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Optical losses due to tracking on solar thermal collectors

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Abstract

For a wide range of operational temperatures, the solar thermal collectors can use optical concentration systems to optimize their efficiency. However, as optical concentration relies on direct solar radiation, it is necessary to use a solar tracker following the sun direction to maximize the amount of useful solar radiation received. The selection of the appropriate tracking systems matching the optical concentration factor is essential to achieve optimal collector efficiency. Otherwise, the concentrator would experience high optical losses due to the inadequate focusing of the direct solar radiation onto its receiver, regardless of its quality. This paper gives the state-of-the-art of the methodologies available to characterize the tracking error of a concentrating collector, a summary of different previous studies done in this subject and of the standardization regarding the tracking accuracy and its influence on the solar collector efficiency. The methodologies and results of the tracking accuracy, incidence angle modifier and optical losses due to tracking errors are presented in this paper for the five collectors studied.

Keywords: *Collector testing; Optical characterization; Solar tracking accuracy; Optical losses*

1. Introduction

Several predictions induces a change in the energy model and the one possibility for serving the world energy demand is the use of renewable and clean energies that are the only one that can support sustainable development by its inexhaustible nature, preserving the environment and distributing the resources locally. The solar energy is one of the main renewable energies with great benefit. Solar thermal energy is able to provide a considerable fraction of the current and future energy demand in both industrial and domestic sectors. This fact is reflected by the growing interest during the last decade in the design of new solar collectors in order to satisfy the increasing electricity and heating demands and replace fossil fuels.

The purpose of a solar tracker is to orient a solar system during the day in order to optimize the incident solar radiation. However, while using optical concentration devices on a solar collector, it is important to use a solar tracker with adequate precision compared to the optical concentration factor and the acceptance angle of the concentrator. Otherwise, the concentrator would sustain high optical losses due to the inadequate focusing of the solar radiation onto its receiver, despite having a good optical quality.

Even though the concentrating solar collectors are mentioned in the International Standards (ISO 9806:2013), the general testing methods cannot always be easily applied to unusual collector designs.

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Moreover, those testing methods consider the solar tracker as part of the solar collector so they do not characterize the impact of its precision on the overall efficiency. Additionally, the international technical committee IEC/TC 117, created in 2012, is dealing with the same issues related to thermal performance and durability of concentrating/tracking CSP systems and their components considering inputs from experts of various countries. In this committee, two working group has been created at the end of 2014 in order to define the testing standards for PTC (future standard IEC 62862-3-2) and for LFR (future standard IEC 62862-5-2), but no characterization of the tracker accuracy is proposed.

Bendt et al. (1979) considered different optical losses when calculating the flux on a receiver for a parabolic trough collector (PTC). The total effective root mean square (RMS) of a surface optical error results by adding quadratically the individual standard deviation of: the deviation of contour from design direction $\sigma_{contour}$, the imperfect specularity of reflector material $\sigma_{specularity}$, the imperfect placement of the receiver $\sigma_{displacement}$ and the imperfect tracking $\sigma_{tracking}$ as schemed in Fig. 1.

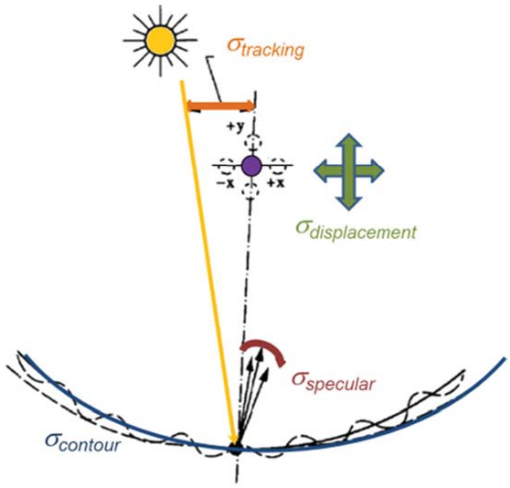

Fig. 1: Optical error from the individual standard deviation

Although the tracking error is not taken into account in current Standards for solar thermal collectors, several studies tried to characterize the tracking error. To do so, some devices could be used in a similar way to the sun-sensors on a closed-loop actuation tracker. But to qualify precisely the tracking error, an accurate electronic device is necessary. Gee (1982) defined a testing procedure and analyzed the angular pointing error on a parabolic through collector (PTC). An encoder was used to record the instantaneous tracking errors with a resolution of 0.03º and then to calculate the RMS (root mean square) of the error. Hession and Bonwick (1984) designed and tested a sun sensor composed of three photo-transistors mounted in a simple structure. This device allowed a solar tracking precision in double-axis better than 0.1º. Bhatnagar et al. (1987) measured experimentally the average tracking error of a tracking system at different solar hours. It was done using their own collector sun-sensor, which consisted in two silicon solar cells placed on either side of a rectangular plate. The error value at noon for the solar tracker characterized in this study was 0.93º. Kalogirou (1996) designed a single-axis tracker using a sun sensor made of three light-dependent resistors (LDRs). The tracking accuracy was estimated of 0.2º for cloudy days (solar radiation of 100 W/m^2) and of 0.05º for sunny days (solar radiation of 600 W/m^2). Arboiro and Sala (1997) presented an improved sun sensor and new strategies for the control unit of solar tracking, using both closed loop and open loop mode. The solar tracker prototype was monitored for one year and presented an accuracy of 0.2º. Sun et al. (2014) used a beam characterization system to evaluate the tracking error of two heliostats from a central tower plant with an estimated accuracy of better than 2% of the positioning angle measurement. Bentaher et al. (2014) analyzed a tracking system for PV panels using a sun sensor composed of two photo-resistors separated on two inclined planes.

Among all the previous studies, none has characterized the tracking error of a linear solar thermal concentrator in actual operation. Moreover, no testing procedure has been developed as the basis for a future standard. As explained before, the tracking system is a critical point of concentrating collectors. In Kalogirou et al. (2004), the importance of an accurate tracking was clearly verified in the experiment. Those experimental data showed the influence, of the incidence angle deviation from the ideal angle, on the collector efficiency of a parabolic trough. For this PTC, a deviation of only one degree in the transversal incidence angle implies an incidence angle modifier (IAM) of 0.8, which means that the energy efficiency decreases by 20%. In some studies, the optical losses due to the tracking deviation was analyzed and discussed. In Hughes (1980), the pointing error was clearly identified as a source of efficiency reduction. The theoretical intercept factor losses due to the tracking error of a point focusing solar collector with ±0.1º error were calculated using a statistical analysis, but no experimental measurements were performed. Grass et al. (2004) mentioned that the tracking error of a collector with a small acceptance angle can have a significant effect on performance. It was also estimated in that study a value of 0.6 % for the tracking error for evacuated tubes collectors (ETC) with integrated tracking reflector, but with no more experimental details.

For all of those reasons, and the previous results mentioned in the previous sections, due to the lack of characterization test procedures, for single-axis tracking solar concentrators, a testing procedure for solar collectors with single-axis solar tracker is defined in this paper. The main objective is to determine the adequacy of the solar tracking system together with the actual concentration optics of the collector. Moreover, the optical losses due to the tracker were calculated on different concentrating tracking collectors in order to estimate the percentage of reduction on the concentrator efficiency. This study aims to contribute to the improvement of tracking errors estimation on single-axis solar trackers for a solar thermal collector, in particular linear trough collectors. And therefore, it also aims to estimate the optical losses resulting from the tracker.

2. Review of the equipments for measuring the tracking error

A review of all the commercial devices which use the “Machine-Vision” method (MV), based on image treatment. Those equipments already existing in the market are designed to characterize the deviations of the trackers and are not part of the actuator or tracking system.

The first device using MV method, the model Trac-Stat SL1 was developed by the company GreenMountain (Fig. 2a) (Pract Engineering & Consulting webpage). This system was composed of two separate independent sensors, one with a narrow acceptance angle and one with a higher acceptance angle. The first sensor has a field of view angle of 5º with an accuracy of ±0.02º. The second sensor has a field of view angle of 60º with an accuracy of ±0.5º. This device is now commercialized by the company Pract Engineering.

The model SunSpear, developed by the company Inspira and based on the patent 2008/0258051 (Heredia, et al., 2008), is a sensor for measuring the pointing error using an image sensor positioned within a collimator tube (See Fig. 2.b). According to the technical specifications, this equipment has a resolution of 1/10000th of angle with a field of view of 1º (Cervantes and Luque-Heredia, 2008; López et al., 2012; Luque-Heredia et al., 2006). Inspira S.L. was bought by the American company SolFocus.

The model TA1 is manufactured by the German company Black Photon (http://black-photon.de/) (See Fig. 2.c). According to the technical specifications, the measurement range is ± 1.2º, the linearity is ± 1.8 % of full scale and the accuracy is ± 2.4 % of full scale (for temperature between 5ºC and 45ºC). Missbach et al. (2012) presented the results of this sun sensor, with a high accuracy showing a standard deviation of 0.01% of full scale with the measurement of a stable LED (light-emitting diode) light source.

The model LAB is manufactured by the company AKKUtrack (http://akkutrack.com/lab/) (protected by the following patents: BO2010A000361, GE2014A000006, WO2011 /154872). According to technical specifications, the field of view is 4.5º per 2.9º, the resolution is ±0.01º and the relative accuracy is ±0.01º (see Fig. 2.d).

The model Heliosensor is manufactured by the German company PSE (Projects in Solar Energy) (http://www.pse.de) in collaboration with the Black Photon company (see Fig. 2.e). According to technical specifications, the field of view is 55º, the resolution is less than ± 0.02º, and the accuracy is less than ± 0.05º for angles less than 15º and less than 0.5 % for the entire acceptance angle.

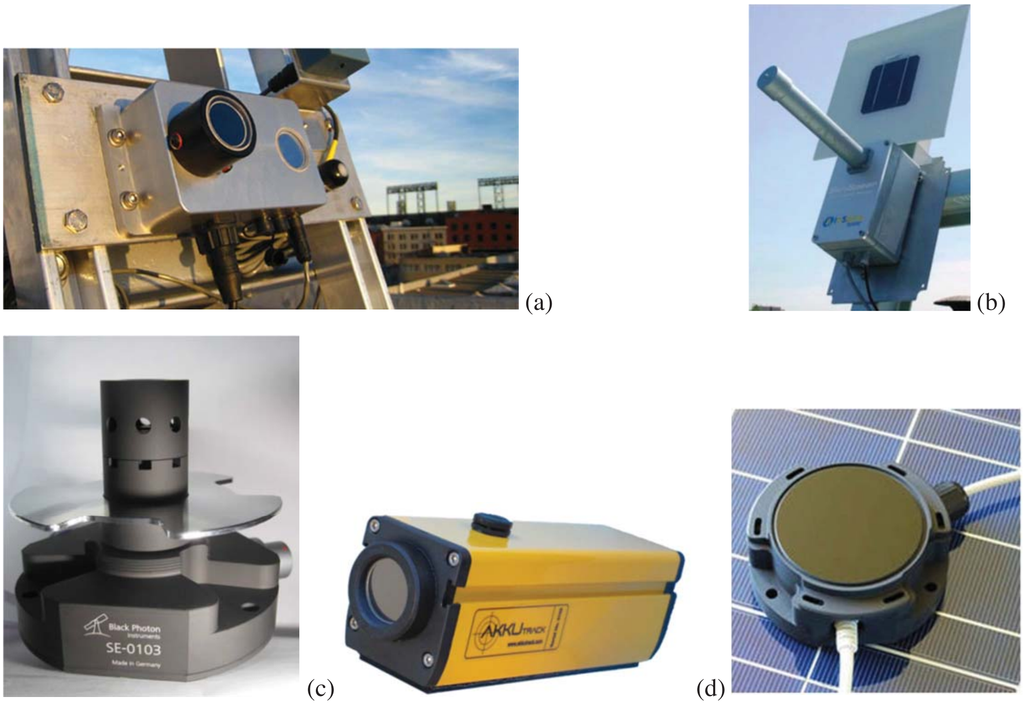

Fig. 2: (a) Tract-Stat SL1 by Pract Engineering (Pract Engineering & Consulting) (b) SunSpear by Inspira (Heredia, et al., 2008) (c) Model TA1 by Black Photon (black-photon.de) (d) Model LAB by AKKUtrack (akkutrack.com/lab) (e) Heliosensor by PSE (www.pse.de)

Table 1 summarizes the specifications of the different devices exposed above. In particular, it compares the accuracy and field of view of several commercial devices

Tab. 1: Characteristics of commercial optical device for tracking error measurement

Model	Manufacturer	Accuracy	Field of view angle
Trac-Stat SL1	GreenMountain Engineering	± 0.02º ± 0.5º	5º 60º
Solar Tracker Tester	Proxima Systems S.L	±1º	20º
TA1	Black Photon	± 2.4% of full scale	1.2º
LAB	AKKU track	± 0.01º	4.5º x 2.9º
SunSpear	Inspira	1/10000th	1º
Heliosensor	PSE	± 0.05º	55º

Most of those optical devices characterize the pointing error on a double-axis tracker and could not be used for a linear concentrator because of their reduced field of view. The GreenMountain Engineering device has a field of view up to 60º but its accuracy (±0.5º) is not suitable for the characterization of the tracking error of a PTC tracker in order to estimate the optical losses.

In order to measure the tilt and orientation of a solar tracker, different sensors could be used, such as the angles sensors, the rotary encoders, the tilt sensors or inclinometers (Prinsloo and Dobson, 2015). Within the angular sensors, there are two types: the absolute encoder and the incremental or differential encoder. The main advantage of those devices is that they keep the information of the position even when the power is off. The magnetic encoders are angle sensors connected to a motor actuator drive, which convert the motor rotation pulse into tracking angles. The differential or incremental encoder record the change in the shaft position of a system, but do not keep the information if the power is off. This encoder needs a microprocessor or a software in order to calculate the position angle and to record this data. Table 2 presents the specifications of the different commercial devices.

Tab. 2: Characteristics of commercial inclinometers

Model	Manufacturer	Repeatability	Resolution	Absolute accuracy	Measure angle
IM 60-2	FIAMA	±0.05°	--	--	±60°
LCA318T-30	RION		±0.1°	±0.1°	360°
P-Series	Measurement Specialties	±0.001°	±0.02°	±5°	--
Pro 3600	MITUTOYO	--	±0.01° (from 0° to 10°)	±0.05° (from 0° to 10°)	--
DJ-1022	Mini Digital Protractor	±1°	0.1°/ 0.01%	--	4x90°
DP-90HC	ZJTM	--	±0.1 °	±0.2 °	4x90 °
ACS-360-1-SV00-VE2-PM	POSITAL FRABA	± 0.02%	±0.01°	±0.1°	360°

3. Materials

This section presents the main characteristics and particularities of the five solar collectors studied during this work. Those collectors have different tracking types and concentrating geometries. The first collector called Sunaitec, from a Portuguese company that manufacture it, is composed of several elliptical concentrators that act synchronized. The second collector is a prototype of variable geometry collector, designed and built by the university of Balearic island (UIB). It is composed of 32 parabolic mirrors, 8 sets of four receiver tubes and a structure that moves the array of receivers with a circular trajectory to maintain the focussing. The third collector is a small size PTC, commercial model PolyTrough 1800, manufactured by the Swiss company NEP Solar AG. The fourth collector was designed for the DIGESPO European project. It is a small size PTC consisting of 4 modules with 4 receivers. The last collector was designed for the EUROTrough European project. It is a large size PTC. All the experiments were carried out in different European facilities. Fig. 3 shows a map with the location of all the collectors and testing bench used during this study.

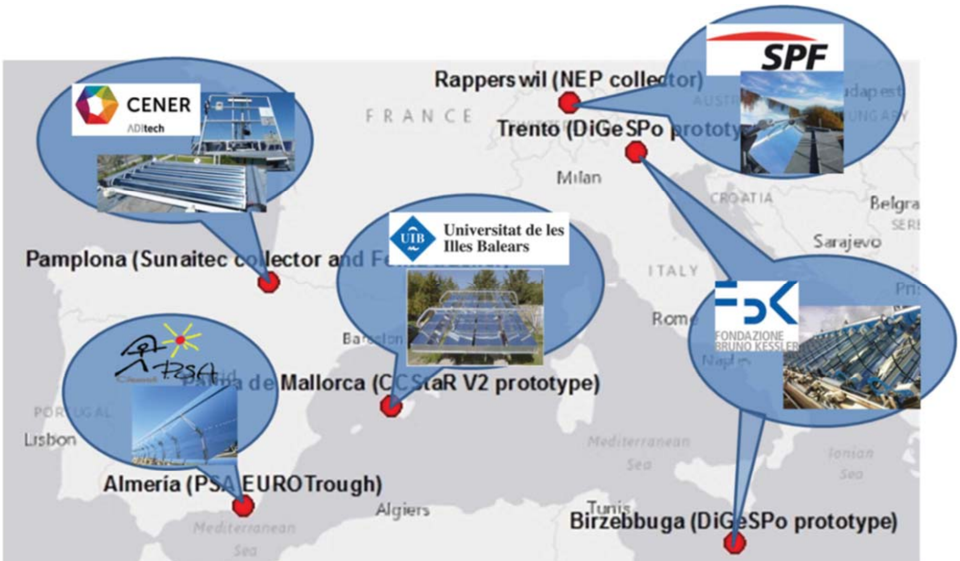

Fig. 3: Defining acceptance angle and relationship between tracking error and optical losses

Table. 3 shows a summary of the main characteristics of the solar collectors used for this study.

Tab. 3: Summary of collector characteristics studied

Solar collector	Sunaitec	CCStaR	NEP	DiGeSPo	EUROTrough
Concentrator type	Elliptic	Fixed-Mirror (fixed reflector and mobile receiver)	Small PTC	PTC with fixed receiver and mobile reflector	Large PTC
Focal length [mm]	Not specified	--	647	200	1710
Collector length L [m]	2.337	576.95 mm	10.347	2.0	75 meters
Receiver tubes	5	4*8	4	4*4	18
aperture area [m2]	1.82	37.4	19.1	12.8	409.9
Concentration factor	4.48	14.4	17.27	33.33	26.2
Actuator	Electric	Electric	Electric	Electric	Hydraulic
Command	Solar sensor (Closed loop)	Algorithm (open loop)	Algorithm (open loop)	Algorithm (open loop)	Algorithm + encoder (hybrid)
Axis and orientation	horizontal EW	tilted NS	horizontal EW	tilted polar NS	horizontal EW

4. Methodology

The optical losses due to the solar tracking are an important characteristic of a solar tracker and need to be characterized experimentally by defining a testing procedure. Thus, the main objective of this study is the characterization of those optical losses on a linear solar concentrator and unconventional collectors, for low and medium temperature applications. The test procedure is based on the angular tracking error θ_{track} and the profile of dependency of the optical efficiency on the tracking error, as scheme in Fig. 4.

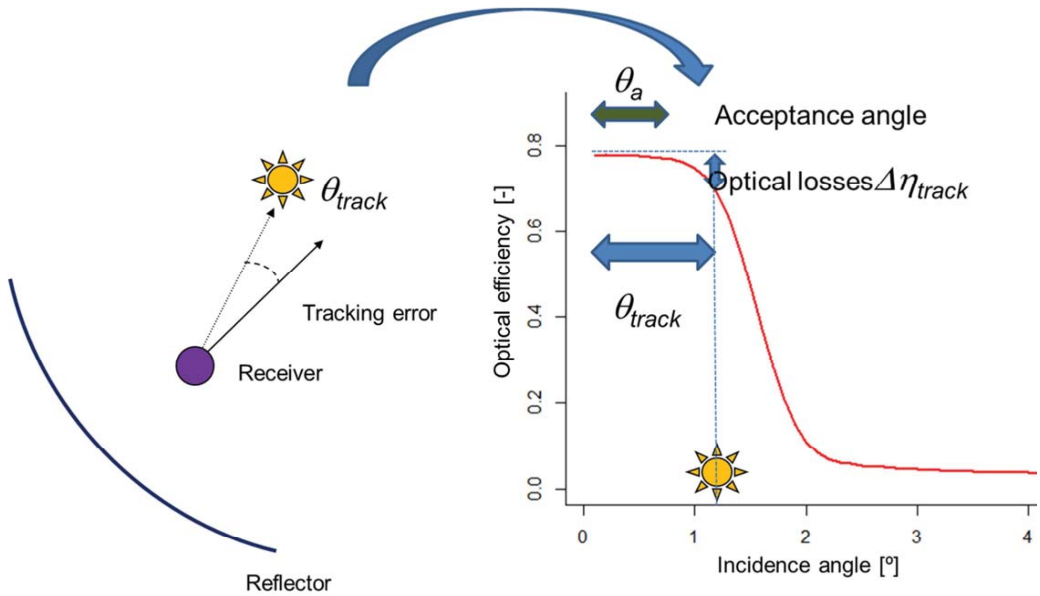

Fig. 4: Defining acceptance angle and relationship between tracking error and optical losses

To achieve this main objective, the following partial objectives were considered:

- Objective 1: Determination of the tracking error θ_{track} on a single-axis solar tracker and analysis for different environmental conditions like wind speed and wind direction. Development of a testing procedure for the characterization of this angular error.
- Objective 2: Characterization of the angular dependency of the optical efficiency to the tracking error, namely incidence angle modifier (IAM) by theoretical simulation and experiment. Demonstration of the utility of ray-tracing techniques in unconventional solar concentrators to determine its optical behavior.
- Objective 3: Calculation of the optical losses due to the tracking error. Determination of the acceptance angle, a key parameters of a solar concentrator, in order to check the accuracy required for the solar tracker to minimize the optical losses of the whole system (tracker and collector).

To reach the objective 1, different testing methodologies were described to quantify the tracking error of solar tracking in single-axis mode. The ad-equation between the precision of the device used to measure the tracking error and the accuracy of the tracker tested was determined. An experimental methodology for the tracking error characterization on a PTC, in the case of horizontal rotation axis, has been proposed, based on the international standard (IEC 62817, 2014) for the design qualification of solar trackers for photovoltaic systems. This proposal leads to the creation of a standard working group in November 2014 within the committee IEC/TC 117 (prIEC 62862-3-2). A statistical analysis was performed to estimate the mean angular error of each tracker.

To reach the objective 2, the optical efficiency was determined for different linear concentrators. The IAM parameter, regarding the beam solar irradiance $K_b(\theta_{track})$, is the one used to estimate the optical losses due to tracking error. The first method to characterize the optical efficiency was done experimentally using International Standards (ISO 9806:2013), the so-called quasi-dynamic test (QDT), monitoring the inputs and outputs of the collectors. The test benches and sensors used for the different collectors are summarized in Table 4.

Tab. 4: Summary of testing facilities

Solar collectors	Sunaitec	CCStaR	NEP	DiGeSPo	EUROTrough
Test location	Pamplona (Spain)	Mallorca (Spain)	Rappeswil (Swizerland)	Malta	Almeria (Spain)
Direct irradiance	Pyranometer - Shaded pyranometer	Pyrheliometer	Pyrheliometer	Pyranometer - Shaded pyranometer	Pyrheliometer
Diffuse irradiance	Shaded pyranometer	Shaded pyranometer	Shaded pyranometer	Shaded pyranometer	--
Temperature	Pt100	Pt100	Pt100	Pt100	Pt100
Flow	Mass flowmeter (Endress Hausser)	Volume flowmeter (Kamstrup)	Volume flowmeter (Endress Hausser)	Mass flowmeter (Micro Motion)	Flowmeter Emerson

The second method was by simulation, using a ray-tracing program OTSun that was developed in Fortran by the UIB, exposed in Pujol Nadal and Martínez Moll (2012) and compared to other commercial software in Osório et al. (2015). From the IAM profile $K_b(\theta_{track})$ was also determined the acceptance angle qa, which is an important factor of the concentrator.

To reach the objective 3, the long-term optical losses due to an imperfect tracking were estimated; an estimation of the long-term and average weighted optical losses due to the tracking error of a solar concentrator. The experimental and simulation results of the IAM on the tracking plane are used to determine the optical losses due to the tracker ($\Delta\eta_{track}$) using the transversal IAM fit $K_b(\theta_{track})$ and the tracking error (θ_{track}), according to Eq. 1.

$$\Delta\eta_{track} = \left(1 - K_b\left(\theta_{track}\right)\right)\cdot 100 \qquad \text{(eq. 1)}$$

As not all the collectors were studied in the same way, Table 5 summarized methodologies used for each sub-objective and collector.

Tab. 5: Methodologies used for each collector and objective

Sub-objetives / Solar collectors	Sunaitec	CCStaR	NEP	DiGeSPo	EuroTrough
1-Tracking error θ_T	Estimation from manufacturer	--	Experimental + Inclinometer	Optical device+ Estimation from orientation	Experimental + Inclinometer
2-IAM $K_b(\theta_T)$	Experimental	Experimental + Simulation	Simulation	Simulation	--
3-Optical losses due to tracking $\Delta\eta_{track}$	Calculation + Experimental	--	Calculation + Experimental	Estimation	--

5. Results

For the first objective, a testing procedure was defined for solar trackers by adapting a testing method from an International Standard IEC for photovoltaic double-axis trackers. The experiments were carried out using a simple procedure to determine the tracking elevation error. In Sallaberry et al. (2014a), a methodology for measuring elevation tracking error using an inclinometer has been defined and tested on a simple double-axis solar tracker at CENER. In Sallaberry et al. (2015a), the same methodology using an inclinometer has been tested on the NEP small-size PTC with EW single-axis solar tracker. In Sallaberry et al. (2015b), the same methodology using an inclinometer has been tested on the EUROTrough large-size PTC with EW single-axis solar tracker. On the DiGeSPo, a prototype device, based on the MV concept, had been designed and tested (Sallaberry, 2015d).

Second, the optical characterization of different concentrating solar collectors was performed through simulation and experiments. In particular, its dependency to the transversal incidence angle along the tracking plane is characterized. The IAM on the tracking plane was studied experimentally on the Sunaitec elliptic trough collector. In Sallaberry et al. (2015b), the IAM testing procedure for tracking collector has been defined and the asymmetrical product behavior for the Sunaitec asymmetric collector has been verified experimentally on a low concentrating/ tracking collector. In Sallaberry et al. (2015a), the IAM was obtained by simulation for the NEP collector. In Sallaberry et al. (2014b), the IAM testing procedure for the CCStaR nonconventional collector has been defined and a simulation ray tracing has been validated experimentally. A good agreement was found between the simulation and the experimental results considering the measurement uncertainties. In Sallaberry et al. (2015c), a theoretical model has been presented to specify the range of the incidence angles which should be tested on variable-geometry collectors to validate the IAM terms in the energy equation balance used on the CCStaR collector. In Sallaberry et al. (2014c) the IAM profile of the NEP collector was also determined by simulation. See Fig. 5 for IAM results in color surface by simulation and in black dot for experiment.

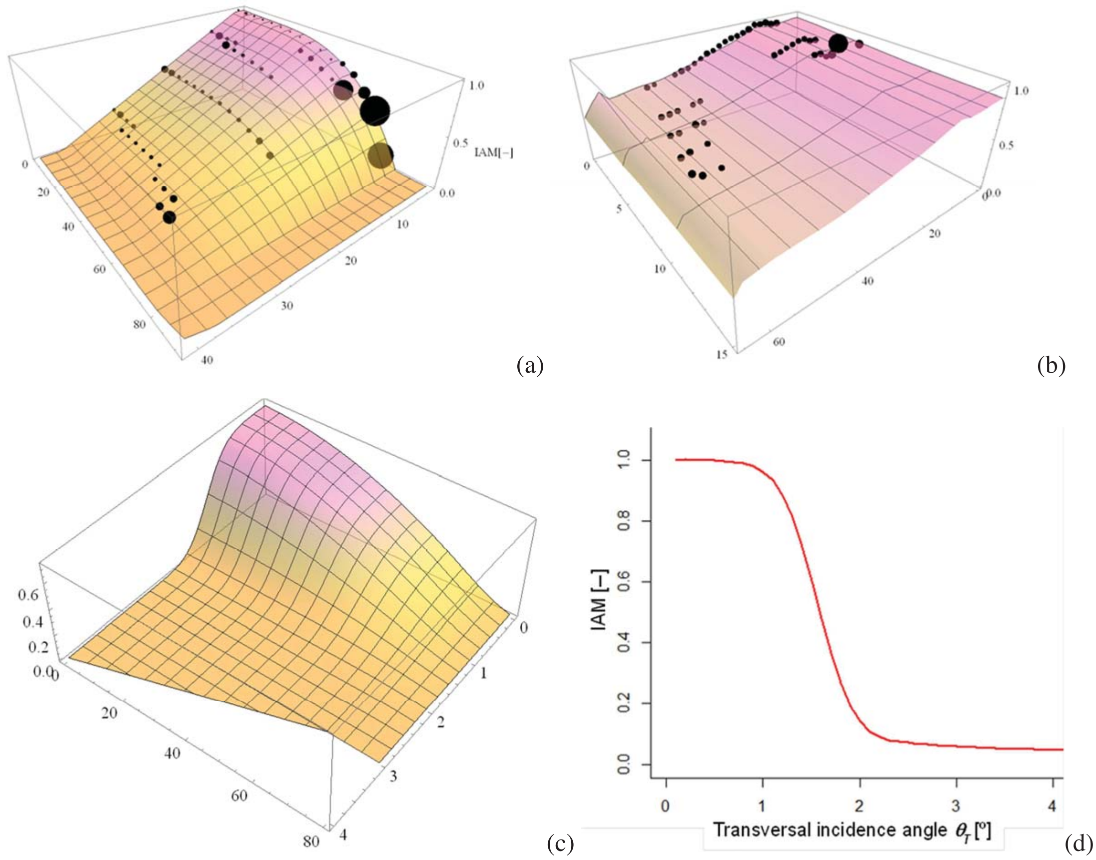

Fig. 5: IAM results by simulation (color surface and red line) and experiment (black dots) for (a) Sunaitec (b) CCStaR (c) NEP (d) DiGeSPo

Third, the long-term optical losses due to the tracking error were estimated using the transversal IAM obtained previously by raytracing simulation or by experiment, and the tracking errors distribution estimation. The impact of the maximum tracking error angle upon the optical efficiency has been determined on different concentrating/tracking collector types. In Sallaberry et al. (2015b), the long term calculation of the optical losses due to a tracker has been defined on the Sunaitec small low-concentration collector. In Sallaberry et al. (2014c), a sensitivity analysis has been performed about the possible source of tracking errors caused by an incorrect positioning of the DiGeSPo concentrating/tracking collector. In Sallaberry et al. (2015a), the average optical losses caused by the solar tracker has been calculated on the NEP small-size PTC. Table 6 summarized the results obtained for the three different sub-objectives,

Tab. 6: Summary of results

Results	Sunaitec	CCStaR	NEP	DiGeSPo	EUROTrough
1-Tracking error θ_T	Estimated ± 5º	Not estimated	± 0.4º	Experimental: between -0.6º and 0.1º / Estimation: ± 0.6º	± 0.3º
2-IAM $K_b(\theta_T)$: Acceptance angle θ_a	2.8º	Variable geometry	0.58º	0.9º	--
2- IAM $K_b(\theta_T)$: Optical efficiency η_{0b}	Experimental 67.7%	Simulation: 68.8% Experimental: 68.7% /	Simulation: 74%	Simulation: 77.7% Experimental: 30.9%	Experimental: 65.6%

3-Optical losses due to tracking $\Delta\eta_{track}$	$\Delta\eta_{track,year}$ = 1.01% 62% of data lower than 1%.	--	$\Delta\eta_{track,weighted}$ = 0.317% 95% of data less than 2.5%	$\Delta\eta_{track}$ up 0.5%	--

Finally, this work (Sallaberry, 2015e) describes the points defined in the International Standards that should be improved in order to ascertain the influence of the tracking accuracy on the overall efficiency of concentrating/tracking solar collectors. Some points have been proposed for a future Standard testing procedure on trackers for solar thermal collectors

6. Conclusions

In this work, solar collectors with different typologies have been tested; all with single-axis tracking and optical concentration (CCStaR V2 prototype with fixed reflectors and mobile receiver; Sunaitec collector with elliptic trough concentrators; NEP PTC single-axis solar tracker; DiGeSPo collector with fixed receiver tube and mobile reflectors). Unlike conventional solar collectors, such as flat plates and evacuated tubes, in the case of concentrating/tracking collectors, there is no clear specific testing procedure from a standard organisation. Furthermore, no testing procedure for the tracking precision exists and the efficiency testing procedures do not take into account all the special features of those collector types. More precisely, the IAM characterization is not completely standardized for unconventional concentrating/tracking collectors.

The main conclusions of this work, related to the three objectives in section 4 are given beneath:

- The characterization methodology of the angular error of tracking systems have been developed and validated experimentally on different solar trackers. The instantaneous angular tracking errors obtained by a simple procedure using digital inclinometer can be implemented and characterize statistically the tracking error distribution.
- The use of ray-tracing simulation has been validated for different types of concentrating solar systems, in which the optical efficiency for some solar incidence angles are difficult to obtain experimentally. Hence, the simulation by ray-tracing programs allowed determining the optical efficiency at any incidence angle. The simulation results have been compared to the experimental ones obtained during testing campaigns using the procedure presented. The agreement was very good.
- The IAM profile obtained previously has been compared to the maximum angular tracking error. In this way, the connection between the concentration optics and the tracker precision has been checked for two collectors.
- Finally, the optical losses of concentrators have been estimated using both the instantaneous angular tracking error measurements and the IAM results. Thus, valuable parameters, the weighted or the long term optical values, could be calculated to quantify the effect of the solar tracker on a concentrator performance.

7. Acknowledgements

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