Report on established joint calibration facility for pyrheliometers at PSA to be operated as ACCESS facility

SFERA II Project	
Solar Facilities for the European Research Area -Second Phase	
Grant agreement number:	312643
Start date of project:	01/01/2014
Duration of project:	48 months
WP11 – Task 1.X	Deliverable 11.2
Due date:	12/2015
Submitted	12/2015
File name:	SFERA2PyrhelCal_D11_2
Partner responsible	DLR
Person responsible	Bijan Nouri
Author(s):	Bijan Nouri, Stefan Wilbert, Ginés García, Lourdes Ramírez, Luis Zarzalejo, Rita Valenzuela, Francisco Ferrera, Christoph Prahl
Dissemination Level	public

List of content

Executive Summary

This deliverable is a result of WP 11 (Task 1.A. Standardized calibration of solar irradiance sensors. Joint facility to calibrate irradiance sensors with high accuracy) within the Joint Research Activities.

Research centers and industry need joint calibration facilities and agreed procedures to calibrate sensors which are used for thermal performance testing and for measuring the solar resource. These sensor calibrations lead to the required high measurement accuracy and reliable test results over all European research centers and industry. Only by achieving high accuracy in the European test facilities, innovative products (collectors, receivers, solar sensors, etc.) can be qualified and developed together with industry.

High quality field pyrheliometers and pyranometers are thermopile sensors which require periodic calibration. The uncertainty caused by the calibration is the most relevant contribution to the overall uncertainty of thermopile sensors. By means of thorough calibration with a well maintained absolute cavity radiometer (ACR) the uncertainties can be reduced considerably. Thus, by establishing a joint calibration facility, the performance of the instrumentation used for CSP efficiency testing at European research centers and in industrial projects can be improved significantly.

The following tasks are carried out in the framework of the calibration activities.

- Set-up of calibration facility for field pyrheliometers and field pyranometers at PSA operated/used by the different research institutions following ISO 9059, ISO 9846 and ISO 9847.
- Parallel measurements of the aerosol optical depth, circumsolar radiation and documentation of the sky conditions with all sky imagers.
- Ensure WRR (World Radiometric Reference)-traceability of solar radiation calibration by participation in absolute cavity radiometer calibration campaigns with DLR’s and CIEMAT’s absolute cavity radiometers.
- Calibration campaigns of field irradiance sensors to improve and standardize the quality of European research facilities. (DLR, CIEMAT, CNRS). In 2016 a 2-week stay (or twice 1-week) of CNRS to calibrate their pyrheliometers at PSA and to exchange know-how is planned. The establishment as an ACCESS facility is planned to be completed by the end of 2017.

This report summarizes the main characteristics of the developed facility. The calibration test bench for pyrheliometer and pyranometer has been set up at the *Plataforma Solar de Almería* (PSA), and includes:

- A heliostat engine which is used as solar tracker. On this tracker a mounting plate for the reference and field pyrheliometers has been installed.

- A Kipp&Zonen 2AP tracker with shading structures for the DHI reference pyranometer.

- A mounting table for pyranometers, temperature - humidity measurements, and precipitation.

- A whole sky imager.

- A wind mast with wind speed, wind direction and ambient temperature measurements.

During June 2014 and September - October 2015 two measurement campaigns have been successfully performed. In total 34 pyrheliometers (19 in 2014 and 15 in 2015) and 18 pyranometers (9 in 2014 and 9 in 2015) have been calibrated already.

The ISO 9059 (pyrheliometer) [ISO, 1990] and ISO 9846 (pyranometer) [ISO, 1993] were used as basis for the calibration process. The pyranometer calibration is performed according to the continuous sun and shade method for most of the pyranometers. In addition, the reference CMP22 pyranometer has been calibrated according to the alternating sun-and-shade method (ISO 9846, [ISO, 1993]).

1 Introduction

The EU-funded research project – SFERA2 - aims to boost scientific collaboration among the leading European research institutions in solar concentrating systems, offering European research and industry access to the best research and test infrastructures and creating a virtual European laboratory. The project incorporates the following activities:

- Transnational Access: Researchers will have access to five state-of-the-art high-flux solar research facilities, unique in Europe and in the world. Access to these facilities will help strengthen the European Research Area by opening installations to European and partner countries' scientists, thereby enhancing cooperation.
- Networking: These include the organisation of training courses and schools' to create a common training framework, providing regularised, unified training of young researchers in the capabilities and operation of concentrating solar facilities. Communication activities will seek to both strengthen relationships within the consortium, creating a culture of cooperation, and to communication to society in general, academia and especially industry what SFERA is and what services are offered.
- The Joint Research Activities aim to improve the quality and service of the existing infrastructure, extend their services and jointly achieve a common level of high scientific quality.
- In the context of the Sfera II project WP 11.1, one of the most relevant deliverables is related to the installation of a joint facility for pyrheliometer and pyranometer calibration.

Pyrheliometers are devices that can be used to measure direct normal irradiance (DNI) when pointed towards the sun using a solar tracker. Pyranometers are devices used to measure global horizontal irradiance (GHI) when they are horizontally levelled with free view to the upper hemisphere. Pyranometers measure diffuse horizontal irradiance (DHI) when they are horizontally levelled with a free view to the upper hemisphere except of a small shading structure that blocks direct sunlight from falling on the pyranometer sensor.

Pyrheliometers are calibrated following the ISO 9059 by comparing the voltage signal of the tracked test pyrheliometer to the DNI from one or a group of reference pyrheliometers.

Pyranometers are calibrated with three different methods. One option following the ISO 9846 compares the voltage signal of the test instrument obtained in the GHI measurement position to the GHI calculated from the DNI and DHI measurements of a reference pyrheliometer and a shaded reference pyranometer. Another option from ISO 9846 is to compare the DNI from a reference pyrheliometer to the DNI derived from the test pyranometer which is subsequently used to measure voltages proportional to GHI (unshaded) and DHI (shaded). Due to the alternating shading and unshading this method is called alternating sun-and-shade method (ASSM). The third option follows ISO 9847. Here, a calibration is performed by comparing a test pyranometer in GHI measurement position to a reference pyranometer.

2 Description of the calibration facility

A calibration test bench for pyrheliometer and pyranometer was implemented at the *Plataforma Solar de Almería* (PSA). The test stand consist of a heliostat which is used as tracker for the reference and field pyrheliometers, a Kipp&Zonen 2AP tracker with shading structures for the DHI reference pyranometer, a whole sky imager which observes the cloud conditions and wind speed, wind direction, ambient temperature and humidity measurements. The entire measurement setup is located within the PSA METAS station (see **Figure 1**).

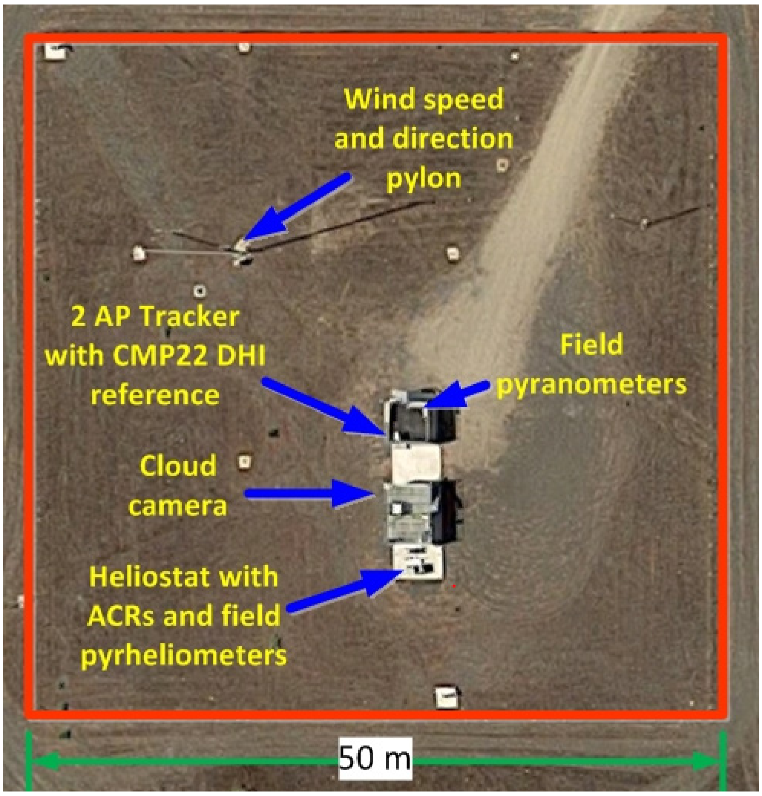

Figure 1. **Overview of calibration measurement setup at the PSA METAS station.**

2.1 Description of references devices

According to the standards that are going to be applied, two different types of reference instruments are needed.

2.1.1 Direct normal irradiance reference

In the case of the pyrheliometer calibration as well as pyranometer calibration the best reference that can be used is an absolute cavity pyrheliometer. Absolute cavity pyrheliometers are often called absolute cavity radiometers (ACR).

There are two ACRs devoted to this installation:

- PMO6-CC 0301 (CIEMAT). This device took part in the International Pyrheliometer

Comparisons IPC-XI and IPC-XII, ensuring the WRR (World Radiometric Reference)-traceability.

- PMO6-CC 0807 (DLR). This device took part in the American National Pyrheliometer Comparison (NPC-2014).

Additional reference devices belongings to the METAS team could be used in specific calibration campaigns.

2.1.1 Global and diffuse irradiance reference

For pyranometer calibration, Kipp&Zonen CMP22 pyranometers are used as reference sensors. There are two of them devoted to this installation:

- SN 140048 (CIEMAT).
- SN 110288 (DLR).

These sensors are traceable to the World Radiometric Reference.

2.2 Pyrheliometer test bench

As a first step, the tracking system of the calibration set-up has been designed in-house by the Instrumentation and Data Group of CIEMAT. This tracking system was installed at METAS (see Figure **2**).

The heliostat tracking system has two movable axes that change their orientation throughout the day, following the sun's path during the calibration period. The device is driven by motors. For exact positioning each axis is equipped with a rotary encoder that allows the sun to be tracked to a precision of less than 0.05 degrees. In addition, a sun sensor is installed to allow a tracking confirmation.

In order to place the devices (references and field pyrheliometers) a mounting plate with a total surface of 1.02 m^2 is added to the heliostat tracking system.

The heliostat is also equipped with a completely data acquisition system (DAS). To perform this, an IMP 35951C model card, with 15 bits + sign digital to analog converter is used; that brings the measurements of 40 channels each second with a global maximum error of +/-9 μV to the range from 0 to 20 mV.

The DNI reference ACRs are placed inside a cabinet. Figure **3** illustrates schematically the used pyrheliometer mounting positions on the mounting plate.

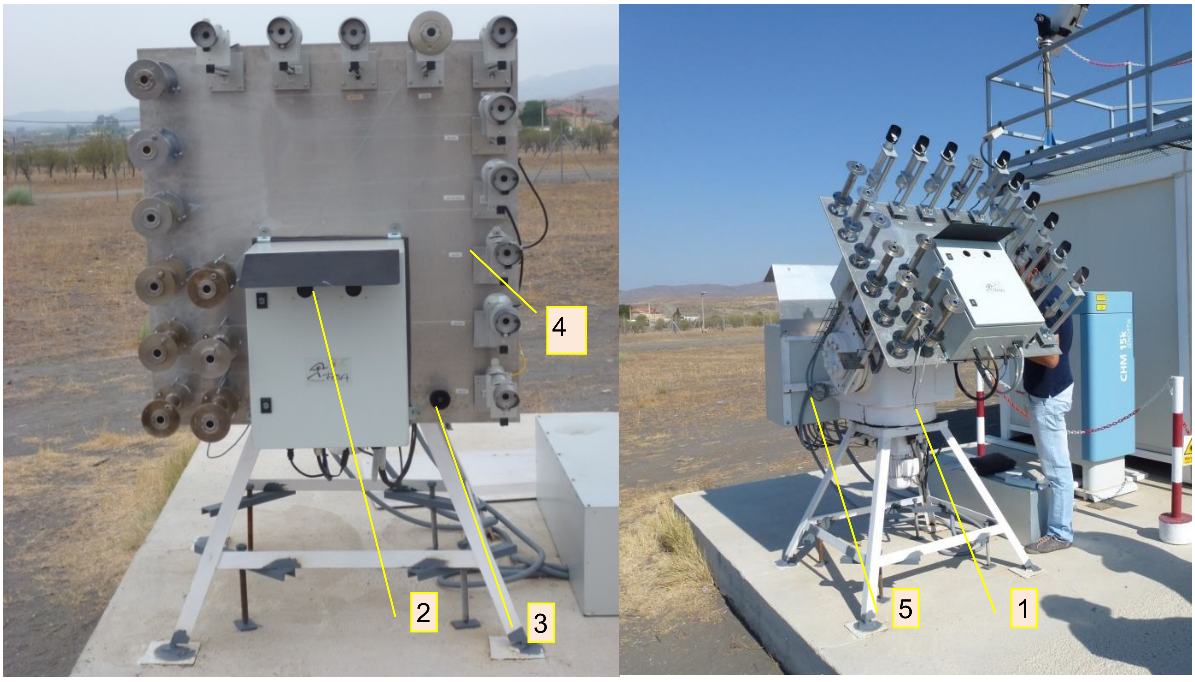

Figure 2. **METAS pyrheliometer calibration test bench: 1) two axes tracked heliostat, 2) two reference ACRs inside cabinet with apertures, 3) sun sensor, 4) mounting plate with field pyrheliometers and 5) cabinet DAS and heliostat controlling.**

	Pos.: 9	Pos.: 10	Pos.: 11	Pos.: 12	
Pos.: 8					Pos.: 13
Pos.: 7					Pos.: 14
Pos.: 6					Pos.: 15
Pos.: 5	Pos.: 19	Abs cavity 1	Abs cavity 2		Pos.: 16
Pos.: 3	Pos.: 4	CIEMAT	DLR		Pos.: 17
Pos.: 1	Pos.: 2			sun sensor	Pos.: 18

Figure 3. **Schematic illustration of pyrheliometer positions according to Figure 2 left.**

2.2.1 Mounting for reference pyrheliometers

Both ACRs are mounted via a M8 screw directly on the pyrheliometer mounting plate. Insulating rings and plates are used to prevent ground-loops. Ground-loops occur simply speaking when you have too many grounds. A correct ground connection leads electrical noise outside of the system to the ground. If ground-loops are possible noise could lead to an unwanted current flow and interferences.

Since the ACRs are directly mounted to the mounting plate parts of the cabinets back plate had to be removed. In order to ensure the seal effect of the cabinet insulating material is used in between the cabinet and the pyrheliometer mounting plate. The alignment of the ACRs is realized via set screws. Both sensors are properly aligned when the included alignment target is in center of the solar image.

2.2.2 Mounting for field pyrheliometers

The Eppley field pyrheliometers are mounted via three screws or threaded rods to the mounting plate. The alignment is realized via two screw nuts at each screw or threaded rod. Other pyrheliometers such as Kipp&Zonen, Hukseflux and Eko devices need an additional support structure. The support structure consists of two clamps, mounted on an adjustable base plate (Figure **4**).

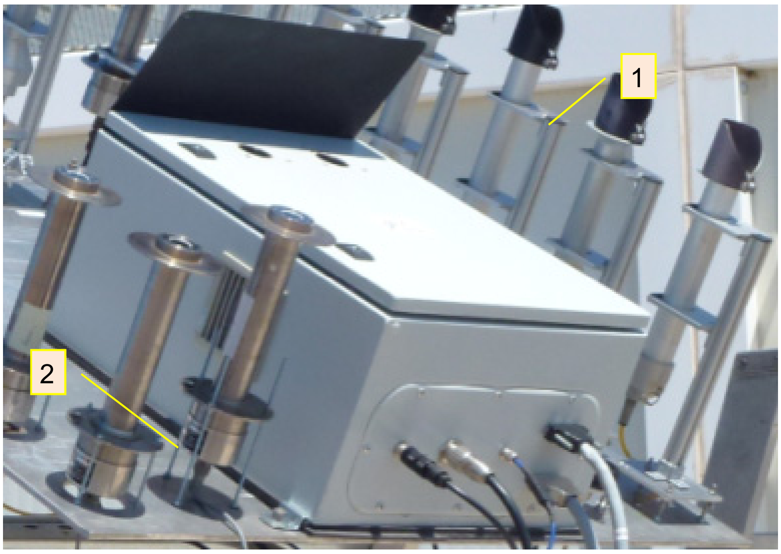

Figure 4. **Mounting structure for field pyrheliometers: 1) support structure for Kipp&Zonen, Hukseflux and Eko pyrheliometers and 2) Eppley NIPs mounted via three threaded rods.**

2.2.3 Pyrheliometer DAS description

For the pyrheliometer measurement an overview of the DAS is presented in the following. The entire system is connected to a control computer which is located in the electronics laboratory of the PSA. The control computer communicates via Ethernet to an industrial serial device server at the METAS site. The industrial serial device server in turn communicates via RS 232 and RS 485 to the remaining components, except the two measures of IMP analogue reed relays which communicate directly with the control computer via SNET.

The IMPs, which are mainly used as A/D converter for the mV signals of the field pyrheliometers, are annually calibrated and have an accuracy of about 9 µV at a range of ±20 mV. Temperature thermistor signals of field pyrheliometers are converted via a transmitter to a 4-20 mA signal and connected to the IMPs A/D converter as well. PT100 temperature signals of field pyrheliometers are connected to an ADAM 4015 A/D converter, which communicates via RS 485 to the industrial serial device server. The test pyrheliometer data is sampled at least once per second and stored every second.

The planned measuring process is defined by the user in advance. The user has to define the number of series and the starting time. The selected settings for the SFERA2 calibration facility are the following. Each series consists of 20 ACR irradiance measurements with a time gap of 2 minutes between two ACR values. The ACR is operated as follows. 60 seconds of open phase with open entrance aperture are followed by a 60 seconds long closed phase with blocked entrance aperture. In the last 10 seconds of each phase the actual measurement takes place with 10 seconds integration time. Hence, each ACR DNI reading corresponds to a 10 second average at the end of the open phase. Between two series a time gap of 4 minutes occurs. When the measuring process is started the internal time of the heliostat and the PMO6 control units are synchronized with the control computer time, which in turn is synchronized with an online time server (UTC).

During measurements the control computer writes an ASCII file, with a resolution of a value per second, for all the signals except the ACR signals. The timestamps are given by the control computer time. The signals of the ACRs are written to the same ASCII file with their own timestamps from the PMO6 control units.

2.3 Pyranometer test bench

The pyranometer test bench is set up on top of the CIEMAT METAS container (see Figure **5**). A mounting plate is used for the field pyranometers. The DAS for all pyranometers

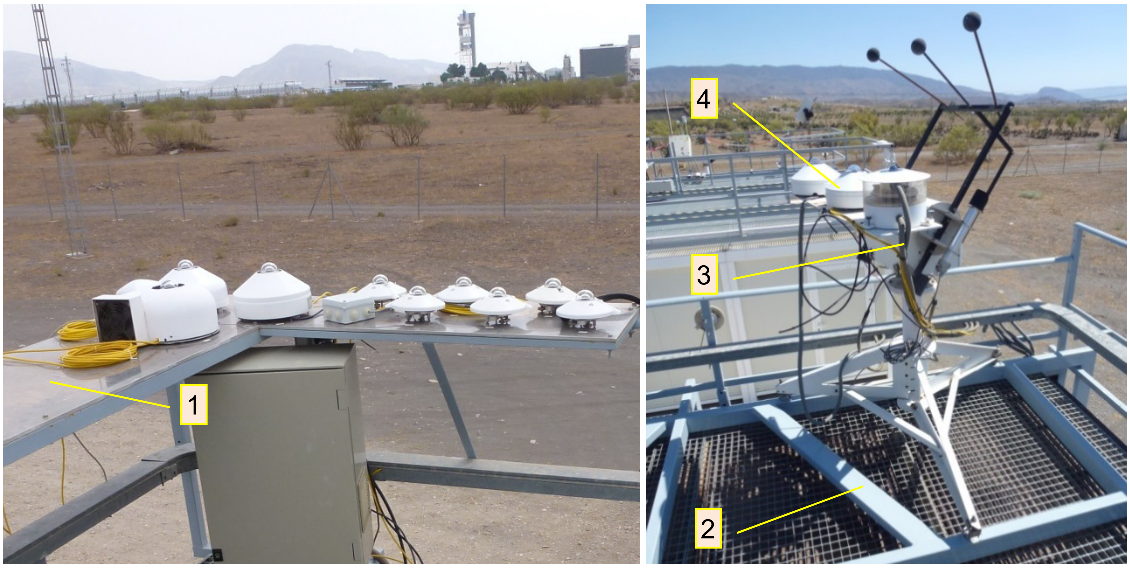

Figure 5. **METAS pyranometer calibration test bench: 1) mounting plate with field pyranometers. 2) CIEMAT container platform: roof decoupled and enforced structure for sun tracker 3) Kipp&Zonen 2AP sun tracker and 4) Kipp&Zonen CMP22 reference pyranometer.**

is positioned inside a cabinet underneath the mounting plate. A Kipp&Zonen 2AP solar tracker with the Kipp&Zonen CMP22 reference pyranometer (DHI) are also located at the roof of the container. To ensure a stable basis for the 2AP solar tracker, an enforced structure has been erected, which is decoupled from the accessible container grid floor.

2.3.1 Mounting of unshaded pyranometers

All pyranometers are mounted via three screws to the mounting plate. The alignment is done using the sensor's own adjusting screws. For the devices with ventilation, the ventilation unit is aligned and the pyranometer is mounted on top of the unit. The ventilation units use the same system of adjusting screws. Both sensors and the ventilation units have integrated water levels for the alignment. Also the reference pyranometer for the ISO 9847 based calibration is mounted in this way.

2.3.2 Mounting for alternating sun-and-shade method (ASSM)

The shading structure of the DHI reference measurement is modified for the alternating sun-and-shade method, which allows calibrating a field pyranometer using a reference pyrheliometer. For this, the rod of the shadow ball has been cut in half and a lockable hinge is placed in between the rod's halves. The hinge can be unlocked manually and the shadow ball can be replaced easily from the shade position (DHI measurement) to the sun position (GHI measurement) and vice versa (see Figure **6**).

Figure 6. **2AP sun tracker with modified shadow structure for alternating sun-and-shade method: Left: shadow ball in shade positon over reference pyranometer (DHI measurement). Right: shadow ball in sun position reference pyranometer free from shade (GHI measurement).**

2.3.3 Pyranometer DAS description

Campbell scientific dataloggers (CR1000 and/or CR3000) are used as DAS for all field pyranometers, including the CMP22 reference pyranometer. The DAS is positioned inside a cabinet underneath the pyranometer mounting plate. The cabinet is connected to a 220 V power supply. A MEANWELL HLG-240H mains adapter provides 12 V DC, which is needed by the CR1000, the CR3000 and the ventilation units. Air circulation is ensured via a fan.

Signals are sampled and stored every second.

The Campbell scientific datalogger is used together with a Campbell scientific NL 115 Ethernet interface and CompactFlash module, which is equipped with a removable CompactFlash card, thus long term data storage is included. The channel configuration is stated in Table 1.

Table 1. Used channels for pyranometer mV signals with accuracies.

	Datalogger channel	accuracy
Field pyranometer	CR1000 single ended ±25 mV CR3000 differential ±20 mV	±(0.06% of reading +3x6.7µV+3µV) ±(0.04% of reading +1.5x0.33µV+1µV)
Reference pyranometer	CR1000 differential ±7.5 mV CR3000 differential ±20 mV	±(0.06% of reading +1.5x2µV+1µV) ±(0.04% of reading +1.5x0.33µV+1µV)

Half bridges with a 10 kΩ resistor are used for the temperature measurements, both for thermistors and PT100. The shields of the signal cables are connected to the datalogger ground which in turn is connected to the cabinet ground and via a protective conductor terminal to the ground of the 220 V power supply.

3 Calibration execution

3.1 Prearrangement and preparation

Well before each calibration campaign, one to two weeks are selected for the planned campaign. Shortly before the measurements start, the weather conditions are reviewed in order to establish the measurement time for the next day.

In the morning of each test day, the teams check that all involved devices including the radiometers are working correctly and ensure that the DAS and the solar tracker are working properly as well. All instruments have to be cleaned before starting the calibration day and have to be kept clean throughout a measurement day (see section 3.2). Cleaning has to be performed carefully in order to allow for consistent results.

- Pyrheliometer calibration facility: CIEMAT staff verifies all components. The measuring process for the pyrheliometer test bench has to be programmed and started via the control computer. Once the heliostat is in tracking mode, the alignment of the heliostat and pyrheliometers is controlled and adjusted if required. The heliostat position can be controlled via an alignment target. When the heliostat alignment is confirmed, each pyrheliometer (including ACRs) is controlled via its proper alignment target. The alignment of a pyrheliometer is corrected if the light spot is not centrically on the target. Thus, alignment errors are always much smaller than the slope angle of the pyrheliometers minus the solar disk half angle (<<0.73°, for 1° slope angle).
- Pyranometer calibration facility: DLR staff is responsible for this part of the installation. The alignment of the pyranometers is controlled via a water level which is integrated into the sensor/ventilation unit housing. A readjustment is necessary if the air bubble of a pyranometer is not centered. Depending on the pyranometer calibration method the alignment of the shading structure relative to the sensor has to be controlled and corrected if required.

3.2 Observation and maintenance during the calibration

After the steps described in the previous section the installation is ready for the calibration. During the calibration the alignment and cleanliness of the devices are checked at least once every hour. If necessary, the devices are realigned or cleaned. Weather conditions are observed and noted during the measurements. Depending on the conditions the calibration can/has to be paused or stopped till the next measurement day. The required meteorological conditions are explained in more detail in section 4. A detailed quantitative analysis of the weather conditions as wind direction, etc. are carried out as part of the post processing via cloud cameras and data from the meteorological stations. Depending on the performed calibration method different devices have to be controlled and action has to be taken if required. In the case of the alternating sun-and-shade method further activity is required as explained below.

- Pyrheliometer calibration with a pyrheliometer reference (ISO 9059). Only the solar tracker test bench including the pyrheliometers is needed.
- Pyranometer calibration:

(1) Alternating sun-and-shade method (ASSM, ISO 9846) using only a pyrheliometer as reference. The pyranometer that is calibrated is subsequently used in GHI measurement constellation and DHI constellation. For that, the automatically tracked shading ball has to be replaced every two minutes from the sun position with no shadow over the reference sensor (GHI measurement) to the shade position with shadow over the test sensor (DHI measurement) and vice versa. The alignment of the shading ball has to be controlled frequently in addition to the radiometers and the DAS. At least 10 series of should be measured. A series consists of (n+1) shaded intervals and n exposed intervals. Each series should include at least 3 intervals, but should not take longer than 36 minutes. The shadow ball is moved immediately after the reading at the end of each shaded/exposed interval.

(2) Continuous sun-and-shade method (CoSSM, ISO 9846): using a reference pyrheliometer and a shaded reference pyranometer to calculate the reference GHI. The test pyranometer measures a voltage proportional to GHI which is compared to the reference GHI. The alignment of the shading device of the reference pyranometer has to be controlled in addition to the radiometers and the DAS.

(3) Pyranometer outdoor calibration with a reference pyranometer (ISO 9847). In this case only GHI from reference pyranometer and that from the test pyranometer is needed. The installation is ready to work in the case of outdoor calibrations.

3.3 Data storage

In the case of the pyrheliometer calibration bench an ASCII file is automatically created during the measurement by the control computer. In the case of the pyranometer measurements, after the test the data is downloaded via RS232 port to a PC with Campbell Scientific PC200W or Loggernet software from the logger. Data are stored in ASCII format.

4 Evaluation

After every test day data is reviewed.

- CIEMAT provides a raw data file (ASCII) of the ACRs and all sensors which are connected to the heliostat DAS (e.g. field pyrheliometer values, devices temperatures, etc.).
- DLR provides an ASCII file with all data which are logged via the pyranometer DAS.

As the first step of the evaluation, the measurements of the test pyrheliometers and pyranometers that were performed during the ACR DNI measurement have to be extracted from the two data files. Subsequently all other data are excluded. The remaining data set is used for the evaluation according to the ISO standards. Two independent evaluation programs are used – one by CIEMAT one by DLR. The results of both evaluations are compared to each other in order to achieve utmost reliability. In the following, the data processing is described.

4.1 Matching data from DAS systems

4.1.1 ACRs and field pyrheliometers

The ACRs are programed to produce series with 20 irradiance values, related to 20 cycles. A cycle consists of 1 minute closed phase (labeled as **C**) and 1 minute open phase (labeled as **O**). Thus, one series corresponds to 40 minutes. Before the actual start of a series the ACR is initializing and the data sets include first a phase labelled as **X**, followed by a phase labelled as **I** and finally a **C** phase. After that, the irradiance measurements related to the 20 **O / C** cycles starts. As explained above, 60 seconds of open phase with open entrance aperture are followed by a 60 seconds long closed phase with blocked entrance aperture. In the last 10 seconds of each phase the actual measurements take place with 10 seconds integration time. Each ACR DNI reading corresponds to a 10 second average at the end of the open phase. The stored irradiance values associated to an open phase are reported in the following closed phase. The signals which are not associated to the ACR's irradiance are reported with a resolution of one second and with their own timestamp.

All signals which are connected to the heliostat DAS are provided in the same raw file. Before any treatment or data evaluation the corresponding timestamps have to be reviewed. The timestamp at the beginning of the file (first column) is the real time where all signals (field pyrheliometers and references) are sampled.

The timestamp related to the start and final instant of the measurement within the **O** phase has to be obtained from the first file column. The starting instant of one **O** phase is obtained from the first row labeled as **O,** and the final one is obtained from the last row of the same **O** phase.

For the test signals, average values must be derived covering the 10 seconds within the ACR irradiance measurement. This has to be done also with the pyranometer data which are logged in a separate file. Time stamps outside the interval for the averaging are not used for the further data processing.

In devices like CHP1 that have an internal temperature measurement and a temperature correction curve provided by the manufacturer, the temperature correction is carried out before the calculation of the average values.

4.1.2 Pyranometers

The time series of the pyranometer data file have to be processed with the matching and averaging process that has been described above for the pyrheliometer DAS file.

Some field devices have an internal temperature measurement (e.g. CMP22) and a temperature correction curve provided by the manufacturer. The temperature correction has to be done prior to the calculation of the average values.

4.1.3 Other meteorological variables

In order to take into account the meteorological variables as is mentioned in the calibration procedures, these data (at least wind speed and direction, and air temperature) have to be collected from additional acquisition systems, as those from DLR meteo station in the south of the dishes or CIEMAT METAS station. The timestamps are also treated as explained above.

4.2 Calibration correction for ACRs

PMO6-CC (0301) CIEMAT ACR took part in the International Pyrheliometer Comparisons (IPC-XI and IPC-XII), ensuring the WRR (World Radiometric Reference)-traceability. The correction factor for the calibration constant of this device was determined in IPC-XI 2010 as 1.000588. The result from the IPC-XII will be published soon.

DLR ACR (0807) took part in the American National Pyrheliometer Comparison in September 2014 and is hence also WRR traceable. The correction factor for the calibration constant of this device is 1.00450.

The multiplication of the raw DNI signals with the individual correction factors for the calibration constants has to be done before any further processing of the data.

4.3 Data filtering

Prior to the evaluation, invalid data have to be filtered. Invalid data result mainly due to unsuitable ambient influences. Additional filtering processes occur during the evaluation, triggered due to high deviations of intermediate results or inadequate series. The data filtering is also performed according to the used ISO standards.

4.3.1 Clouds

For the calibration of pyrheliometers and the calibration of pyranometers with the continuous sun-and-shade method (CoSSM) there should be a minimum angular distance from clouds to the sun of 15° according to the standards. For the alternating sun-and-shade method a higher angular distance of >45° is required. For pyranometer calibration it is furthermore required that the variation of the DHI caused by cloud movement is less than 1 % in 10 seconds. Movies of the METAS cloud camera can also be used for visual subjective verifications of the angular distance on the clouds to the sun (see Figure **7**). When the limits are exceeded, timestamps are noted for the subsequent data filtration during the evaluation.

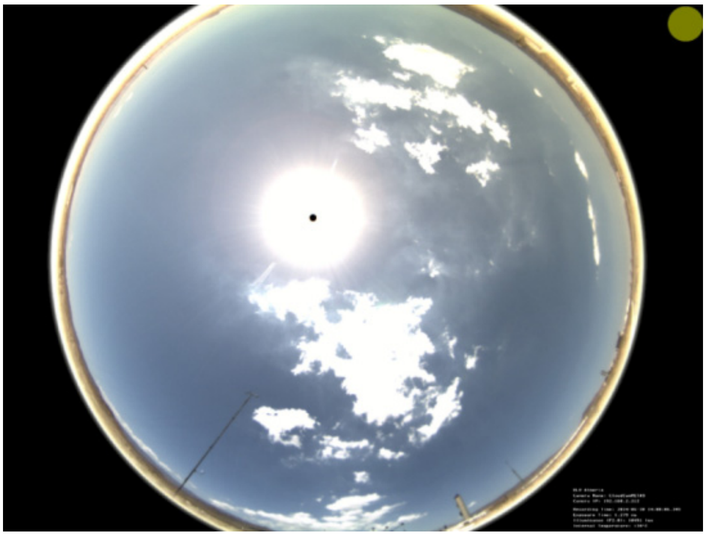

Figure 7. **METAS cloud camera image 30.06.2014 14:00:00 (UTC+1) of invalid measurements**

The clear sky conditions also are monitored via a whole sky imager (WSI), which can distinguish between sunny and cloudy conditions. Image processing of the WSI aims to detect cloud positions via image segmentation methods. The camera is geometrically calibrated, so each image pixel can be associated to a certain elevation and azimuth angle. With this information, an acceptance radius around the solar disk can be projected to the image to visualize and check the required distance of the cloud to the sun. The images during the calibration campaign are processed and an ASCII table is created including the minimum angular distance of clouds to the sun and the cloud cover. The quality of the calibration is hence enhanced and the effort to select valid periods could be reduced significantly. The left hand side of **Figure 8** shows the acceptance circle around the sun of 15° (blue). The distance of the closest detected cloud is represented by the green line. The right hand side of **Figure 8** shows an invalid timestamp which will be filtered automatically during the evaluation.

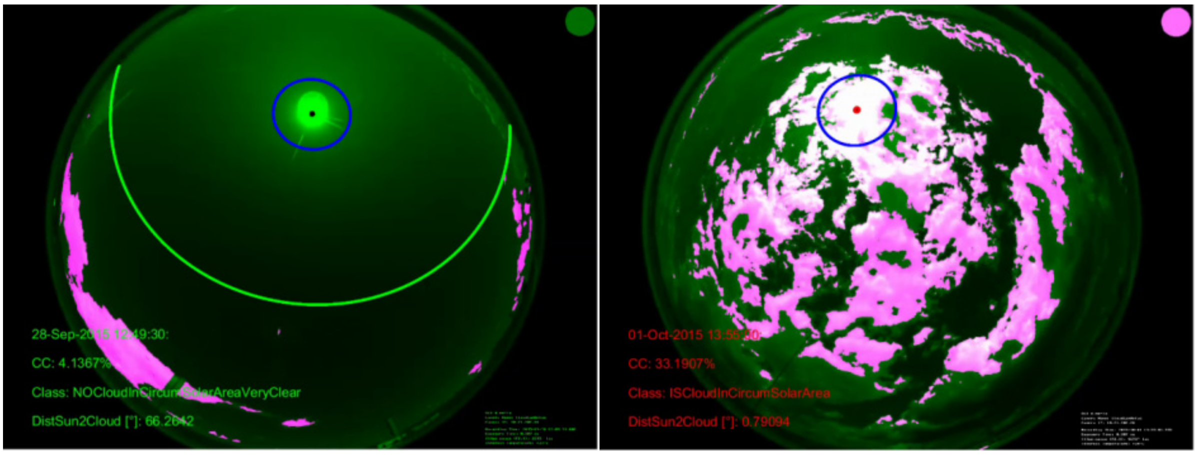

Figure 8. **Left: Clear sky conditions where the sun is shown as a black dot. The blue ring around the sun shows the acceptance circle for pyrheliometer and CoSSM (15°) and the green ring indicates the distance of the closest clouds. Right: Invalid conditions. The dot marking the sun is plotted red, since clouds are inside the acceptance circle.**

4.3.2 Irradiance level

Depending on the standard that is been applying, different levels of DNI and GHI have to be taken into account. For instance, in the case of the pyrheliometer evaluation following the ISO 9059, all data are filtered with a DNI below 700 W/m². Values above 300 W/m² could be used, but the text advises that "*irradiance values exceeding 700* W/m².*are preferred"*. For the pyranometer evaluation DNI values above 300 W/m² are considered as valid as long as all other criteria are fulfilled.

4.3.3 Wind speed

Wind is especially problematic if it the wind direction coincides with the solar azimuth angle within ±30°. No further limits are specified in the ISO 9059 or 9846. NREL recommends an upper limit for the wind speed of 5 m/s if the wind direction matches the solar azimuth within ±30° [Reda et al., 2013]. Under these conditions a noticeable influence of the wind speed especially on the ACR measurements is expected. Wind data can be used from the DLR meteo station in the south of the dishes as well as from the CIEMAT METAS station.

4.3.4 Ambient air temperature

In the calibration report the range of mean air temperature has to be included. Temperature data can be used from the DLR meteo station in the south of the dishes as well as from the CIEMAT METAS station.

4.4 Calculation sensitivities of field devices

The mathematical treatment of the irradiance and voltage readings is briefly described in the following. More details are described in the ISO standards 9059, 9846 and 9847.

4.4.1 Pyrheliometer

Calculate the preliminary calibration factors $F(i,j)$ for each reading *i* in a series *j* and $F(j)$ for each series *j*:

Equation 1

$$F(i,j) = \frac{E_{SP}(i,j)}{V_{FP}(i,j)} \text{ and } F(j) = \frac{\sum_{i=1}^{n} E_{SP}(i,j)}{\sum_{i=1}^{n} V_{FP}(i,j)} \quad \left[\frac{W}{m^2 mV}\right]$$

E_{SP}: DNI value of the reference pyrheliometer in W/m²

V_{FP}: DNI voltage signal of the test pyrheliometer in mV

Also calculate the deviation of $F(i,j)$ from $F(j)$ for each series *j*. In the case that $F(i,j)$ deviates by more than 2 %, reject those data entries.

Calculate the final calibration factor for the filtered data according to

Equation 2

$$F = \frac{1}{m}\sum_{j=1}^{m} F(j) \quad \left[\frac{\mathrm{W}}{\mathrm{m^2 mV}}\right]$$

The responsivity of the test pyrheliometer is derived from the quotient of the final calibration factor.

Equation 3

$$R = \frac{1}{F/1000} \quad \left[\frac{\mathrm{m^2 \mu V}}{W}\right]$$

4.4.2 Pyranometer (Continuous sun-and-shade method)

From the filtered data calculate the mean responsivity of a series j :

Equation 4

$$\overline{R_j} = \frac{\frac{1}{n}\cdot\sum_{i=1}^{n} V_G(i)}{\frac{1}{n}\sum_{i=1}^{n}\left(E_{SP}\cdot\sin(\gamma(i)) + V_D(i)\cdot F_D\right)} \quad \left[\frac{\mathrm{m^2 mV}}{\mathrm{W}}\right]$$

γ: Solar elevation angle

F_D: Calibration factor of the reference pyranometer

V_D: DHI voltage signal of the reference pyranometer in mV

V_G: GHI voltage signal of the test pyranometer in mV

n: number of readings in one series

Note that in ISO 9846 the factor 1/n is missing in the denominator. This is an obvious error which has been removed for our evaluation. All sets of three signals that deviate by more than 5 % from $\overline{R_J}$ are excluded. If a series is reduced to less than 50 % of the original data set by the filtering the complete series is removed.

The final responsivity is then calculated from the filtered data from *m* series according to:

Equation 5

$$R = \frac{1000}{m} \cdot \sum_{j=1}^{m} \overline{R_J} \quad \left[\frac{\mathrm{m^2 \mu V}}{\mathrm{W}}\right]$$

4.4.3 Pyranometer (Alternating sun-and-shade method)

Calculate the responsivity $R_j(i)$ for each set of measurements (shaded, exposed, shaded) and the mean responsivity $\overline{R_J}$ within a series j. A series consist of *n* exposed and *n*+1 shaded intervals, as explained above the pyranometer is subsequently shaded and unshaded. The pyranometer's voltage readings are short averages taken immediately before the end of each shaded/exposed interval.

Equation 6

$$R_j(i) = \frac{V_G(2i) - 0.5 \cdot [V_D(2i-1) + V_D(2i+1)]}{V_I(2i) \cdot F_P \cdot sin(\gamma(2i))} \text{ and}$$

$$\overline{R_J} = \frac{\sum_{i=1}^{n} V_G(2i) - 0.5 \cdot [V_D(2i-1) + V_D(2i+1)]}{\sum_{i=1}^{n} V_I(2i) \cdot F_P \cdot \sin(\gamma(2i))} \quad \left[\frac{\mathrm{m^2 \mu V}}{\mathrm{W}}\right]$$

n number of exposed intervals in the series *j*

i correspondents to the number of the triplet in the series that consists of three intervals. The value 2*i* corresponds to exposed readings, 2*i*-1 is the shaded reading before this exposed reading and 2*i*+1 the shaded reading after it.

γ: solar elevation angle

F_P: calibration factor of the pyrheliometer in W/m²/µV

V_D: mean DHI voltage signal in µV

V_G: mean GHI voltage signal in µV

V_I: DNI value (pyrheliometer) in µV

Reject those $R_j(i)$ which deviate by more than 1% from $\overline{R_J}$, if more than $n/2$ are rejected cancel the whole series.

From the remaining data calculate a corrected value for $\overline{R_J}$, the final responsivity and the final calibration factor.

Equation 7

$$R = \frac{1}{m} \cdot \sum_{j=1}^{m} \overline{R_j} \quad \left[\frac{\mathrm{m^2 \mu V}}{\mathrm{W}}\right] \text{ and}$$

$$F = \frac{1}{R} \quad \left[\frac{\mathrm{W}}{\mathrm{m^2 \mu V}}\right]$$

4.4.1 Evaluation and presentation of the results

The measured raw data, the preliminary responsivities and the selected responsivities after different sort out steps are plotted vs. the time, solar zenith angle and the series number respectively. The visualization helps to detect a drift in the results with time or solar position. Furthermore, statistical parameters are determined such as the standard deviations of the deviation of the calibrated irradiance to the reference (std), relative standard deviation (rsd) and root mean square deviation (rmsd) which are defined as follows:

Equation 8

$$std = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(x_i - y_i - \overline{(x_i - y_i)}\right)^2}$$

$$rsd = \frac{std}{\bar{y}} \cdot 100$$

$$rmsd = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - y_i)^2}$$

x: Analyzed data

y: Reference of analyzed data

n: Number of data points in evaluated data sets

The availability of two reference pyrheliometers is used to derive three different calibration results. Once the calibration is performed with the average of both ACRs as the reference DNI. Two more calibrations with only one DNI as the reference are determined alternatively. Deviations between the three results can be used to determine malfunctions.

Also the temporal drift of the obtained calibration constants to the previous calibration constants are determined and included in the results. Calibration protocols are created and include detailed information on the calibration conditions.

5 Conclusion

In the context of the SFERA2 project the METAS partners, CIEMAT and DLR have installed a joint test bench for pyrheliometer and pyranometer calibration at the Plataforma Solar de Almería (PSA) that includes:

- A heliostat engine which is used as solar tracker. In this tracker a mounting plate has been installed for the reference and field pyrheliometers.
- A Kipp&Zonen 2AP tracker with sensor table and shading structures for the DHI reference pyranometer.
- A mounting table for field pyranometers.
- A whole sky imager
- Ambient temperature, humidity, wind speed and wind direction measurements.

Up to now, the installation is ready to perform the following types of calibrations:

- **Pyrheliometer calibration with a pyrheliometer reference (ISO 9059).** Only the solar tracker test bench is needed as main device, for both: test pyrheliometers and references.
- **Pyranometer calibration with a pyrheliometer (ISO 9846).** This standard "is mandatory for secondary standard and recommended for reference pyranometer calibration. For other applications, ISO 9847 may be used". In ISO 9846 there are two possible methods:

  (1) Alternating sun-and-shade method (ASSM): using only a pyrheliometer as reference. The pyranometer that is been calibrating, is tested under alternating sun and shade intervals.

  (2) Continuous sun-and-shade method (CoSSM): using a reference pyranometer and a reference pyrheliometer. For calibrating a pyranometer under test, the DHI from the reference pyranometer is used in addition to the DNI from the solar tracker test bench.

- **Pyranometer calibration with a pyranometer (ISO 9847).** In this case the GHI signals from the test and the reference pyranometer are compared.

Two successful measurement campaigns have been accomplished during June 2014 and in September/October 2015. A total of 34 pyrheliometers and 18 pyranometers have been calibrated according to ISO 9059 and ISO 9846 in 2014 and 2015. In 2015 capabilities of the pyranometer calibration facility were expanded with the alternating sun-and-shade method.

This allowed calibrating reference pyranometers. The results of these calibrations will be reported in deliverable “D11.3 Report on calibration campaigns for pyrheliometers” of the SFERA2 project.

References

[ISO, 1990] International Organization for Standardization, ISO 9059:1990 Solar energy - Calibration of field pyrheliometers by comparison to a reference pyrheliometer, international standard, Geneva (Switzerland) 1990

[ISO, 1993] International Organization for Standardization, ISO 9846:1993 Solar energy - Calibration of a pyranometer using a pyrheliometer, international standard, Geneva (Switzerland) 1993

[ISO, 1992] International Organization for Standardization, ISO 9847:1992 Solar energy - Calibration of a pyranometer using a reference pyranometer, international standard, Geneva (Switzerland) 1992

[PMOD, 2009] Physikalisch-Meteorologisches Observatorium Davos, PMO6 Operating Manual (Version 2.1), Tech. Rep., Davos (Switzerland)

[Kipp, 2008] Kipp&Zonen, CMA&CMP Instruction Manual (Version 0806), Tech. Rep., Delft (Netherlands) 2006

[Reda et al., 2013] Ibrahim Reda, Mike Dooraghi and Aron Habte, NREL Pyrheliometer Comparison September 16 to 27, 2003 (NPC-2013), Tech. Rep., National Renewable Energy Laboratory, Golden, Colorado (USA) 2013

List of Figures

List of Tables

List of abbreviations and definitions

WRR	World Radiometric Reference
PSA	Plataforma Solar de Almería
ACR	Absolute Cavity Radiometer
DAS	Data Acquisition System
WSI	Whole Sky Imager
METAS	Meteorological Station for Solar Technologies
ASSM	Alternating Sun-and-Shade Method
CoSSM	Continuous Sun-and-Shade Method
DNI	Direct Normal Irradiance
GHI	Global Horizontal Irradiance
DHI	Diffuse Horizontal Irradiance
rsd	Relative standard deviation
std	Standard deviation
rmsd	Root mean square deviation