R2.4 Topic report for WP2 solar thermal collectors

Concentrating / tracking collector component characterization

CENER

Fabienne Sallaberry, Enric Mateu Serrats

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Summary of work carried out, main results and recommendations for standard revision

Contact Info

Address: Ciudad Innovación,7
31621 Sarriguren- Navarra-Spain
Tel. : +34 948252800
Fax : +34 948270774
E-mail: emateu@cener.com

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1 Summary

This document gives an overview of the existing characterization test methods for concentrating / tracking solar thermal collector components. Up to now, there are no specific standards available for such components. The standardization activities have two different approaches; the first one is covered by the QAIST project and deals with low to medium temperature applications which is contributing to the work of the ISO/TC180 and the CEN/TC312 technical committees for the new ISO EN solar thermal collector standard, the second one deals with high temperature / high concentration applications (Concentrated Solar Power: CSP) covered by the technical work developed within the Spanish technical committee: AENOR/CTN206 and the recently created international committee: IEC/TC117. The main existing component characterization test methods which are described in this document come from CSP applications. The component characterization test methods described include the receiver, the reflector and the tracking system.

2 Introduction

This report is part of the topics reports from the WP2 Solar thermal collectors of the QAIST project. This document deals with concentrating / tracking collectors and it is focused on their component characterization methods.

Description of work carried out

The following topics have been elaborated within the WP2 of the QAIST project:

- Description of the standardization activities related with concentrating/tracking collectors and their components. Within these activities there are two different approaches: low to medium temperature applications and high temperature applications (CSP)
- Overview of the concentrating/tracking solar thermal collectors available on the market or close to commercial stage
- Description of different existing methods for characterization of the main components of a concentrating/tracking collector like receiver, reflector and tracking system. The methods mainly come from high temperature applications (CSP) and the experience gathered until now with some of these testing methods. The receiver test methods include the thermal and optical characterization methods. The reflector characterization includes a material overview, different reflectance measurement methods and their durability and accelerated ageing tests. The tracking system includes an overview and some proposals for the characterization of the tracking accuracy.
- Recommendations for standard revision related with concentrating / tracking collector components

3 Standardization activities

Nowadays, the concentrating collector components do not have specific standards for performance and durability characterization. Some parallel standardization activities have been established recently. These activities involve different regional and international standardization committees due to the wide spectrum of concentrating solar thermal collector applications:

- Low to medium temperature applications: This is the scope of the QAIST activities supplying the technical background for the standard EN 12975 revision concerning performance and durability of concentrating/tracking collectors and their components. The WG1 from the technical committee CEN/TC312 is leading the revision activities and it was agreed with the ISO/TC180 that the standard ISO 9806 will also be revised in parallel having the EN 12975 as a base due to its higher level of development. In the joint meeting in September 2011 in Kassel, ISO/TC180 and CEN/TC312 agreed to develop a global standard for solar thermal collectors and components under the Vienna Agreement with CEN lead (launch foreseen in 2013). In the same meeting it was agreed to create a multi-part standard on collector components and materials, also under Vienna Agreement with some parts lead by CEN and others by ISO:

    - ISO lead – Part 1: Evacuated tube durability and performance
    - ISO lead – Part 2: Heat pipes for evacuated tubes - Durability and performance
    - CEN lead – Part 3: Absorber surface durability
    - CEN lead is foreseen for other parts to be considered like glazing and insulation materials.

  Concentrating collector components like Receiver, Reflector or Tracking system could thus also be included as new parts in the near future, based on the existing test methods described in the following chapters.

- High temperature applications: or concentrated solar power (CSP). At the beginning of 2010 the Spanish Association for Standardization and Certification (AENOR) has created a new subcommittee inside the electricity production technical committee (AEN/CTN206) to deal with standardization activities related with solar thermal electric plants. This subcommittee is comprised of R&D Centres of excellence in renewable energy and Spanish industrial partners.

The aim of this subcommittee[1] is to create a series of Spanish Standards (UNE) that will define procedures to qualify components (receiver tubes, sun tracking systems, reflectors, etc.), subsystems (solar field, thermal storage system and power block) and complete CSP plants. Within this subcommittee, three different working groups (WG) have been created concerned with different aspects of the CSP plant: the first working group deals with standardization aspects related to the solar field and the CSP plant as a whole; the second working group develops standardization procedures related to the components of solar thermal power plants; and the third working group is focused on the standardization of thermal storage systems for CSP applications.

Due to the lack of standardization in this field, the Spanish Committee launched a proposal to the International Electrotechnical Commission (IEC) for the establishment of a new IEC Technical Committee. The request was accepted – twenty countries voted in favour, and nine of them communicated their interest to participate actively in the work. So the IEC SMB (Standardization Management Board) approved the creation of the IEC/TC117 Solar Thermal Electric Plants, allocating the secretariat to the Spanish National Committee. The kick-off meeting held on March 7th and 8th,2012 in Madrid agreed on the work program and the Spanish CSP working items will be considered at international level. The standard first drafts (in Spanish) are expected to be ready by spring 2012 and will be used as a work base for IEC/TC117.

In the near future it is expected a close collaboration between the recently created IEC/TC117 and the ISO/TC180 related with the concentrating/tracking collectors and their components.

4 Concentrating collectors overview

This chapter gives an overview of the concentrating collectors available on the market or close to commercial stage. The overview includes not only the medium temperature collectors[2] for “process heat” applications on the temperature level 80℃ to 250℃, but also concentra ting collectors that are in the high temperature range (up to 400ºC) for utility scale power generation, see Figure 1.

[1] M.Sanchez et al. “Overview of activities related to the development of Spanish standards for concentrating solar thermal power plants.17th Symposium on Concentrating Solar Power and Chemical Energy Systems - SolarPACES 2011, Granada,Spain.

[2] Process Heat collectors - State of the Art within task 33/IV. IEA SHC Task 33/Solar Paces Task IV

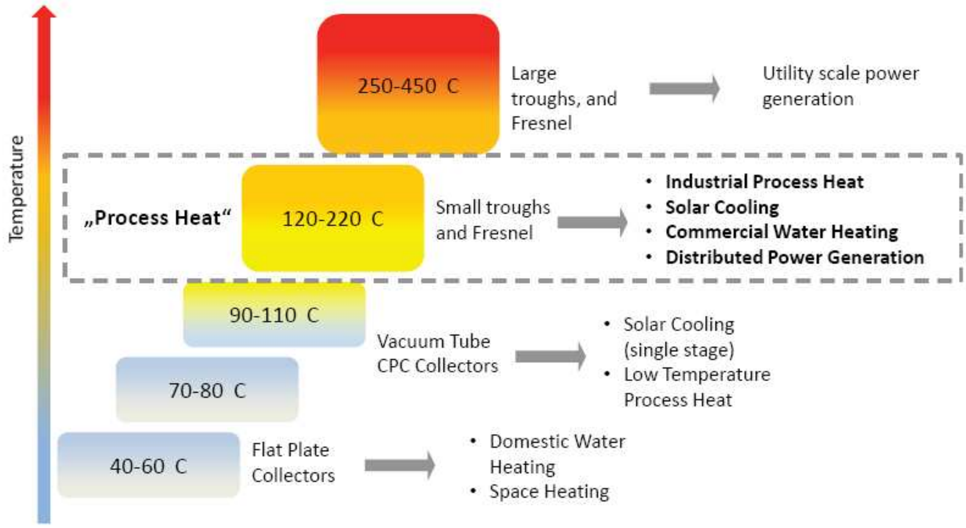

Figure 1. Temperature range and applications of solar thermal collectors

Figure 1 and Table 1 show that there is a wide variety of designs for concentrating collectors and different technical solutions to reduce the collector thermal losses at higher operating temperatures. In the temperature range from 80 up to 120ºC: there are evacuated tube collectors, advanced flat-plate collectors and stationary low-concentration collectors, like CPC collectors without tracking. These collectors have a global solar radiation full use and are suited for applications like single effect solar cooling and low temperature process heat.

In the temperature range from 120ºC up to 250ºC there is a wide variety of designs and collector module sizes for tracking concentrating collectors with high concentration ratios. The designs include small parabolic troughs, linear Fresnel reflectors, and fixed mirror concentrators. These collectors use almost only the direct solar radiation and are suited for applications like: double effect solar cooling, industrial process heat, water heating and distributed small scale power generation.

This wide variety of concentrating collector designs generates significant difficulties for its performance and durability testing that need to be faced:

- Different tracking mechanisms
- Active/passive fail-safe devices and control strategies
- Different heat transfer fluids, (like pressurized water, thermal oil, ...)
- Big collector module dimensions, difficult to handle for laboratory tests.
- In some cases only in-situ performance measurements can be performed due to the collector module size
- Hard to obtain some incidence angle modifiers, without 2-axis tracking test platform due to big collector module dimensions
- Some durability tests can be difficult to handle

- New testing facilities are needed for accurate performance measurements within the collector temperature operating range. Up to now, most testing laboratories can carry out performance tests only until 100ºC

Table 1 gives an overview concentrating collectors available on the market, describing their main technical features and temperature operating range.

Table 1. Concentrating collectors overview

Manufacturer and model (Country)	Image	Collector type	Module dimensions	Receiver type	Reflector material	Heat transfer medium	Temp. range
Abengoa – IST PT-1 (Spain)		Parabolic Trough	width:2,3 m length:6,1 m	Selective coating & borosilicate glass envelope	Aluminium	Water or steam	Up to 250ºC
Absolicon X10T (Sweden)		Parabolic Trough	width:1,1m length:6 / 10m	PV/T	-	Water	100ºC to 200ºC
AOSOL Maxi CPC (Portugal)		Flat plate stationary CPC C=1,5	width:1,2m length:2 m	Sunstrip absorber	Aluminium	Water	Up to 120ºC
CHAPS (Australia)		Parabolic Trough	width:1,5m length:24 m	PV/T	Glass-on-metal mirrors	Water	Up to 150ºC
Tecnologia Solar Concentradora CCStar (Spain)		Fixed mirror concentrator C=10	width:5,2m length:8,4 m	Sydney evacuated tubes	Aluminium	Water	90ºC to 200ºC
Chromasum MCT (USA)		Linear Fresnel	width:1,2m length:3,39 m	Stainless steel, U-tube	Coated aluminium	Water	Up to 200ºC
Industrial Solar LF-11 (Germany)		Linear Fresnel C=25-40	width:8 m length:4 m	Schott PTR® 70	Flat glass mirrors, aluminium 2ary reflector	Water or steam up to 250ºC, thermal oil	Up to 400ºC
It-Collect (Germany)		Parabolic Trough C=5	width:0,5 m length:2 m	Steel with glass envelope	Aluminium	Water or thermal oil	Up to 200ºC
NEP Solar PolyTrough 1200 (Australia)		Parabolic Trough C=45	width:1,2 m length:24 m	Several options	Composite carrier reflector	Water	120ºC to 220ºC

Manufacturer and model (Country)	Image	Collector type	Module dimensions	Receiver type	Reflector material	Heat transfer medium	Temp. range
Solargenix Power Roof (USA)		Fixed mirror concentrator C=86	width:4 m length:24 m	Similar to Solel UVAC with silver coated 2^{ary} reflector	Aluminium based	Water	Up to 350ºC
Solarlite 4600 (Germany)		Parabolic Trough C=66	width:4,6 m length:6 m	Evacuated receiver	Thin glass mirror	Water or steam	Up to 400ºC at 55 bar
Solel IND 300 (Israel)		Parabolic Trough	width:1,3 m length:6 m	Evacuated receiver	Silver coated aluminium	Water or thermal oil	Up to 330ºC
Solitem PTC1800 (Germany)		Parabolic Trough C=43	width:1,8 m length:5,02 m	Selective coated tube with glass envelope	Coated aluminium	Water, steam or thermal oil	100ºC to 250ºC
Soltigua FTM (Italy)		Linear Fresnel	width:5,24 m length:19 m to 38 m	Selective coated tube with glass envelope	Polished aluminium sheets	Water or thermal oil	Up to 250ºC
Soltigua PTM (Italy)		Parabolic Trough	width:2,4 m length:13 m to 26 m	Selective coated tube with glass envelope	Polished aluminium sheets	Water or thermal oil	Up to 220ºC
Sopogy SopoNova 4.1 (Hawaii-USA)		Parabolic Trough C=61	width:1,63 m length:4,1 m	Selective coated tube with glass envelope	Aluminium, polymeric laminate	Water	50ºC to 270ºC
Suntrac 25TC (USA)		Flat plate tracking parabolic trough	width:1,22 m length:2,44 m	Selective coated tube	Extruded aluminium	Water	60ºC to 120ºC
Trivelli Energia (Italy)		Parabolic Trough	width:1,25 m length:8,2 m	Selective coated tube with glass envelope with/without vacuum	Aluminium or silvered plastic	Water or thermal oil	Up to 320ºC
SRB (Spain)		Ultra high vacuum FPC C=1,8 to 7,9	width:0,6 m length:3 m	Ultra evacuated flat plate	Aluminium based	Water or thermal oil	320ºC (without concentration)
Isomorph solar (Germany)		2 axis tracking flat mirror concentrator	width:4,6 m length:2,75 m	PV/T	Aluminium	Water	100ºC

From Table 1 concentrating collector overview the following conclusions about the components and technical solutions can be derived:

- In general, for the temperature range from 200ºC to 400ºC the type of receivers used consist of a selective coated steel tube usually insulated with vacuum and enclosed by a borosilicate glass tube. Up to 200ºC, the receiver tubes mounted are the ones also used by regular evacuated tube flat plate collectors (heat pipe or direct flow). For higher temperatures the receivers are the ones used for CSP applications, like Schott PTR70 or Solel UVAC, using thermal oil as a heat transfer fluid.
- The type of reflector more used is the coated aluminized mirror. This mirror is made of a polished aluminium substrate, an enhanced aluminium reflective layer and top/back protective layers to withstand outdoor conditions. An example of this reflector type can be the Miro-Sun from Alanod.

5 Receiver characterization

There are no specific standards for the receiver tube (Heat Collecting Element) performance and durability tests.

5.1 Thermal characterization

The existing thermal characterization tests have different approaches and levels of testing complexity to obtain the thermal losses curve of a receiver. From the thermal losses test the receiver emittance can be obtained (with known vacuum level). According to the type of test bench used the thermal characterization methods can be:

- Outdoor test benches: Test benches using thermal oil loops for the performance test of a whole parabolic trough solar collector assembly (SCA) [3] like the LS3-HTF loop from PSA or a parabolic trough collector module mounted in a rotating test bench platform (with azimuth tracking) [4]. In both previous test benches the mass flow and the temperature difference between input and output are measured with the collector module oriented to the sky but in the shadow in order to determine the receiver thermal losses at a certain operating temperature.
- Indoor test benches which reproduce the receiver tube operating conditions in a controlled environment like a laboratory. The receiver operating temperatures are obtained by means of electrical heating

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[3] [19] V.E. Dudley, G.J.Kolb, M.Sloan, D.Kearney. “Test Results SEGS LS-2 Solar Collector”. SAND94-1884, Sandia National Laboratories, December 1994

[4] P.Heller, M. Meyer-Grünefeld, M. Ebert, N.Janotte, B.Nouri, K.Pottler,C.Prahl, W.Reinalter, E.Zarza. “KONTAS – A Rotary Test Bench for Standardized Qualification of Parabolic Trough Components”. SolarPACES 2011 - International Symposium on Concentrating Solar Power and Chemical Energy Systems. Granada

sets which radiate the metallic absorber tube of the receiver. When stationary temperature conditions at a certain temperature are reached the electrical power supplied to the heating sets is equivalent to the receiver thermal losses at that temperature. Reproducing the test at different operating temperatures allows to obtain the characteristic receiver thermal losses curve and the thermal emittance for a temperature range from 100ºC to 500ºC. This testing procedure was developed by NREL[5] and adopted by other R&D test centres and receiver manufacturers, some of them took part in the only inter-comparison test performed up to now[6].

A part from the previous tests are there several technical reports about the failures during operation of CSP plants and tests which complement the thermal loss curve like the vacuum level analysis or the use of different gases to reduce the receiver thermal losses[7].

As an example the following figures show the thermal characterization results measured at CENER test bench for a parabolic trough receiver.

Figure 2. CENER thermal characterization test bench

5 F.Burkholder, C.Kutscher. "Heat Loss Testing of Schott's 2008 PTR70 Parabolic Trough Receiver". Technical Report NREL/TP-550-45633, May 2009

6 S.Dreyer, P.Eichel, T.Gnaedig, Z.Hacker, S.Janker, T.Kuckelkorn, K.Simly, J.Pernpeintner, E.Luepfert. "Heat loss measurements on parabolic trough receivers". SolarPACES 2010 - 16th International Symposium on Concentrating Solar Power and Chemical Energy Systems. Perpignan, France

7 G.Gong, X.Huang, J.Wang, M.Hao. "An optimized model and test of the China's first high temperature parabolic trough solar receiver". Solar Energy- August 2010. Elsevier Ltd

Table 2. Parabolic trough receiver thermal characterization results at different absorber temperatures

To (ºC)	Ta (ºC)	Tabs (ºC)	Tgl (ºC)	HL (W/m)	uHL (W/m)	ε (-)	u(ε) (-)
100	21,0	111,8	24,2	16	± 3	--	--
100	20,9	111,6	23,8	16	± 3	--	--
200	21,4	210,6	30,9	40	± 5	--	--
200	21,6	210,7	31,2	39	± 5	--	--
300	20,5	307,6	41,8	101	± 9	0,0785	± 0,0068
300	20,6	307,7	42,0	98	± 8	0,0764	± 0,0063
350	20,9	353,3	50,7	145	± 14	0,0819	± 0,0076
350	21,0	354,0	51,1	140	± 14	0,0786	± 0,0076
400	22,2	399,0	61,0	198	± 5	0,0833	± 0,0019
400	22,3	398,5	61,2	200	± 5	0,0848	± 0,0020
500	22,6	508,0	89,3	447	± 4	0,1020	± 0,0007
500	22,6	508,1	89,3	443	± 4	0,1012	± 0,0007

Ta: ambient temperature,
To: target temperature,
Tabs: absorber temperature,
Tgl: glass envelope temperature,
HL: Heat Losses, uHL: Heat losses uncertainty,
ε: emittance, uε: emittance uncertainty.

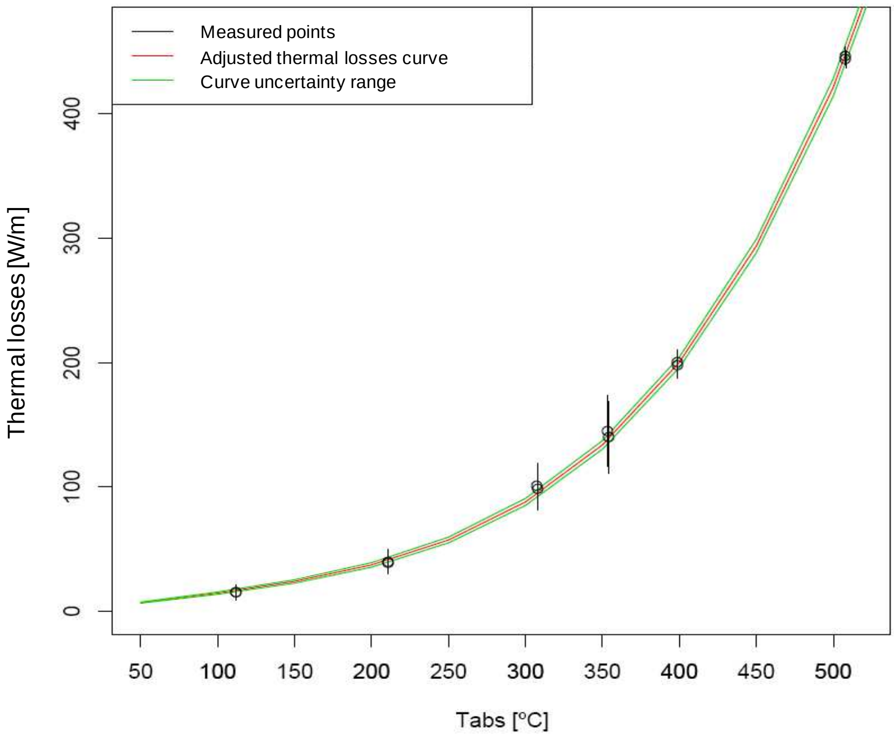

Figure 3. Heat loss values per unit length at measured absorber temperatures with their associated uncertainty and the linear fit confidence interval

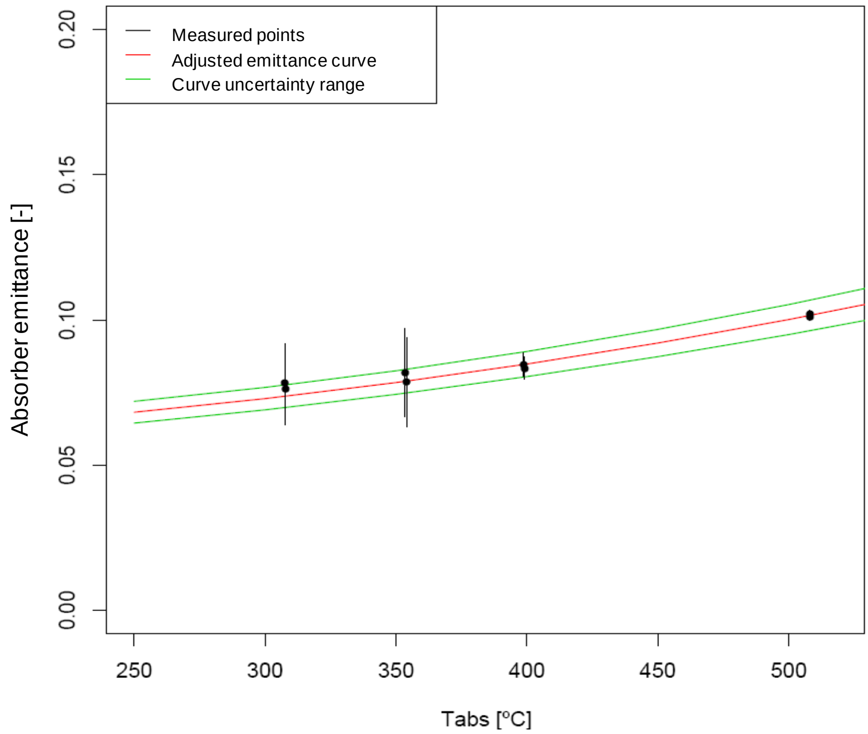

Figure 4. Calculated absorber thermal emittance at measured absorber temperatures with their associated uncertainty and linear fit confidence interval

5.2 Optical characterization

The existing optical characterization test methods for tubular receivers can be grouped in two categories: the destructive method and the non destructive method.

The destructive characterization method and the measurement equipments are based on the standard ASTM E424-71 and uses samples to measure the optical properties. Among the measurement devices the following ones can be highlighted:

- UV-VIS-NIR reflectance measurement equipment, able to measure at variable angle according to the ASTM standard.
- Far IR Fourier Transform measurement equipment with accessories to measure reflectance / emittance.

The biggest disadvantage of the destructive method is that is conceived for measuring flat samples and it’s difficult to adapt to tubular samples because the integration sphere ports are not well suited for that.

The non destructive characterization method allows measuring the optical properties without destroying the receiver: it is performed to the whole receiver tube. There are several methods to measure the optical properties of the receiver tube or the solar transmittance (τ_s) and solar absorptance (α_s) or the optical efficiency ($\tau\alpha$ product).

Evacuated receivers used with parabolic trough collectors can be characterized in terms of their optical efficiency which is the fraction of sunlight striking the receiver tube that is absorbed. It is equal to the product of the transmittance of the glass cover (τ) and the absorptance of the metallic absorber surface (α). NREL has recently presented an outdoor transient test procedure to measure the $\tau\alpha$ product[8]. The receiver is filled with cold water and exposed to outdoor solar radiation. The slope of the temperature vs. time curve is taken symmetric about the average glass temperature (the point at which there is no heat loss or gain from the absorber tube), and this is used to determine $\tau\alpha$. This method has the advantage of using the actual solar spectrum and has an uncertainty of ±2%. Preliminary measurements of a receiver tube resulted in a $\tau\alpha$ product that is reasonably close to the manufacturer's specifications.

In the same way, DLR is also able to measure the optical efficiency of a parabolic trough receiver; it is tested on test benches under conditions of natural sunlight and in a elliptical linear solar simulator setup. The test results in a single value accounting for all optical properties except thermal emittance. High reproducibility of the measurements allows for comparison and benchmarking of different products of the same dimensions in their optical efficiency value. Both error propagation analysis and test series show that the goal of less than 0.5% uncertainty can be achieved in comparing different products of similar geometry to a reference in the solar simulator test bench. The measurement method and the setup configuration aim at standardized receiver performance evaluation[9].

Another method for non destructive optical characterization is the one developed by CENER[10]. The optical characterization test bench is able to perform non destructive spectral transmittance and reflectance measurements, in the wavelength range from 300 nm to 2500 nm, at any angle and length position of the receiver tube which enables to conduct uniformity analyses of the optical properties at receiver tube level, a step beyond the state of the art of existing destructive measurement techniques. Furthermore, the optical test bench is designed to integrate heating elements to measure the receiver optical properties at different absorber temperatures. The measurement accuracy of the test bench has been studied based on a receiver sample measurement campaigns with the absorber tube at ambient temperature. Based on the obtained results a uniformity analysis for the optical properties of a complete receiver has been performed for the first time, outlining some conclusions about the key measurement parameters.

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8 C.Kutscher, F.Burkholder, J.Netter. "Measuring the optical performance of evacuated receivers via an outdoor thermal transient test". SolarPACES 2011 - 17th International Symposium on Concentrating Solar Power and Chemical Energy Systems. Granada

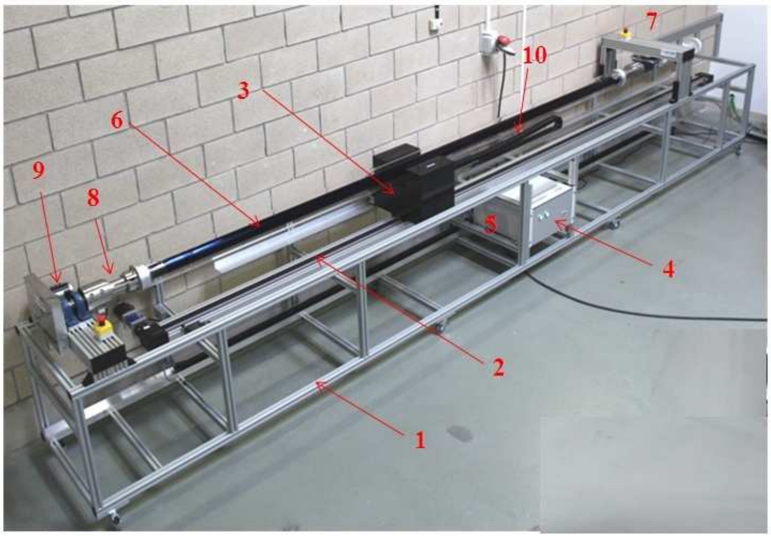
9 J.Pernpeintner, N.Lichtenthäler, B.Schiricke, E.Luepfert, T.Litzke, W.Minich. "Test benches for the measurement of the optical efficiency of parabolic trough receivers using natural sunlight and solar simulator light". SolarPACES 2010 - 16th International Symposium on Concentrating Solar Power and Chemical Energy Systems. Perpignan, France

10 E.Mateu, M.Sanchez, D.Perez, A.Garcia de Jalón, S.Forcada, I.Salinas, C.Heras. "Optical characterization test bench for parabolic trough receivers". SolarPACES 2011 - 17th International Symposium on Concentrating Solar Power and Chemical Energy Systems. Granada

Test procedure:

- Calibration of the receiver sample measurements against the reference tubular standards for τ / ρ and detector signal gain adjustment for the whole λ range. Air as reference τ=1.
- The measurement campaign is defined setting up a list of sample length positions, a list of wavelengths, and the λ step for the range from 300 nm to 2500 nm.
- Optimum angle search for τ and ρ measurements at a certain receiver length position.
- A simultaneous measurement of τ and ρ is performed after the optimum angle search. Then a simultaneous measurement of τ and ρ for the same receiver angular and length position is repeated.
- Step 3 for a new receiver length position of the measurement list. Process stops with the last of the 66 positions (every 5 cm) of the measuring campaign.
- With τ and ρ spectral curves for the 66 positions, the parameters of solar reflectance (ρ_s) and solar transmittance (τ_s) are determined by integrating the values over the same λ energy ranges of the direct solar irradiance (G_b) spectra according to the reference standards ISO 9845-1 and ASTM G173.

As an example the following figures show the optical characterization results measured at CENER test bench for a parabolic trough receiver.



1. Supporting frame structure
2. Linear movement unit
3. Optical sensor head (OSH)
4. Light source and wavelength scanning module (WSM)
5. Signal acquisition and data treatment
6. PTR sample under test
7. Calibration area: tubular standards
8. Special PTR sample fixings
9. Rotating system
10. Cable chain

Figure 5. CENER optical characterization test bench

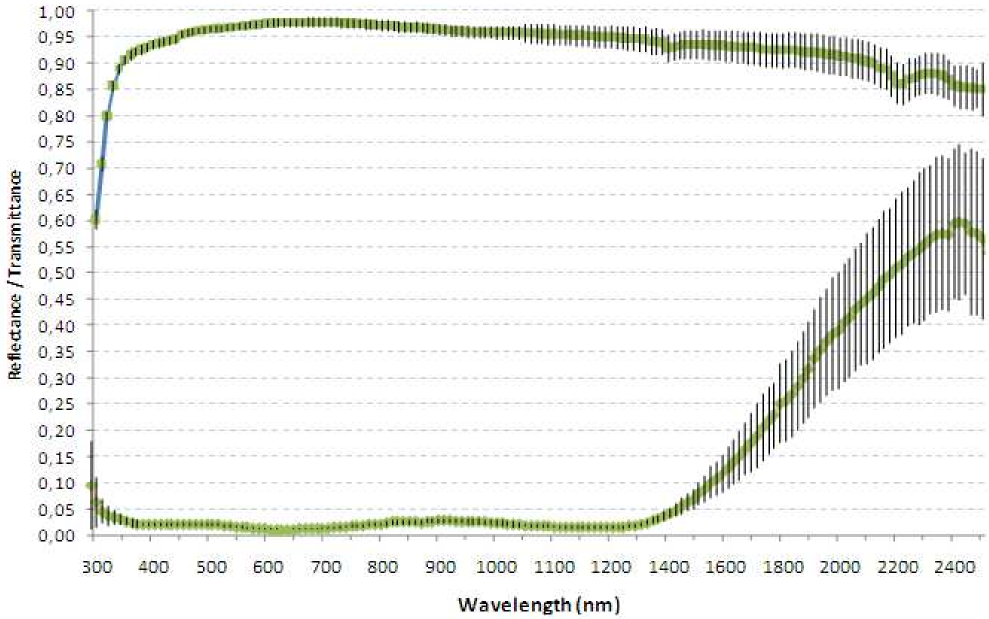


Figure 6. Spectral measurements for τ and ρ mean values with 2stDev bars from a receiver tube test campaign

Table 3. Parabolic trough receiver optical characterization results integrated with the solar radiation direct spectral distribution according to ISO and ASTM standards.

		Solar Transmittance		Solar Reflectance		Solar Absorptance
		τ_s	StDev	ρ_s	StDev	α_s
ISO	measuring set 1	95,70%	0,61%	4,18%	0,44%	95,82%
	measuring set 2	95,74%	0,66%	4,16%	0,42%	95,84%
ASTM	measuring set 1	95,75%	0,58%	3,75%	0,38%	96,25%
	measuring set 2	95,78%	0,63%	3,74%	0,36%	96,26%
ISO	average	**95,72%**	0,63%	**4,17%**	0,43%	**95,83%**
ASTM	average	**95,76%**	0,60%	**3,75%**	0,37%	**96,25%**
	difference	-0,05%	0,03%	0,42%	0,06%	-0,42%

6 Reflector characterization

6.1 Reflector materials overview

Solar reflector materials used mainly in concentrated solar power (CSP) are based on several constructions like metalized thick and thin glass mirrors, front surface aluminized reflectors, silvered polymers, and multilayer dielectric designs.

The mirrors usually have a support structure to give them the rigidity they require and on which a film of a highly reflective material is deposited. In general, the support structure that provides the rigidity to the mirror is a metal, glass or plastic plate, while the reflective material is usually silver or aluminium.

Metal plate supports are usually made of polished aluminium and have no added reflective material. However, these mirrors have very poor outdoor durability due to degradation of the optical characteristics of metal. Their main advantage is their low cost, but as they are not durable, they are not usually used industrially.

On the other hand, plastic supports are usually used to in the form of thin sheets on which the reflective film is deposited and must be attached to another rigid support. To date, this type of mirrors are not very durable against weather conditions and get dirty faster than in other cases because this type of plastic is electrostatically charged by wind and attracts dust.

The low-iron glass support option on which a reflective film is deposited is the one most widely used to date because it has none of the above problems. The reflective material is usually deposited on glass and is protected by a layer of copper and another of paint to protect it from outside agents. There are thus two different possibilities to shape the mirror, either the support itself is rigid or the mirror is flexible and takes on the shape given it by the structure it is attached to.

Table 4. Overview of available mirror types (Sun & Wind Energy review 2/2011)

Manufacturer	**Product description**	**Solar weighted reflectance**
Flabeg (Germany)	Monolithic glass mirror made from low-iron float glass	> 93.5% (average according to ISO 9050, air mass =1.5).
Guardian (USA)	Laminated glass mirrors	95.1% (Guardian) to 96.2% (Ciemat) direct
Rioglass (Spain)	Monolithic mirror made from tempered glass	>94% hemispherical
Saint-Gobain (France)	Monolithic mirror made from tempered glass	>94% hemispherical
Alanod (Germany)	Coated aluminium band	86.8% to 88.3% direct
Alcan Specialty Sheet (Germany)	Coated aluminium band	Solar Surface 990 model: 75% specular, 85% hemispherical Solar Surface 992 model: 83% specular, 88% hemispherical
Hydro (Norway)	Silver coated polymer mirror foil applied onto aluminium	max. 94%
SkyFuel (USA)	Large size parabolic trough collector, based on silverised polymer applied onto aluminium	93% hemispherical

The most commonly used material to date for collector reflector mirrors is the glass substrate mirror with silver deposition which reaches a maximum reflectivity of around 93.5%

6.2 Reflectance measurements

The Standard ISO 9050 (Glass in building — Determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors) gives details on the reflectance measurement that could be performed on a reflector even if the scope is for glasses. The reflectance is measure between 300 nm to 2500 nm for quasi-parallel almost normal radiation incidence. For the measurements, the incidence angle on the sample shall be less than 10º from the normal to the surface, and the acceptance angle shall be less than 5º. The accuracy in reflectance measurement should be about ± 0,01.

The Standard ASTM E 424 – 71 test methods cover the measurement of solar energy transmittance and reflectance of materials in sheet form. The solar reflectance measurements ρ can be performed, according to this standard, using a spectro-radiometer (method A) or a pyranometer (method B). With the method A, the reflectance is measured between 350 nm to 2500 nm. The solar reflectance is then calculated with normalized weighted ordinates energy intervals of twenty selected ordinates wavelength, as follows:

$$\rho = \sum_{\lambda=350\,nm}^{\lambda=2500\,nm} \rho(\lambda)E(\lambda)$$

The Standard ISO 9845-1 (Reference solar spectral irradiance at the ground at different receiving conditions) gives the spectral distribution of direct normal (with a 5,8º field-of-view angle) and hemispherical (on an equator-facing, 37º tilted plane with an albedo of 0,2) solar irradiance for air mass 1,5.

The Standard ASTM G173 – 03 gives tables for reference solar spectral irradiances: direct normal and hemispherical incident on a sun-facing plane tilted to 37° from the horizontal, in the wavelengt h range 280 to 4000 nm. The data are related to the absolute air mass of 1,5 and the direct irradiance contains a circumsolar component for a field of view of 5,8° centred on the sun.

In all those standards the procedure to calculate the solar reflectance is given based on the spectral reflectance measurements and weighted with solar energy, summarized as follows:

$$\rho(SW,\theta,\varphi) = \frac{\int_{\lambda_1}^{\lambda_2} \rho(\lambda,\theta,\varphi)E_\lambda(\lambda)\partial\lambda}{\int_{\lambda_1}^{\lambda_2} E_\lambda(\lambda)\partial\lambda}$$

Where:

- $\rho(SW, \theta, \varphi)$: solar weighted reflectance
- $\rho(\lambda, \theta, \varphi)$: sample specular reflectance at a wavelength λ, with an incidence angle θ and an acceptance angle φ.
- $E_\lambda(\lambda)$: solar radiation spectral distribution at a wavelength λ
- λ_1 : wavelength range lower limit

- λ_2 : wavelength range upper limit

For hemispherical reflectance measurement the acceptance angle φ is 2π as all the reflected light is measured.

For concentrated solar power (CSP) applications it is more convenient to integrate the specular spectral reflectance curve over the direct normal solar spectral irradiances and for low temperature solar collector applications to integrate the hemispherical spectral reflectance curve over the global solar spectral irradiances.

The optical measurement is not specified in most of those Standards. However the SolarPACES report “Measurement of solar weighted reflectance of mirror materials for concentrating solar power technology with commercially available instrument” (Version 1.1 May 2011) makes a summary of the different techniques and commercial instruments used for mirror measurements in CSP applications.

The main instrument to measure spectral reflectance is the spectrophotometer. This instrument is a photometer (a device for measuring light intensity) that can measure intensity as a function of the light source wavelength. Spectrophotometers are commonly used for measurements of transmittance, absorptance and reflectance of solutions and opaque materials making them effective for wide areas of application. To select the specific wavelength a monochromatic is used. The hemispherical reflectance is measured using an integrating sphere to detect all the diffuse light reflected by the sample. The diffuse light can be cut with a light-trap in the integrated sphere. As a result the spectral specular reflectance is:

$$\rho_s(\lambda) = \rho_h(\lambda) - \rho_d(\lambda)$$

The specular reflectance can also be measured directly without an integrating sphere but the accessories for the measurement of specular reflectance have a specific acceptance angle φ that should be well-defined. Generally, the acceptance angle is too large in CSP applications and so the information is lost, but for low-temperature application it is enough.

Reflectometers are measurement devices that measure the intensity of the light source after reflection on a sample without spectral wavelength selection. Reflectometers that are equipped with integrating spheres may be suitable for hemispherical reflectance measurements if their sphere is large enough. The solar-weighted reflectance value achieved with a reflectometer utilizing only one or a few discrete wavelength bands as a light source is always an approximation with lower accuracy than the one which can be obtained with a spectrophotometer. Their capabilities are not suitable for evaluating the specular reflectance of solar mirror materials. It is important for CSP applications that the reflectometer measures the radiometric radiance of reflection.

6.3 Durability and accelerated ageing tests

Based on the IEA (International Energy Agency) Task 27: Solar Building Facade Components: Final Report-Subtask B-Part2, IEA Solar Heating and Cooling Programme (2007), the degradation tests have been summarized:

Table 5. Screening testing for solar reflectors[11]

Degradation mechanism	**Critical periods of high environmental stress**	**Suitable accelerated test methods and range of degradation factors**
Degradation of the protective layer	At high cumulative dose of solar irradiation, photooxidation, hydrolysis, acid rain	Weatherometer tests: ISO 4892 Plastics - Methods of exposure to laboratory light sources (UV, temperature and RH) Condensation test + irradiation SPART 14 - acid rain modification of SAE J1960, which is a weatherometer test ASTM G155-00ae1 Standard practice for operating xenon arc light apparatus for exposure of non-metallic materials
Corrosion of the reflecting layer	Under humidity conditions involving reflector water condensation	Salt spraying and hostile gases-SP method 2499 A, also corresponding to ISO/CD 21207 method A
Surface abrasion	Wind, hail, cleaning	ASTM D4060-01 Standard Test Method for abrasion resistance of organic coatings by the taber abraser ISO 11998:1992 Paints and varnishes - determination of wetscrub resistance and cleanability of coatings
Surface soiling	Moisture, dust, dirt	ASTM D3274-95 Standard Test Method for evaluating degree of surface disfigurement of Paint Films by microbial (fungal or algal) growth or soil and dirt accumulation
Degradation of the substrate	Moisture, pollutants, acid rain, hail	Hail: ASTM E822-92(1996) Standard practice for determining resistance of Solar Collector covers to hail by impact with propelled ice balls ASTM E1038-98 Standard Test Method for determining resistance of Photovoltaic Modules to hail by impact with propelled ice balls
Loss of adhesion of protective coating	Moisture, pollutants, acid rain, hail, icing, UV, Thermal expansion	Hail: ASTM E822-92(1996) Standard practice for determining resistance of Solar Collector covers to hail by impact with propelled ice balls ASTM E1038-98 Standard Test Method for determining resistance of Photovoltaic Modules to hail by impact with propelled ice balls EN 12975-2 cap 5.10 Impact resistance test Icing: Build up of ice layers MIL-STD 810 E, Method 521 Icing /Freezing rain ISO 2653, ice formation, Test C Frost appearance IEC 60068-2-39,Z/AMD, combined sequential cold, low air pressure and damp heat test Thermal expansion: IEC 60068-2-14, Test N, Change of Temperature MIL-STD 810 E, Method 503.3, Temperature shock: ISO 10545 - Part 9 Ceramic tiles determination of resistance to thermal shock

[11] Task 27: Solar Building Facade Components: Final Report-Subtask B-Part2, International Energy Agency Solar Heating and Cooling Programme (2007).

The solar thermal industry is investing a lot of effort in reducing the time to market, and the need to predict the service lifetime is a key aspect in order to optimise processes and products. As a consequence, methods of predicting long term performance or durability have become broadly used for a sustainable and successful product commercialization. This involves the development of durability methods for:

a) quantitative characterisation of environmental stress suitable for service life prediction

b) test tailoring in environmental resistance testing

c) performance analysis to elaborate relations between component performance and material properties

d) predictive failure analysis to investigate relationships between failure, degradation and life-limiting processes in terms of chemical change of materials

e) risk analysis to estimate the effect of different failure modes with respect to reliability and safety.

The degradation factors from environmental stresses in service conditions need to be evaluated and measured to predict the component expected service life from the results of accelerating ageing tests.

The general standard IEC 60721[12] can be used as a starting point, this standard contains recommendations for classifying stress severity for various climatic, mechanical, chemical, biological and electrical environments:

- IEC 60721-1 Classification of environmental parameters and their severity. Introduction to the standard.
- IEC 60721-2 Environmental conditions appearing in nature. Temperature and humidity, precipitation and wind, air pressure, solar radiation and temperature, dust, sand, salt mist/wind, earthquake vibrations and shocks, fauna and flora.
- IEC 60721-3 Classification of groups of environmental parameters and their severities. Storage, transportation, stationary use at weather protected locations, stationary use of non-weather protected locations, ground vehicle installations, ship environment, portable and non-stationary use.

Although some standards are applicable to photovoltaic (PV) modules, they could be also used for solar thermal collectors. The standard IEC 61215 is applicable to photovoltaic (PV) modules, see the tests and testing conditions in the following table:

Table 6. Tests and testing conditions for PV modules

[12] IEC 60721, Classification of Environmental Conditions, International Electrotechnical Commission, P.O. Box 131, CH - 1211 Geneva 20, Switzerland.

Test	Testing conditions
UV degradation test	5 kWh/m^2 between 280 nm and 320 nm 15 kWh/m^2 between 280 nm and 385 nm
Thermal cycles test	200 cycles from -40 to 85 º C
Humid heat test	1000 hours 85ºC, 85% HR
Hail impact test	Ice ball impact, 25 mm diameter and 23.0 m/s speed

The international standard IEC 62108 specifies the minimum requirements for the design qualification and type approval of concentrator photovoltaic (CPV) modules and assemblies suitable for long-term operation in general open-air climates as defined in IEC 60721-2-1. Those durability tests are similar to the standard IEC 61215 specific to photovoltaic modules, see the tests and testing conditions in the following table:

Table 7. Tests and testing conditions for CPV modules

Tests	Testing conditions
Visual inspection (part 10.1)	Visual inspection No major visual defects
Electrical performance (part 10.2)	Outdoor, clear sky conditions DNI > 700 W/m^2, wind speed < 6 m/s.
Thermal cycling test (part 10.6)	T_C from –40 ℃ to T_{max}. 500 cycles if T_{max} = 110 ℃, 1000 cycles if T_{max} = 85 ℃, 2000 cycles if T_{max} = 65 ℃,
Damp-heat test (part 10.7)	1000 h at 85 ℃ and 85 % RH or 2000 h at 65 ℃ and 85 % RH
Humidity freeze test (part 10.8)	T_{max} and 85 % RH for 20 h followed by 4 h cool down to –40 ℃; 20 cycles if T_{max} is 85 ℃; 40 cycles if T_{max} is 65 ℃.
Hail impact test (part 10.9)	At least 10 shots of 25.4 mm diameter ice ball at 22.4 m/s on areas where an impact by hailstone falling from 45° around the vertical line is possible.
Water spray test (part 10.10)	1 h water spray on each of four orientations.
Mechanical load test (part 10.13)	2400 Pa on front and back, 1 h each, total of 3 cycles
UV conditioning test (part 10.15)	Expose to UV accumulation of 50 kWh/m^2. (This test could be combined with the outdoor exposure test of 10.16)
Outdoor exposure test (part 10.16)	Expose to DNI accumulation of 1000 kWh/m2 when DNI > 600 W/m^2.

NREL has leaded an experience summary in accelerated indoor and outdoor exposure tests[13] for solar reflectors with different reflector constructions[14]. It is very important to check the concordance between the accelerated ageing tests results and the real service conditions according to outdoor measurements. Since last decades also significant experience has been collected from CSP applications.

Table 8. Main ageing tests carried out by reflector manufacturers

Tests	**Standard**	**Testing conditions**
Salt spray (NSS)	EN ISO 9227	480 hours
Salt spray (CASS)	EN ISO 9227	120 hours
Climatic cycling	EN ISO 6270-2	10 cycles: 4h at +90ºC, 4h at -40ºC
Humidity	EN ISO 6270-2	480 hours at 40ºC/ 100%HR
UV	ISO 11507	2000 hours
Paint adhesion	ISO 2409	Cross-Hatch test
Tempered glass	EN 12150-2	Burst test to check the temperate characteristics
Hail impact test	EN 12975	Ice ball impact, 25 mm diameter and 23.0 m/s speed

The salt spray tests under corrosive atmospheres aim to characterize the behaviour of different materials subjected to the influence of high salt content atmospheres such as those found by the sea, deserts, etc. They are really commonly used for the surface finish.

The climatic cycle tests aim to characterize the resistance of protective paint layers to sudden changes in temperature and continuous condensation on them.

The humidity tests aim to characterize the behaviour that might be expected in protection layers under severe exposure conditions, when there is a continuous condensation on the surface (embrittlement, discoloration, wrinkling and corrosion).

[13] T.Fend *, B. Hoffschmidt, G.Jorgensenb, H. Küster, D. Krüger , R. Pitz-Paal , P. Rietbrock , K.J. Riffelmann Comparative assessment of solar concentrator materials, Solar Energy 74 (2003) 149–155.

[14] C.E. Kennedy, K. Terwilliger, Optical Durability of Candidate Solar Reflectors, Journal of Solar Engineering (2005) Transactions of the ASME Vol. 127 262-269.

The UV resistance test provides information on the protection of the reflecting surface to the combined action of moisture and UV radiation.

7 Tracking system characterization

7.1 Tracker overview

The sun-tracker is the general name used for devices which enables a solar collector to follow the sun in order to minimize the angle of incidence.

There are three types of drives used to move the tracker:

- Active-electric drive systems which transfer electrical energy to AC motors, DC brushed motors or DC brushless motors to create rotational motion.
- Active-hydraulic drive systems which use pumps to generate hydraulic pressure which is transferred through valves, pipes, and hoses to a hydraulic motor or cylinder.
- Passive drive systems use differential fluid pressures generated by different shading gradient to drive the tracker axis.

From the active drive type, there are two main types of tracking method:

- Open-loop control, which does not use sun position sensor or any feedback but uses mathematical calculations of the sun position (based on the time of day, date, location, and so on) to determine where the tracker should be pointing and drives actuators accordingly.
- Closed-loop control which uses some sort of feedback (such as an optical sun position sensor or the module power output) to determine how to drive the actuators and position the payload.
- Hybrid control which combines the mathematical sun position calculations (open loop ephemeris code) with the type of sensor data used in a closed feedback loop.

From the Closed-loop control type, by differential illumination of electro-optical sensors a differential control signal occurs which is used to drive the motor and to orient the apparatus in such direction where illumination of electro-optical sensors become equal and balanced. In addition, the photodiodes can be mounted on tilted planes in order to increase the photocurrent sensitivity and, also the shading device is presented as a collimating tube which prevents diffuse irradiation from entering the sensor and masking a precise measurement of the sun alignment position.

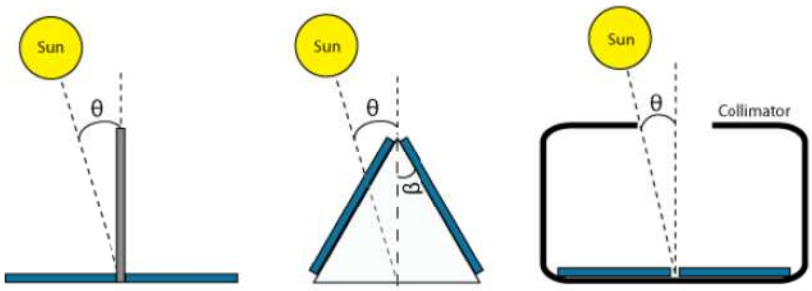


Figure 7 Shade balancing principle (a) sun-pointing sensors (b) tilted mount of photo sensors (c) precise sun pointing by means of a collimator.

Moreover sun trackers can be grouped into classes by the number and orientation of the tracker's axes. The two possible types are the single axis and the dual axis trackers. The single axis trackers have one degree of freedom that acts as an axis of rotation and the dual axis trackers have two degrees of freedom that act as axes of rotation.

For the single axis tracker, there are several common implementations: horizontal single axis trackers, vertical single axis trackers, and tilted single axis trackers.

The axis of rotation for horizontal single axis tracker is horizontal with respect to the ground. The axis of rotation for vertical single axis trackers is vertical with respect to the ground. The trackers with axes of rotation between horizontal and vertical are considered tilted single axis trackers.

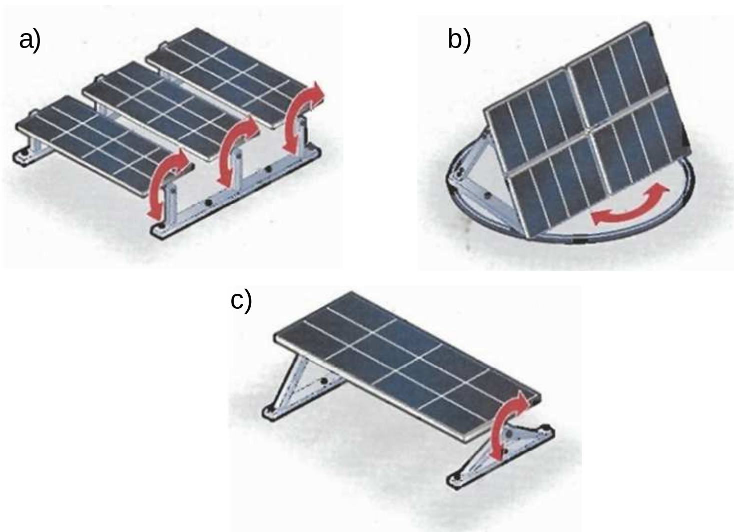


Figure 8 Single axis trackers: a) horizontal, b) vertical and c) tilted.

For the dual axis tracker, there are several common implementations: the tip - tilt dual axis tracker and azimuth-altitude dual axis tracker.

A tip–tilt dual axis tracker has its primary axis axes horizontal to the ground. The secondary axis is then typically normal to the primary axis. An azimuth–

altitude dual axis tracker has its primary axis vertical to the ground. The secondary axis is then typically normal to the primary axis.

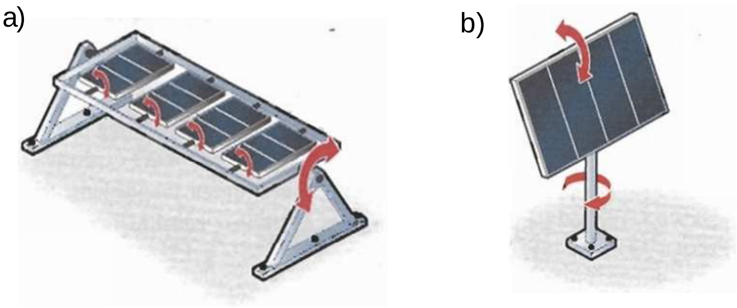


Figure 9 Dual axis trackers: a) tip - tilt and b) altitude-azimuth.

For solar thermal (ST) applications the main trackers types used are the horizontal or tilted single axis trackers. In the horizontal one the tracking could be oriented East-West or North-South.

7.2 Tracking accuracy

There is currently no industry-wide defined standard for specifications of solar trackers. Each vendor designs, builds and specifies the functionality and accuracy without uniform definition. Therefore, it is difficult to specify the requirements to compare the products from different vendors, and to verify the quality of the products.

For photovoltaic (PV) applications there is an International IEC Standard under development for sun trackers but it is not published yet. For thermal applications there is no standard at the moment. But as the main purpose of the sun trackers for PV and for ST is the same the upcoming IEC Standard could be used to define the main parameters to be characterized.

The main parameter to be defined for a sun-tracker would be the pointing error. This instantaneous measured quantity is the angle between the pointing vector of the solar system aperture and the pointing vector of the sun.

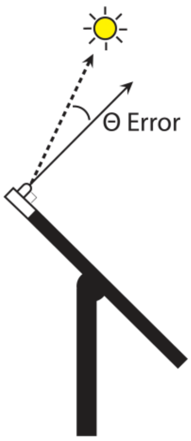


Figure 10 - General Illustration of Pointing Error (IEC Standard Draft)

The measurement of the pointing error could be directly determined using an optical sensor mounted on the tracker in the same plane as the solar system and measures the relative sun position.

A possible experimental tracking accuracy measurement can be obtained by using two flat parallel planes that are a specified distance from each other, one having a pinhole in it so as to project the sun's location in a measurable format.

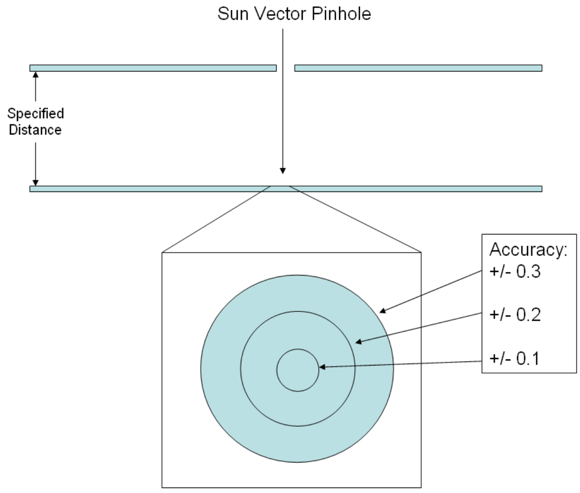


Figure 11 - Two flat parallel plates at a specified distance, one having a pin hole for sun light to be tracked on specified diameter circles that ultimately measure 0.1, 0.2, and 0.3 degree accuracy rings (more if necessary) (IEC 62727 TS Ed.1)

Alternatively, a lens or other optics could be used to cast an image of the sun on the detector. The projected image of the sun may be recorded and analyzed with photosensitive paper, a photodiode array, an image sensor (CCD or CMOS imager), or other similar sensors.

This measurement is only applicable to dual-axis trackers.

8 Recommendations for standard revision

The described component characterization methods have different approaches depending on the test or R&D centres. The existing tests methods and the new ones need to be validated trough intercomparison if possible in order to check their validity and/or limitations.

In the case of the receiver characterization test methods, such intercomparison has already been performed by some R&D centres and receiver manufacturers for the thermal characterization test, obtaining measurement results that show a good agreement. In this case the test method is ready and it has already been included in the CSP component draft standard developed by AENOR/CTN206 standardization technical committee. This method will be will be adopted in a later stage, as a technical work document at international level, by the IEC/TC117. The optical characterization method for receivers has still to be check in order to see the equivalence of different characterization test approaches.

In the case of reflector characterization test methods, there are several reference standards but they are not specific for solar thermal applications, and the optical measurement is not specified in most of them. For the reflectance measurements, the Task III working group of the SolarPACES has elaborated a guideline document: “Measurement of solar weighted reflectance of mirror materials for concentrating solar power technology with commercially available instrument”, which makes a summary of the different techniques and commercial instruments used for mirror measurements in CSP applications. This guideline probably will be used as a technical work document by the IEC/TC117. For the accelerated ageing test methods, further development is needed in order to find the degradation factors specific for solar thermal (from low to high temperature applications) and determine the correlation between the indoor accelerated test time and the outdoor real service time.

In the case of the tracking system, the information described in this document is already part of the technical specification developed by the IEC/TC82 “IEC 62727 TS Ed.1: Specification for solar trackers used for photovoltaic systems”.