. The final stability of the surviving series is tested later, when outliers are discarded. The N_s series (with a total of N_2 ($N_2 < N_1$) data points) that satisfy the requirements F1 to F4 described above are subject to the following data processing in order to discard outliers and determine the new constant for the test instrument.

2) Outlier rejection stage: The simultaneous recorded values for the test (or field) and the reference instrument are indicated $V_F(i,j)$ and $V_R(i,j)$, respectively. Both quantities are expressed in units of mV. The constant of the reference instrument is indicated as F_R and that of the test instrument as F, both expressed in units of Wm^{-2}/mV. A given irradiance measurement (in W/m^2) is expressed as $G = F_R V_R = F V_F$.

If the reference instrument is well characterized, its constant will be corrected for the typical conditions (instrument temperature, solar incidence angle, solar azimuth) for a series j and will be expressed as $F_R(j)$.

For each of the N_s series, a test constant (in Wm^{-2}/mV) is calculated as

$$F(j) = F_R(j)\,\frac{\sum_{i=1}^{N_r} V_R(i,j)}{\sum_{i=1}^{N_r} V_F(i,j)}. \quad (3)$$

For each measurement within series j, the individual factors

$$F(i,j) = F_R(j)\frac{V_R(i,j)}{V_F(i,j)} \quad (4)$$

are calculated. Data records (i,j) for which the relative absolute deviations exceed more than 2% the series factor are discarded as outliers [1, Sec. 5.4.1.3]. Explicitly, if the condition

$$\left|\frac{F(j) - F(i,j)}{F(j)}\right| < 0.02 \quad (5)$$

is not satisfied, the record (i,j) is rejected. After discarding these points, $N(j)$ and N_s are updated (if a series has less than 21 points, it is rejected). Finally, Eq. (3) is used to obtain the revised factors $F(j)$ for the remaining series.

A preliminary constant F for the field instrument is obtained as the simple average over the filtered series:

$$F = \frac{1}{N_s}\sum_{j=1}^{N_s} F(j). \quad (6)$$

As a final statistical repeatability check, the standard requires that all series which include or are close to solar noon should have a standard deviation which is less than 0.5% of the final calibration factor F. For all series j for which the average solar angle satisfies $\omega(j) < 5^\circ$ (about 20 minutes from solar noon), the standard deviation σ_j of $F(i,j)$ from its mean $F(j)$ is computed, and the condition $\sigma_j < 0.005\,F$ is tested. Series which do not comply are discarded.

3) New constant calculation: With the remaining series, provided $N_s > 15$, the final constant F is obtained from Eq. (6) and the standard deviation σ_F from this mean is also calculated and reported in the calibration certificate as it represents the variability throughout the calibration.

This organization of the data by series results in more complex (and sometimes awkward) programming schemes. However, it should be noted that the stability of solar irradiance is an important issue when comparing instantaneous readings from different instruments, because the different response time of the test and the reference instrument is a potential cause of discrepancy, unrelated to the accuracy of the test instrument. This effect is present under conditions with high irradiance variability (due to mixed conditions with scattered clouds) and would increase the calibration uncertainty artificially. In order to minimize this effect, the standard demands stable sunshine conditions.

B. Alternative implementation based on robust regression

The alternative implementation of the calibration procedure proposed in this work follows closely the norm ISO-9847:1992 outlined in the previous Section, but considers a different data processing based on robust regression techniques. The initial data collection is the same in both cases, but in the alternative scheme the outlier rejection and the overall data organization differ.

1) Select clear-sky conditions: The data is not organized in series at all. Filters F1 to F4 described in Section II-A are applied sequentially. The set of N_2 points that satisfy these requirements is subject to the data processing described below in order to discard outliers.

2) Discard outliers: A linear relation $\hat{V}_F = A + BV_R$ is assumed between the test and reference signals. Robust regression is an alternative to least squares regression when data are contaminated with outliers or influential observations. In the implementation described here, the robust linear fitting routine `rlm` of the MASS package of the R statistical software [9] has been used. It is based on the iterated re-weighted least squares (IWLS) method [10]. Simply put, this allows the determination of the fit parameters in a way which is less sensitive to potential outliers than in standard root mean squared regression methods.

A robust fit is performed on the N_2 filtered points, and initial parameters A and B are determined. The vector of residuals $\epsilon(i)$ $(i = 1, 2, \ldots N_2)$ is calculated for each pair (V_F, V_R) as

$$\epsilon = \hat{V}_F - V_F = A + B \times V_R - V_F. \quad (7)$$

The mean of the residuals, $\bar{\epsilon}$, and the standard deviation from the mean, σ, are also calculated. In this step, the $N_2 - N_3$ data points whose residual differs from the mean by more than one

Table I
CHARACTERISTICS OF RADIOMETERS

Brand	Model	Serial #	Class [4]	Typical use	Response time (95%)	Typical uncertainty (P95)
Kipp & Zonen	CMP 22	110282	Secondary Standard pyranometer	Reference pyranometer	5 s	2%
Kipp & Zonen	CMP 10	163323	Secondary Standard pyranometer	Precision measurements	5 s	3%
Kipp & Zonen	CMP 6	090778	First Class pyranometer	Field measurements	18 s	6%
Licor	200 R	100551	Photovoltaic radiometer	Field measurements	10 μs	5%

standard deviation are discarded as outliers. The remaining N_3 points satisfy the condition

$$|\varepsilon(i) - \bar{\varepsilon}| < \sigma. \tag{8}$$

If a new regression is done with the clean data $(V_F(i), F_R(i) \times V_R(i))$, the parameter B is the new constant for the test pyranometer.

However, in order to depart as minimum as possible from the standard method, the calibration factor is calculated from the N_3 *clean* data points as the average:

$$F = \frac{1}{N_3} \sum_{i=1}^{N_3} F_R(i) \frac{V_R(i)}{V_F(i)}. \tag{9}$$

The standard deviation from the mean, σ_F, is also calculated and reported. The constant of the reference instrument, $F_R(i)$, is assumed corrected for systematic errors, according to the conditions of each data point i.

C. Uncertainty estimation

The combined uncertainty in F combines quadratically the statistical uncertainty from the previously described methods (type A) with other operational uncertainties due to several factors (type B) [3]. For the examples discussed in this paper, we consider three sources of type B uncertainty: (i) u_{FR} is the standard (P68) uncertainty in F_R as obtained from the calibration certificate of the reference pyranometer and $\delta_{FR} = u_{FR}/F_R$ its relative version, (ii) $\delta_{tr} = 0.25\%$ is the relative standard uncertainty of the calibration procedure by comparison to a standard (estimated based on experience) and (iii) $\delta_{dir} = 0.25\%$ is the relative estimated standard uncertainty associated to the correction of directional errors in the calibration of the reference instrument, also based on experience. For this estimate, and for simplicity, we ignore the small corrections made to the reference constant. Then, the final test constant is of the form $F = F_R < \kappa >$, where $\kappa(i) = V_R(i)/V_F(i)$ and $< . >$ indicates the average over the corresponding data records (Eqs. (6) and (9)). This average has a standard combined uncertainty u_κ and a relative standard combined uncertainty δ_κ, obtained from the dispersion of the readings and the documentation of the data acquisition system. Thus, the relative standard combined uncertainty in F is estimated as

$$\delta_F = \sqrt{\delta_\kappa^2 + \delta_{FR}^2 + \delta_{tr}^2 + \delta_{dir}^2}. \tag{10}$$

The final expanded uncertainty, $U_F = k \times u_F$, is expressed to P95 confidence level using a coverage factor $k = 2$ (assuming normally distributed deviations) and the new constant for the test pyranometer is reported as $F \pm U_F$. The same general framework applies to both methods, although the calculation of δ_κ differs for each method.

III. Some examples

As a first step towards a validation of the proposed method, the data from a recent calibration performed in the Solar Energy Laboratory in July 2018, was processed according to both methods, as described in Sec. II-A and II-B. We shall refer to them as method A (standard method) and method B (alternative method), respectively. The results reported correspond to three different radiometers categorized according to ISO 9060:1990 [4]: a Secondary Standard pyranometer, a First Class pyranometer and a commercial photodiode-based sensor, as described in Table I.

A Secondary Standard pyranometer Kipp & Zonen CMP22 was used as a reference. This pyranometer was last calibrated at PMOD (World Radiation Center, Davos) in April 2014 and has an assigned constant 111.86 ± 0.75 Wm^{-2}/mV, with traceability to the World Radiometric Reference [11] and is normally kept in storage at the Solar Energy Laboratory (LES). Its reported uncertainty is based on a coverage factor $k = 2$ for a 95% level of confidence with a normal distribution. So, its standard combined uncertainty is $u_{FR} = 0.38\,\mathrm{Wm}^{-2}/\mathrm{mV}$ and the relative standard combined uncertainty is $\delta_{FR} = 0.3\%$.

The data was recorded as described in the introduction and according to the general ISO 9847:1992 recommendations. Global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI) where recorded at 1-minute intervals using a Fischer Scientific DT85 data acquisition system. The maximum error in its $30\,\mathrm{mV}$ scale es $u_V = 0.0025 \times V + 0.003\,\mathrm{mV}$, with V in mV. The diffuse irradiance was measured with another Secondary Standard pyranometer (Kipp & Zonen CMP22, serial 120420) equipped with a CM21 Shadow ring, also from Kipp & Zonen. This pyranometer was last calibrated at LES in march 2017. The DHI data was corrected using the daily factor recommended by the manufacturer.

The data collection lasted for fifteen days (10 to 25 of July 2018) and resulted in 9160 daylight data records, which were analyzed according to both methods (A and B). Table II shows a summary of the filtering procedures based on the data of the reference radiometer and the diffuse irradiance data. Only

Table II
FILTERING RESULTS FROM METHOD B

Description	Condition	Records	%
daylight records	$\cos\theta_z > 0$	9160	100.0
solar altitude	$\alpha_s > 20°$	5792	63.2
overshoot	$k_t < 0.90$	9084	99.2
clear sky 1	$k_t > 0.60$	4703	51.3
clear sky 2	$k'_t > 0.60$	4682	51.1
low diffuse fraction	$f_d < 0.20$	1993	21.8
Pass all filters		1750	19.1
After outlier rejection	(average)	1611	17.6

Table III
RESULTS FROM METHOD B

Radiometer model	Previous constant ($\mathrm{Wm^{-2}/mV}$)	New constant ($\mathrm{Wm^{-2}/mV}$)	Expanded uncert. ($\mathrm{Wm^{-2}/mV}$)
CMP10	110.5	110.0	2.4 (2.2%)
CMP6	71.1	71.0	1.5 (2.1%)
200R	94.5	92.4	2.7 (2.9%)

1750 records (less than 20% of the daytime records) pass all the filters and are used in the determination for the new constants. These data points, selected for clear-sky condition, are shown in blue in Fig. 1.

As described in Section II-B, a robust fitting procedure is performed twice with outliers discarded after the first fit using condition (8). The resulting 1611 data records are used to determine the new constant from Eq. (9). The expanded uncertainty is calculated according to Eq. (10) and the results for the three test radiometers are summarized in Table III.

The pyranometers (CMP10 and CMP6) are very stable and their constants are expected to change less than 1% per year, depending on type and age of the instrument. These instruments where calibrated 20 and 25 months ago respectively, so their constants have changed by 0.3% and 0.1% per year, respectively. The photodiode radiometer was last calibrated 12 months ago and has changed 2.2% in a year. The expanded uncertainty for photodiode radiometer's constants is typically larger than that of pyranometers. In all the examples above, the old constant is within the uncertainty range of the new constant as expected.

The same data was processed according to the standard method described in Section II-A. In this case, there is an initial filtering procedure (low solar altitude and diffuse fraction) and the data records are assembled into several series which are then filtered (point-wise) to satisfy the additional standard requirements for stable, clear-sky, data sets.

Table IV summarizes the results obtained taking as initial data set the 9160 daytime records shown in the first row of Table II. The initial filters pre-select mostly clear-sky points. These 643 points are arranged into 72 contiguous series. Each data point in a good series must satisfy $k_t > 0.60$ and $k'_t > 0.60$, in order to enforce clear-sky conditions. Once this set is processed as described in Section II-A, the new candidate constant is determined and outliers are removed. A set of 34 series results after the outlier rejection step and the final constant is determined. The results are summarized in Table V and can be compared to those in Table III.

Table IV
FILTERING RESULTS FOR METHOD A

Description	Records	%
daylight records	9160	100.0
solar altitude & low f_d	643	7.0
contiguous series	72	100.0
clear-sky series	34	47.2

Table V
RESULTS FROM METHOD A

Radiometer model	New constant ($\mathrm{Wm^{-2}/mV}$)	Expanded uncertainty ($\mathrm{Wm^{-2}/mV}$)
CMP10	110.2	3.9 (3.5 %)
CMP6	71.0	2.7 (2.7 %)
200R	92.1	3.5 (3.5 %)

In Table VI we compare the results from both methods. For the three radiometers, the new constants derived from both methods have consistent values. Constants obtained by one method are well within the P95 confidence interval of the constants from the other. In fact, the constants derived from the method A are all within the P67 $(k = 1)$ uncertainty limits of the constants derived from method B and their relative difference is below 0.3% for all radiometers.

Table VI
COMPARISON BETWEEN METHODS A AND B

Radiometer	New constant method B ($\mathrm{Wm^{-2}/mV}$)	New constant method A ($\mathrm{Wm^{-2}/mV}$)	relative difference (%) of alt.
CMP10	110.0 ± 2.4	110.2 ± 3.9	0.2
CMP6	71.0 ± 1.5	71.0 ± 2.7	0.0
200R	92.4 ± 2.7	92.1 ± 3.5	0.3

The expanded uncertainty from method A is consistently larger than the one from method B. Since the dominant term in both cases is the statistical uncertainty from the measurements, this is somewhat unexpected. it is possible that since both measurements are not independent, their covariance must be considered in a more thorough uncertainty analysis. Also, the differences in the outlier removal stage may be affecting the uncertainty assessment. A detailed analysis of its causes will not be attempted at this preliminary stage and it is left for future work.

IV. Conclusions

Two methods for radiometer's calibration based on solar global horizontal irradiance data and the ISO-9847:1992 stan-

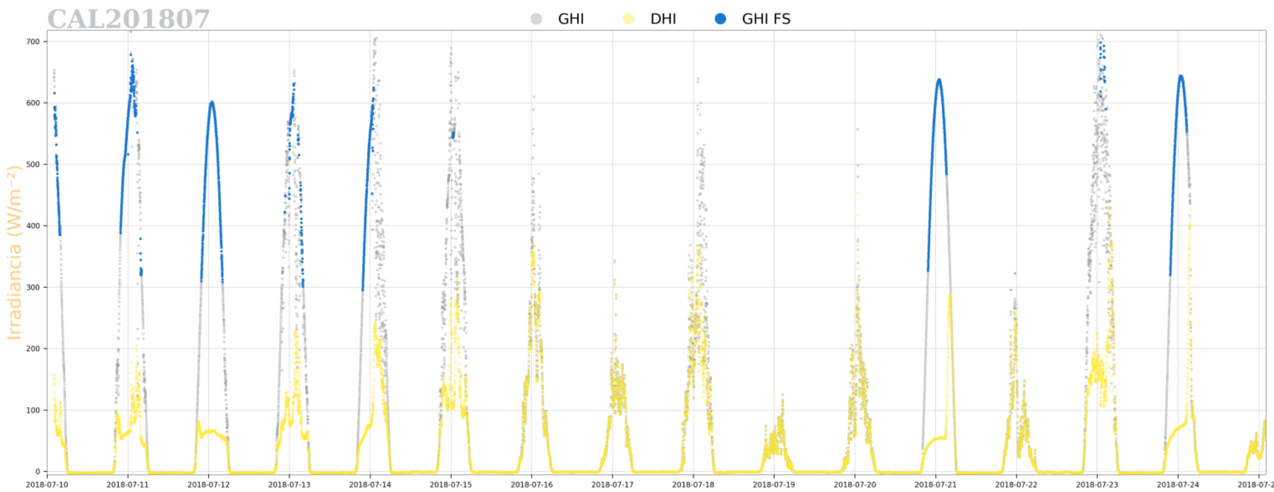

Figure 1. Time series of GHI (gray) and DHI (yellow) irradiance data. In blue, the clear-sky data points that satisfy all filters in Table II.

dard have been discussed and compared in specific examples involving different test radiometers. The standard method works on series of contiguous data points and has the advantage that instabilities in the signals are easier to detect and suppress. However, the data points from the same series cannot be considered independent and in the calculation of the compound uncertainties, the covariance terms may have to be considered, complicating the data analysis with respect to the alternative method, which does not group data into series. Method B filters the data points to select clear-sky conditions and discards outliers using a robust regression fit. It then compares the test and reference radiometers using these data points and obtains the new constant from them. The uncertainty calculations and programming in this method are direct and simple and the results are consistent with those from the standard method.

As a concrete example, three different type of radiometers have been calibrated under both methods and the constants are consistent within one standard uncertainty. In fact, in these examples, the differences in the constants obtained from both methods are below 0.3% in all cases while the typical expanded uncertainty (P95) in the constants is in the range from 2% to 3%. These results show that the alternative data processing scheme gives consistent results, at least under the particular climate of Uruguay.

Finally, we mention that after 25 years in use, the standard ISO-9847:1992 [1] could benefit from a thorough revision and modernization, which could include explicitly the calibration of photodiode radiometers and recommend a unified uncertainty calculation procedure.

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