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Long-term behavior, accuracy and drift of LI-200 pyranometers as radiation sensors in Rotating Shadowband Irradiometers (RSI)

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Abstract

Rotating Shadowband Irradiometers (RSI) are frequently used for solar resource assessment at remote sites due to their significantly higher robustness for soiling, their lower power and maintenance requirements and their cheaper acquisition and operation in contrast to pyrheliometer on tracker systems. The primordial lower accuracy of their photodiode sensor, usually a LI-200 pyranometer from LI-COR Inc., is mainly caused by restrictions of their spectral sensitivity and temperature dependence. However accuracy is notably increased by application of corrections to the raw sensor response. Thus, finally a coincidence of DNI measurements from RSIs with high-precision pyrheliometer measurements within 15 W/m² (root mean square deviation for 10 min averages) for actual values, less than 3 % for daily DNI and within approximately 1.5 % of the monthly and annual sum is reached. Within this contribution, the long-term behavior of the LI-COR sensor is examined with regard to the drift of the photodiode sensitivity. This is analyzed from recalibrations of 30 sensors after one to four years and from long-term studies lasting from one to several years. If a significant drift appears, the corresponding uncertainties can be reduced through recalculation of the previous measurement data for the total measurement campaign. Furthermore, studies about the coincidence and deviation of the responses for global, diffuse and direct irradiance of RSI measurements between several individual RSIs and to reference measurements from high-precision thermopiles are presented for different time resolutions.

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Keywords: irradiation measurement; DNI, pyranometer; photodiode; drift; accuracy; Rotating Shadowband Irradiometer; RSI; RSP

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1. Introduction

Rotating Shadowband Irradiometers (RSI) are frequently used for solar resource assessment due to their usually significantly lower affinity for soiling as well as their lower requirements for power supply and maintenance [1]. This is even more important at remote and unmanned sites where skilled staff is hardly available for proper maintenance of the sensors. Moreover, they hold cheaper acquisition and operation costs than high-precision thermal thermopile sensors. This is especially true when Direct Normal Irradiance (DNI) data is demanded for the prospected site and application. The primordially lower accuracy of the used sensing element of an RSI, usually a LI-200 pyranometer from LI-COR Inc., is mainly caused by restrictions of the spectral sensitivity of the silicon photodiode and its semiconductor-specific temperature dependence [2,3]. However, as the associated measurement errors are systematic, they can be notably reduced by application of corresponding corrections on the raw sensor response [4,5]. Finally, a coincidence to high-precision pyrheliometer measurements of within 15 W/m² RMSD (root mean square deviation) for instantaneous DNI data with 10 minutes time resolution and within 1.5 % of annual sum of the DNI are reached [6,7].

Besides the corrections, the RSI needs to be calibrated thoroughly during a sufficiently large period and separately for the three irradiance components global, direct and diffuse irradiation, including the applied corrections [7,8]. The transferability of the calibrations performed at a site like e.g. the Plataforma Solar de Almería (PSA) to different places and climatic zones could be shown with coinciding results from RSI measurements to high-precision irradiation data from thermopiles within 1.5 % for the long-term DNI sum [9].

In this paper, further investigations on the accuracy and long-term characteristics of RSI measurement data are presented as well as an update on the drift analysis of the sensitivity of the LI-200 photodiode. The latter is derived from the change of the corresponding calibration factor at the recalibrations performed at PSA after between several years of field operation at different sites. Together with the evaluation of long-term parallel measurements, the expectable accuracy of RSI measurements in the field is estimated. The results are valid only for RSI measurements with application of DLR corrections [5] on the raw RSI response and calibration by DLR according to method 1 in [7].

Nomenclature

CF	Calibration Factor
DNI	Direct Normal Irradiance
DHI	Diffuse Horizontal Irradiance
GHI	Global Horizontal Irradiance
PSA	Plataforma Solar de Almería
RMSD	Root Mean Square Deviation
RSI	Rotating Shadowband Irradiometer
WMO	World Meteorological Organization

2. Accuracy distribution of irradiance measurement data from RSIs

The raw response of the LI-200 photodiode sensor was found to vary slightly among individual exemplars in dependence on the radiation intensity [10]. Therefore, the corrections for RSI irradiance measurements have been developed for the three irradiation components (GHI, DNI and DHI) from raw sensor response data sets of more than 20 different RSIs. The corrections consist of empirical functions which have been fitted to meet data from high-precision reference data of thermopile sensors. Common corrections comprehend dependencies on sensor temperature, air mass, incidence angle and (partially) radiation components [4,5]. The coefficients were determined by minimizing the RMSD of the combined corrected RSI data sets from the reference data. A few individual and sensor specific calibration factors finally allow adjusting the measurement results during the calibration process to meet the true irradiance values of each component as precise as possible. Thus the corrections are supposed to yield the true irradiance at average, however with a slight remaining uncertainty of the actual value depending on the prevailing ambient and atmospheric conditions and with a certain sensor specific deviation.

The remaining deviation of the corrected RSI values of a single instrument is shown in Figure 1 for the three irradiation components in dependence on the component irradiance intensity. The plotted data represents a typical data set from measurements with an RSI at PSA. The bulk of the measurement points lies within ±10 W/m², with a notable portion within a range of ±20 W/m², but only few single measurements with a higher deviation. The RMSD is usually in the range of ±7 to ±10 W/m² for the GHI, ±10 to ±15 W/m² for DNI and ±5 to ±8 W/m² for DHI.

The GHI (pyr.) measurement points represent the deviation between the GHI measured with a thermal pyranometer and the calculated reference GHI (from DNI, solar elevation and DHI, according to WMO recommendation). Measured and calculated GHI are supposed to coincide within the measurement uncertainty of the thermopile sensors with an RMSD of ±3 to ±6 W/m² and give an estimation (for comparison purposes) what is at best achievable with premium quality pyranometers for reference GHI data (similar for DNI from pyrheliometers).

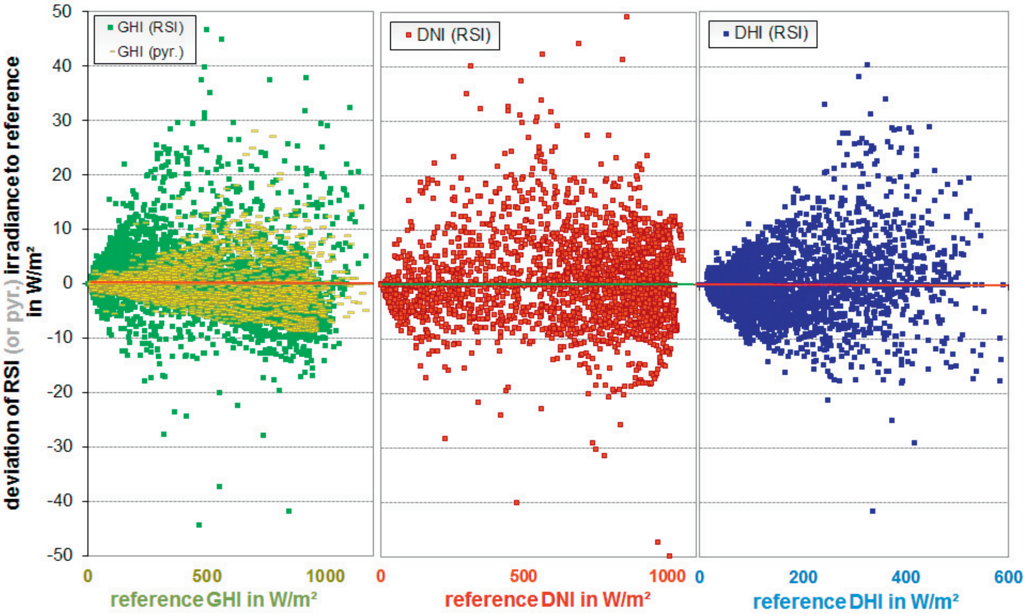

Figure 1: Absolute deviation of a typical data set of RSI-measured irradiance from corresponding high-precision reference data in 10 minutes time resolution for the three irradiance components. For GHI, also the deviation between the GHI measured with a thermal pyranometer and the calculated reference GHI (from the reference DNI and DHI) is plotted as yellow bars and may serve as a measure of the reachable accuracy.

Figure 2 shows a corresponding frequency distribution of the deviation of the corrected RSI measurements from the reference high-precision values for all irradiance components and a measurement period of over one year. The raw, uncorrected DNI from the RSI shows a peak coinciding with the reference value but a broad second local maximum with nearly the same occurrence probability around +20 W/m². Still notable frequencies are found for DNI overestimations by more than 50 W/m². The frequency distributions of the raw GHI and DHI are not plotted here to preserve clarity of the graph. The interested reader may study the impact of the correction functions on the raw data in [5].

With application of the corrections and a thorough calibration of the RSI, the deviations reduce significantly. The DHI clearly has the narrowest and most symmetrical distribution with nearly all values meeting the reference values within ±5 W/m². The distribution for GHI shows its peak also well coinciding with the reference measurements and steep trailing edges within clearly less than ±10 W/m². However, a side bulk with around 3 % occurrence of underestimation of the reference GHI by about 10 W/m² exists. The distribution of the corrected DNI has a fairly symmetric but rather broad distribution with its peak coinciding with the reference irradiation. Flat-angle edges with notable non-zero occurring frequencies up to deviations of more than ±30 W/m² are obvious.

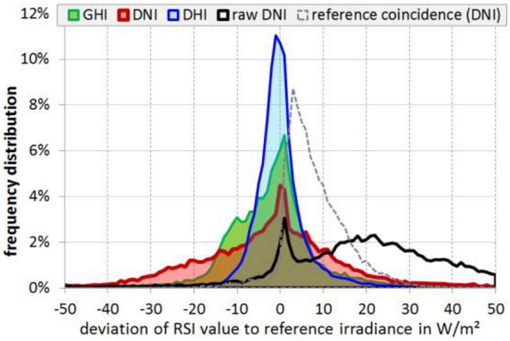

Figure 2: Frequency distribution of the deviation spread of corrected RSI measurements from its corresponding thermopile reference value, for the raw, uncorrected DNI response and the coincidence of the reference measurement values within the measurement uncertainty.

The deviation between calculated and measured DNI of the reference thermopile data set (denominated “reference coincidence”) is included in the plot like above GHI-ref. Identically, it represents the reachable uncertainty of the reference data set; its calculation is described in [11,12]. The reference coincidence has a peak close to zero deviation, falling to insignificant frequencies at 20 W/m² and thus a distribution with a similar width like DHI and GHI.

3. Long-term behavior of RSIs measurement uncertainty

The acceptability of using RSIs for precise irradiance measurements is often questioned even by experts with the reasoning of the lower accuracy when compared to ideally maintained thermal sensors. However, RSIs are acceptable for solar resource assessment and often even preferable according to our investigations and experience: the instantaneous accuracy of RSI measurements is indeed lower than that of top-quality thermopile sensors, but this usually equals out on the long term, if proper calibration and application of corrections are provided. Even more, they usually overcompensate the accuracy issue found for ideal maintenance by a notably lower sensitivity for soiling and thus in remote sites in dry and arid regions often proved to deliver results which are closer to the truth than pyrheliometer measurements [1,12]. Moreover, their procurement costs are less than half of those of automatic trackers with thermal sensors. In the following, the long-term behavior of RSI measurement data is presented and discussed concerning the coincidence with thermopile measurements in daily and monthly resolution.

3.1. Daily irradiation

Figure 3 shows the varying deviation of daily RSI irradiation to thermopile measurements for one exemplary site in a dry and arid region with high aerosol load, altitude approximately 200 m above mean sea level, for the duration of more than 3.5 years of parallel operation.

The thermopiles are supposed to have been cleaned daily, the RSI in weekly scale, with a generally high soiling load at site. During certain periods, the cleaning frequency of both equipments might have been lower due to administrative or time issues of the local personnel. Therefore, periods with longer prevailing over- or underestimating values followed by abrupt changes of the deviations sign are explainable. On the other hand, this gives valuable information on the magnitude of the impact on the data accuracy.

Relative deviations of the daily irradiation range for all components from less than 1 % up to values of 4 % are reached. For DHI - due to the lower absolute value - deviations up to 10 % are observed. In single occasions at heavily cloudy days, even higher relative values are detected and explain the outliers. However, the deviation is more or less equally distributed in both directions. The mean bias is -0.3 % for GHI and -0.5 % for DNI, with a standard deviation of 1.9 % for GHI and 2.6 % for DNI. The thermopile reference measurements, giving the at best achievable uncertainty, coincide in an order of 2 %.

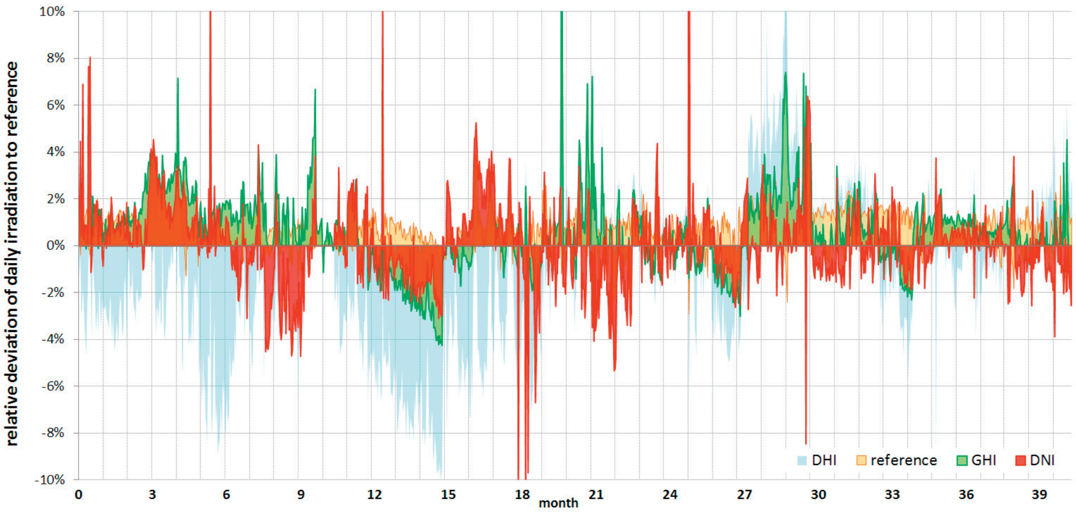

Figure 3: Long-term comparison of more than 3.5 years of daily irradiation from RSI to thermopile sensors at a remote site in arid and dry area with high aerosol load. The “reference” curve represents the uncertainty of the reference measurements according to the coincidence curve above. Each vertical grid line represents the duration of one month.

3.2. Monthly irradiation

The following graphs show monthly irradiation data, Figure 4 for DNI and Figure 5 for GHI. Here measurements from nine different LI-200 sensing heads are presented, mounted at several different sites in different climatic zones. The monthly DNI deviation rarely exceeds the 2 % limit with the exception with three months where the maintenance on site by local staff was poor. The standard deviation of the monthly DNI was 1.2 % at a mean bias of -0.4 %. The deviation of the monthly GHI yields a slightly higher spread to values of more than 3 % and with an only minimal higher standard deviation of 1.4 % at also -0.4 % mean bias.

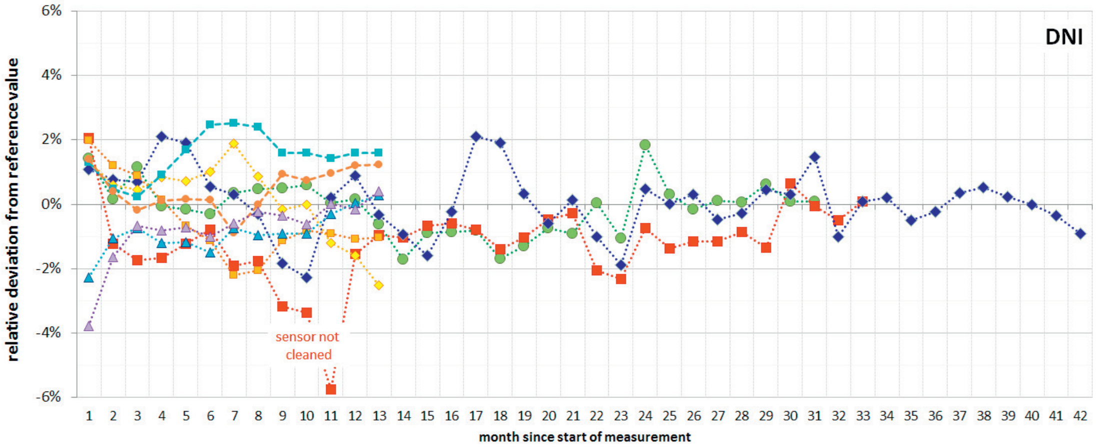

Figure 4: Long-term comparison of monthly DNI from RSI to thermopile measurements at several sites over the number of operated months. Different markers and colours represent different stations.

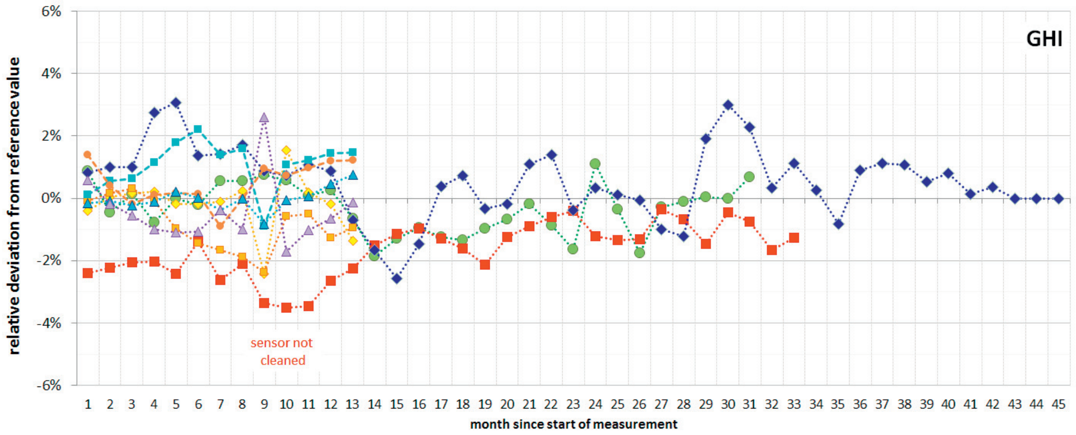

Figure 5: Long-term comparison of monthly GHI from RSI to thermopile measurements at several sites over the number of operated months. Different markers and colours represent different stations.

Figure 6 and Figure 7 show the frequency distributions of the relative deviation of the daily and the monthly DNI (left graph) and GHI (right graph) integrals. The RSI irradiation data remains within an uncertainty of usually less than 3 %. The black thick line represents the mean of all LI-200 sensors.

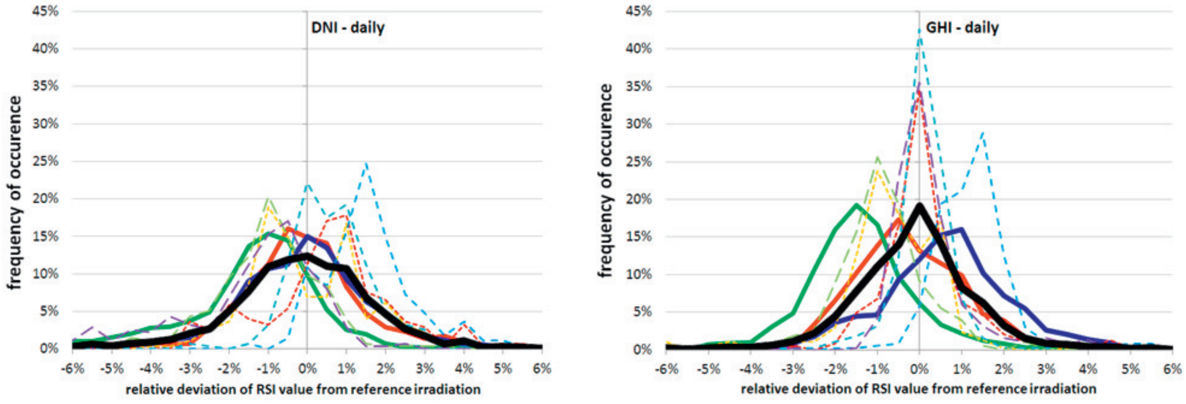

Figure 6: Frequency distribution of the relative deviation of the daily irradiation for DNI (left) and for GHI (right) for 9 different LI-200 sensing elements with respect to thermal sensors. Different lines represent different stations; the black line shows the average of all stations.

With respect to the annual irradiation, the variations equal even more out, leading to a mean bias over the various analyzed sites and instruments with -0.6% for GHI and DNI and a standard deviation of 0.6 % for DNI and 1 % for GHI. Even the instrument at the site with the highest deviation showed a value of -1 % difference to the high-precision reference measurements and thus easily within the uncertainty of even the high-precision equipment. Therefore, properly calibrated RSIs completely fulfill the requirements of solar resource assessment. The definitely higher impact on bad irradiation measurements originates from often inexistent, lacking or even bad maintenance and insufficient control of the measurement equipment. The knowledge about the necessity on regular control of the equipment and data is regrettably not as wide spread as it should.

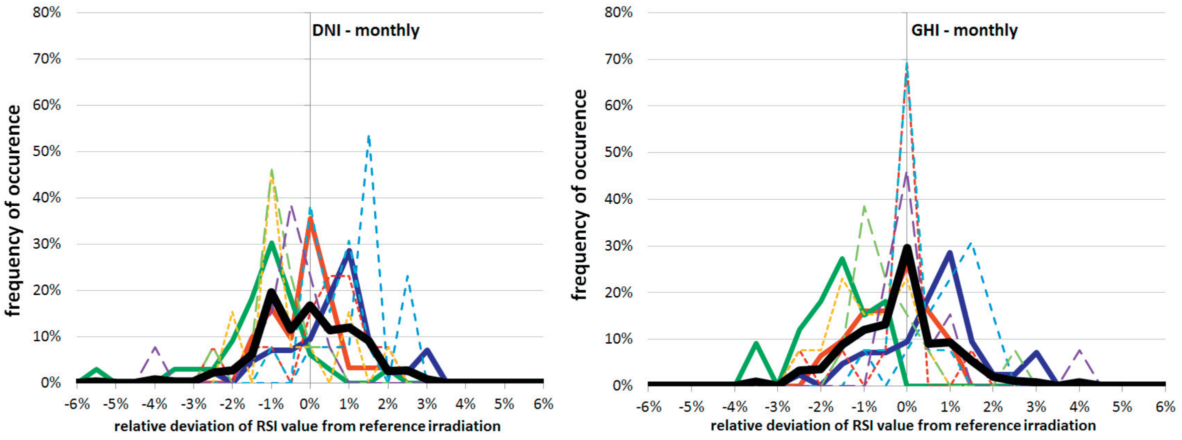

Figure 7: Frequency distribution of the relative deviation of the monthly irradiation for DNI (left) and for GHI (right) for 9 different LI-200 sensing elements with respect to thermal sensors. Different lines represent different stations; the black line shows the average of all stations

4. Drift of the LI-COR LI-200 photodiode sensor sensitivity

The stability of the sensitivity of the LI-COR LI-200 photodiode was investigated from the change of the calibration factor CF derived during between two calibrations of the RSI sensor by DLR at the Plataforma Solar de Almería. In total, 30 recalibrations of RSPs have been analyzed until now. Details on the calibration procedure can be found in [5] and [7].

4.1. Drift of the photodiode sensitivity from recalibration

The long-term behavior of the LI-COR sensor is examined with regard to the drift of the photodiode sensitivity. Figure 8 shows the relative drift of the sensitivity of the LI-200 from the change of the RSI calibration factor CF for the DNI component in dependence on the time since the last calibration. While most of the sensing heads remain rather stable, some even within the 1 % calibration accuracy of the reference thermopile instruments, some single exemplars show a notable higher drift within the range of 2 %/a as given by the manufacturer. A recalibration of the sensor heads after 2 years remains nevertheless recommendable.

The calibration factor for GHI and DHI is not presented here; its drift however is in the same order of magnitude.

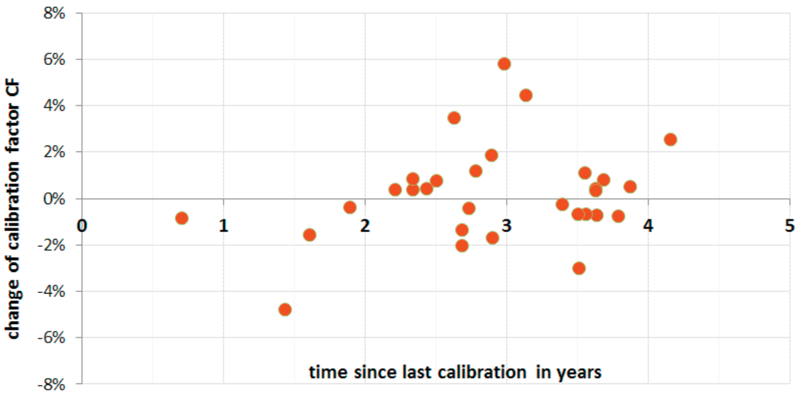

Figure 8: Magnitude of the change of the DNI calibration factor CF over the period between calibrations.

The annual drift rate of the sensitivity of the LI-200 pyranometers is calculated from the change of its CF and the corresponding period since the last calibration. Figure 9 illustrates and lists the derived values. Besides one sensor with a change of 3.4% within one year, all sensors are within the specified range. Indeed the instrument got conspicuous delivering suddenly suspect values; possibly this was caused by an external influence. If such a significant drift is detected with the recalibration, the previous measurements should be recalculated with a temporally interpolated series of calibration constants in a first approximation unless a reason connected to a certain event can be stated as probable cause for the change of the sensor sensitivity. The measurement error usually remains within the order of the drift plus usual RMSD. Nevertheless, the sensor head should be examined and preferably exchanged.

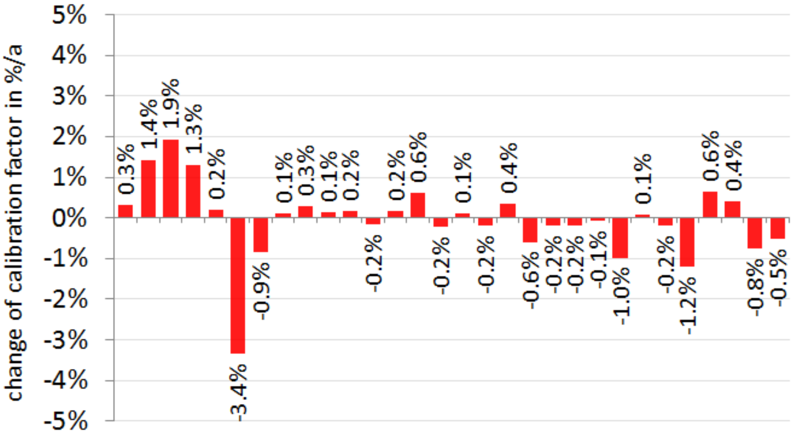

Figure 9: Change of calibration factor CF (per year) since last calibration.

4.2. Duration of a thorough RSI calibration under natural daylight conditions

The LI-200 pyranometer is purchased pre-calibrated with an uncertainty of ± 5 %, typically ± 3 % [13] as sensor for GHI measurements, frequently used in agriculture and greenhouse applications. Pre-calibration is done against an Eppley Precision Spectral Pyranometer (PSP) under daylight conditions for several days. For its application in RSIs, where also DHI and DNI is measured, the RSI sensor head needs a recalibration again to reach the required accuracies. Whereas the spectral distribution for global irradiance does not vary strongly with time and day, it does for direct beam and even more for diffuse irradiance. Hence, a calibration of the RSI at different days results in different calibration factors *CF* depending on the prevailing weather and corresponding atmospheric conditions. The systematic deviations of actual raw measurement values are usually widely adjusted by applying the mentioned corrections; however, the whole variety of spectral and atmospheric conditions should be available during the calibration period with sufficient frequency to derive proper calibration factors. DLR is performing RSI calibrations at the Plataforma Solar de Almería (PSA) with comparisons of corrected RSI irradiance values against high-precision measurements acquired with high quality and daily maintained thermal sensors [6,14].

The evolution and fluctuation of the potential calibration factors for DNI is shown in Figure 10 as deviation of the *CF* when derived with shorter duration of the calibration compared to the mean *CF* as calculated from the whole period. The *CF* is derived exemplary for each single day within the half year period from July to December and as floating values with weekly and monthly duration. The graph shows clearly a high variation of the *CF* in daily scale with deviations from less than -6 % to over +2 % to the “true” mean value, depending on the weather conditions of the respective day. This becomes better in weekly scale, however still with maximum deviations of less than -4 % to nearly +2 %. For a duration of one month, the deviation remains within an uncertainty of approximately ±1 %. Besides, no seasonal dependence is observed within the analyzed period. It is supposed that during approximately one month all relevant weather conditions occur with sufficient frequency at the location of the PSA to allow an equilibrated calibration. Thus, a minimal duration for the calibration of RSIs of not below one month is recommended for PSA site.

The sufficiency of the one month period and the finally truly necessary calibration period when all relevant sky conditions have occurred is of course dependent on the location and may easily be different at other sites. For example in regions with long-lasting strongly hazy and aerosol-burden skies like the Arabian Peninsula, atmospheric conditions with clean, dark blue clear skies with irradiances up to 1000 W/m² are seldom in summertime and may require correspondingly extended calibration periods. The PSA site however seems adequate for the performance of calibrations throughout the complete year. Validation at several other sites in MENA region and Asia confirm the PSA calibration within 1.5 % [9].

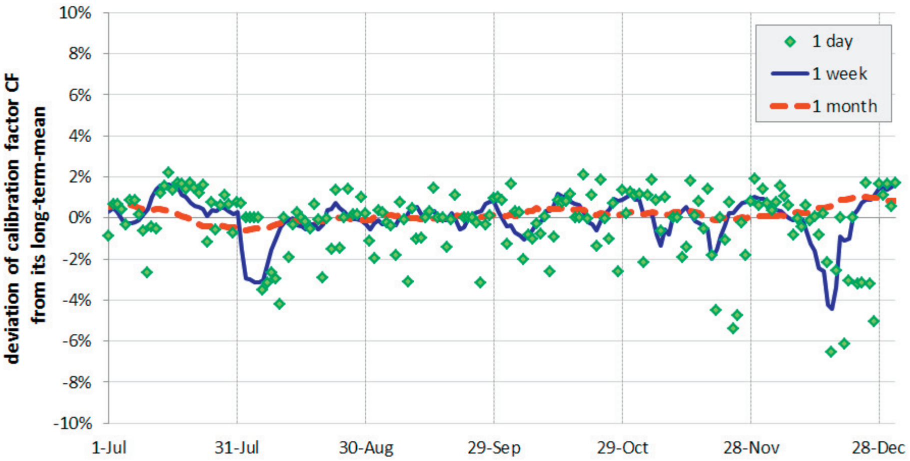

Figure 10: Long-term comparison of pyrheliometer and RSI measurements, variation of calibration constant CF for DNI with duration of the calibration process.

5. Summary and outlook

The accuracy of RSI irradiance values and irradiation data has been studied from parallel measurement data of RSIs and high-precision thermopile instruments available from several sites worldwide in differing climatic zones. The analysis was performed for different time scales of the data for RSIs calibrated at PSA and via application of DLR corrections for the RSI raw response. With proper installation, an accuracy of ±7 W/m² RMSD is reached for GHI and about ±10 to ±15 W/m² for DNI for mean irradiance values with 10 minutes time resolution. The RMSD for DNI in the case of RSIs exceeds that for GHI due to the calculation of the DNI from the uncertainty-afflicted GHI and DHI. As these RMSDs are widely constant over the irradiance intensity, it translates to the corresponding percentage depending on the actual irradiance value; giving a percentage value is only reasonable with information on the range and frequency of the irradiance data it refers to.

In daily scale, an indication of relative values is feasible: the overall uncertainty of GHI and DNI is similar for both within ±3 % with an RMSD of ±2 % for GHI and with ±2.6 % for DNI values. For monthly resolution, the DNI gets with an RMSD of ±1.2 % even better than the GHI with ±1.4 %. At average from available measurement data, the annual DNI derived with an RSI according to the cited calibration and correction methods showed a standard deviation of ±0.6% and ±1 % for GHI. On the long run, no severe drift was detected, the deviations on single days and at special atmospheric conditions equal out.

Besides the accuracy and long-term study, the drift of the LI-200 photodiode was analyzed. Whereas most of the 30 recalibrated LI-COR sensors showed a merely small annual drift rate, a few suffered higher drifts in the order of 2 % per year, one even more. Recalibration of the RSI sensor heads after 2 years is recommended.

Furthermore, the RSI needs to be calibrated before use. Otherwise, erroneous measurement data of up to 8 % and more may result [7]. A thorough calibration at a suitable site with and against high-precision thermopile instruments is preferable to a short-term calibration on site. The calibrations at PSA with the corrections developed by DLR deliver valid measurement results within the stated range also at other sites.

Further work will analyze the weather conditions in detail to derive a method to evaluate the conditions during the calibration and optimize the duration of the calibration period.

A detailed study about RSI performance is actually performed under the COST-WIRE framework at MeteoSwiss in Payerne [15]. The results are expected to be published by the end of 2013. Although RSIs fulfill the requirements for solar resource assessment, further enhancements of the sensor accuracy and the value of the RSI data are being investigated. One example is the development of algorithms that determine circumsolar irradiance using conventional RSIs [16]; the integration of this parameter in RSI measurement data will be available upcoming.

More detailed information on the important topic sensor soiling, which for solar resource assessment at remote locations easily outranges the here cited accuracies, can be found in [11].

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