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First Self-Aligned Heliostat Prototype at the Plataforma Solar de Almería

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Abstract. It is a generally admitted fact that the optical aligning process of faceted heliostats in a Solar Power Tower Plant (SPTP), also called heliostat canting, introduces an assembly time penalization as well as a potential error in heliostat optics conformation [1, 2]. This double penalization influences both the solar field setup time and the optical quality of the SPTP. Aware of this fact, in 2014 the Plataforma Solar de Almeria (PSA) developed and patented a method to self-align facets and thus avoid the critical canting phase of a heliostat [3]. To experimentally demonstrate the feasibility of the self-aligning facet process, a small reflector composed of six facets and 9m^2 of reflecting surface was designed and fabricated. The success of that experience has led to the development of a first 18.5m^2 prototype of a self-aligned heliostat, which has been installed at the CESA-1 Heliostat Field (PSA) in 2022.

Keywords: Heliostat Canting, Facet Self-Aligned Process, Heliostat Set-up Optimization.

1. Design considerations: Advantages associated with the self-aligned heliostat concept.

1.1 Facet

Facet is no longer an imaging system per se. It is now a simple reflecting element without any kind of associated revolution geometry for optical purposes. Figures 1 A, B, C, D show a prototype of this kind of facet throughout the manufacturing process, consisting on a sandwich of metallic substrate glued to a second surface high specularity mirror under vacuum conditions. This square facet of 0.86m side can be screwed to the heliostat supporting structure, due to its metallic perimeter margin provided with drilled holes (Figure 1B). The implications of this change in the facet paradigm are: a) it simplifies and cheapens the manufacturing process, because the optical and careful forming process is suppressed; b) there is a single universal facet model for the entire heliostat field, i.e., from the point of view of the initial assembly of facets in the SPTP, as well as for the successive replacements, any facet can be mounted on any heliostat of the field, since it does not have its own optical characteristics (geometry and focal length) but copies those imposed by the heliostat's support structure, and it is thus automatically focused and aligned.

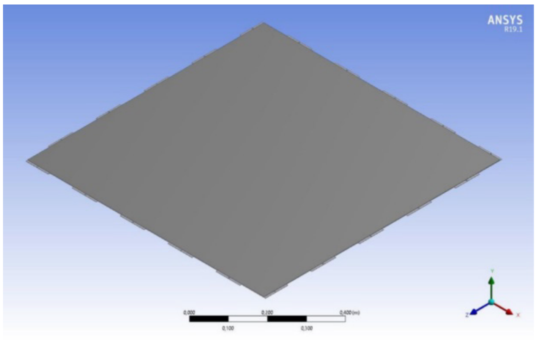


Figure 1A. ANSYS model of the individual facet.

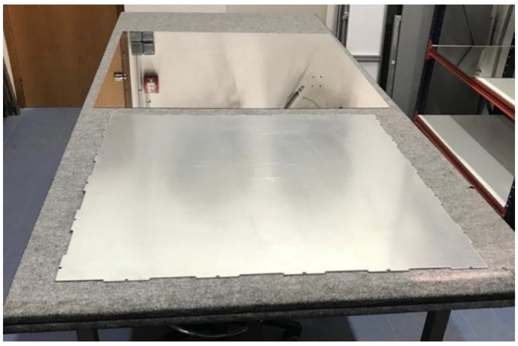


Figure 1B. Facet components before the glass-metal sandwich fabrication process. Perimeter is drilled for bolting to support structure.

Figure 1C. Facet during the glass-metal sandwich fabrication process under vacuum condition.

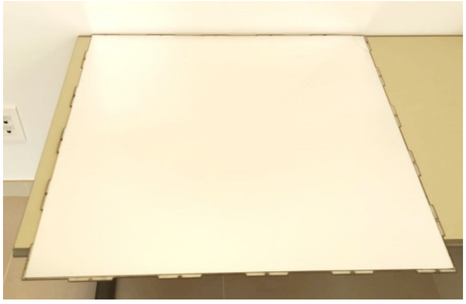


Figure 1D. Facet after the glass-metal sandwich fabrication process.

1.2 Supporting structure

It now takes the relevant role of the new heliostat concept, so it is not only the supporting structure of the facets, but it is also provided with a well-defined geometry with feasible technological construction and affordable cost. This is achieved through a novel design and manufacturing process by means of a water-jet machine. According to an input CAD file, the water-jet machine manufactures a set of trusses capable of being easily assembled to each other, in order to generate a mechanical surface of revolution of any size and geometry by simply screwing, requiring neither qualified personnel nor precision instruments. By simply changing the parameterization of the input CAD file, the water-jet machine will manufacture trusses of different curvature and/or length, so that the resulting geometry of the surface of revolution will be different and, therefore, different in size and/or focal length of the resulting heliostat. As a result of the above, the facets are then just screwed onto the mechanical surface of revolution generated by the trusses, in such a way that, by copying it geometry, they are automatically focused and aligned without any further task, thus achieving a specular surface of revolution. So, if necessary, each heliostat in the field could have its own focal length with great precision.

Figure(s) 2A, B shows the understanding facets self-alignment concept.

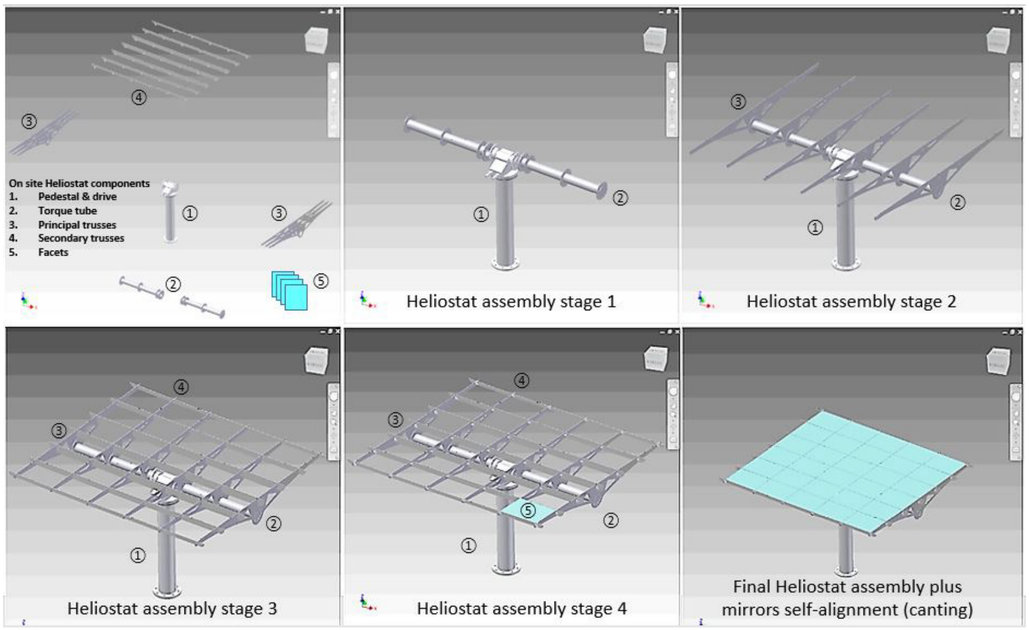


Figure 2A. Understanding facets self-alignment concept (I).

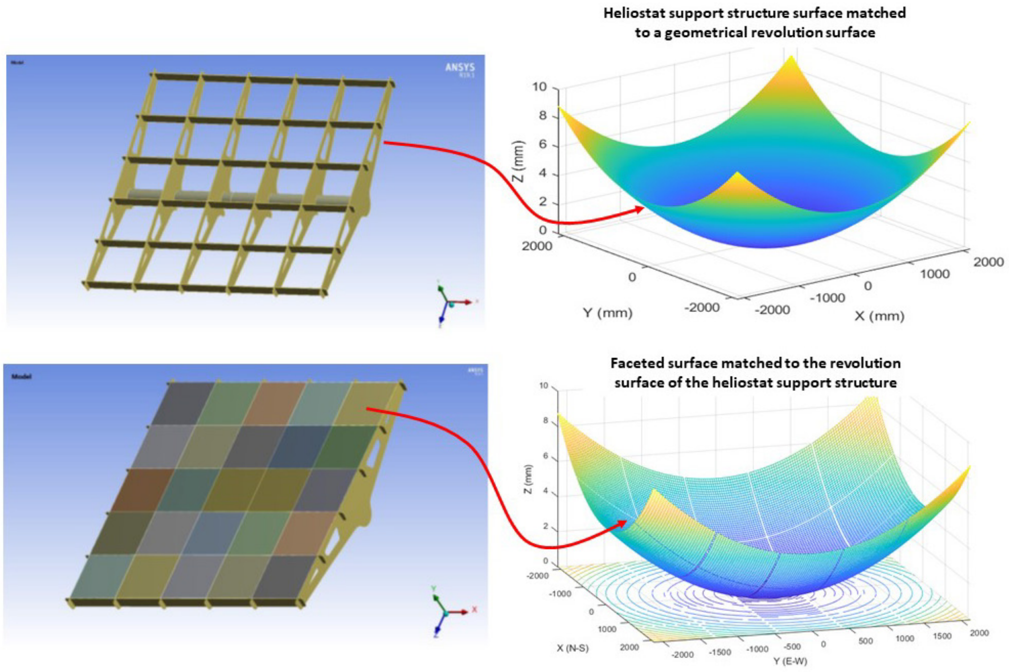


Figure 2B. Understanding facets self-alignment concept (II). Up: After trusses assembling (left), heliostat supporting structure fits to a revolution surface (right). Down: After facets assembly to the supporting structure (left), the reflecting structure fits to the previous revolution surface (right), thus achieving the focusing and alignment (canting) of the facets at once. Precision instruments and expert personnel are therefore removed from the heliostat setup process at the SPTP.

2. Description of the tasks performed in the development of the first self-aligned heliostat prototype, to be assembled and evaluated at the CESA-1 Heliostat Field Facility.

2.1 On the design of the prototype heliostat support structure. Case studies of structural deformations of the heliostat in different loading states. Conclusions.

Figure 3 shows the results of the optimization with ANSYS Mechanical concerning the material and thickness of the trusses and facets of the 18.5m^2 heliostat prototype developed by PSA-CIEMAT, under 2 heliostat load states, corresponding to an elevation angle of 23º with and without 25 km/h headwind (load conditions 3 and 4 respectively).

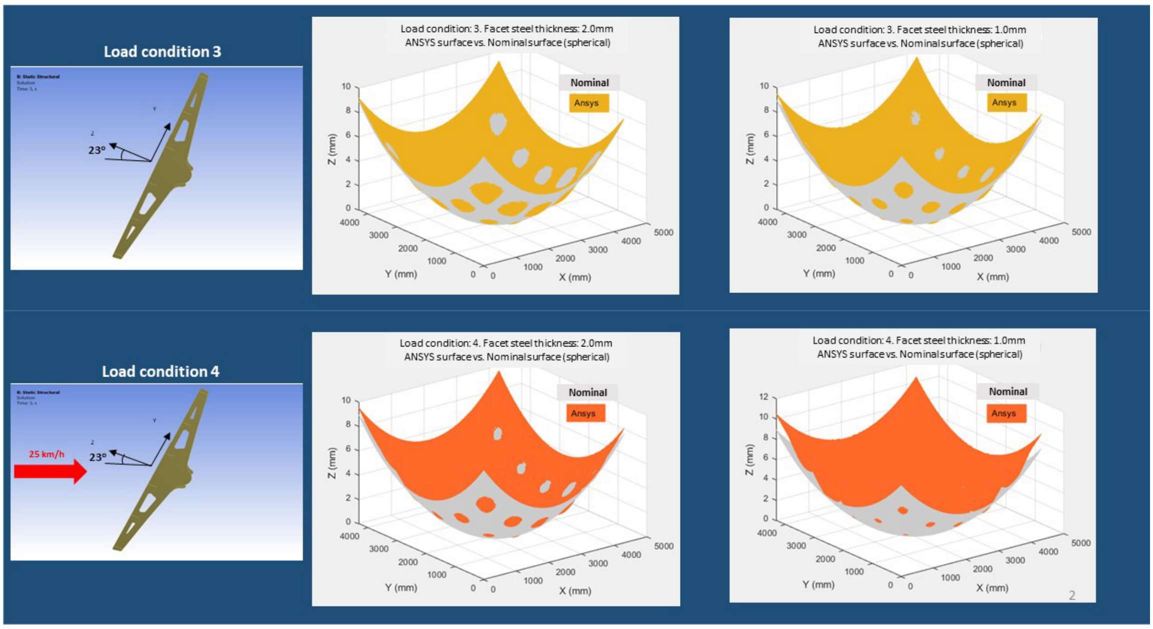


Figure 3. ANSYS Mechanical analysis of structural deformations in different heliostat loading states vs. nominal support structure (spherical, 256m focal length)

Results:

Trusses: Material: steel. Thickness: 10mm.

Facets: Metallic part. Material: Steel. Thickness: 2mm. Specular part. Material: Second surface silver-glass mirror. Thickness: 1mm.

With this configuration of materials and thicknesses, the best compromise between the nominal and the expected real support structure is achieved, in terms of minimizing costs while maintaining the stiffness and shape compatible with the demanding optical quality.

Moreover, based on the characteristics of the glass-metal sandwich materials, iterative calculation with ANSYS optimizes the thicknesses and demonstrates that the perimeter bolting of the facet to the supporting structure is able to achieve, with sufficient approximation, the expected geometry, curvature and orientation, without applying additional force in any other place of the facet.

2.2 Testing facets with glass-metal sandwich typology

This topic includes: Accelerated Aging Tests campaign of glass-to-metal samples with different types of adhesives and thicknesses, carried out at the PSA Optical Aging Characterization Laboratory (OPAC). Result and conclusions.

An accelerated aging test campaign was performed at the OPAC facilities (in cooperation between CIEMAT and DLR), under the framework of the SOLTERMIN Project, in order to analyze the durability of a new reflector material developed by CIEMAT. This reflector material (facet) is composed by a silvered-glass reflector glued to a steel support, because this is the configuration of the real size facet on the heliostat, which has perimetrically drilled holes in the metal substrate to screw it to the supporting structure. The main goal of this durability analysis is to assess the performance of the glass-metal assembly and different adhesive options.

2.2.1 Methodology

The reflector materials are composed by a silvered-glass reflector sample of 10 x 10 cm² and 1 mm thickness glued to a steel support of 1 mm thickness and approximately the same area of the reflector. Three different adhesives (A1, B1, B2) were tested (see Figure 4 as an example), and a fourth material only with the silvered-glass reflector was also included as a reference. A1 adhesive is the model S20 by SIKA. For confidentiality issues the data of adhesives B1 and B2 cannot be disclosed. All samples contain edge protection in each of the 4 edges. The edges were beveled to increase the durability of the material but do not correspond to factory-like c-shape edge protection. 3 samples per material and test were included. The accelerated aging tests carried out on the 4 reflector materials are summarized in Table 1.

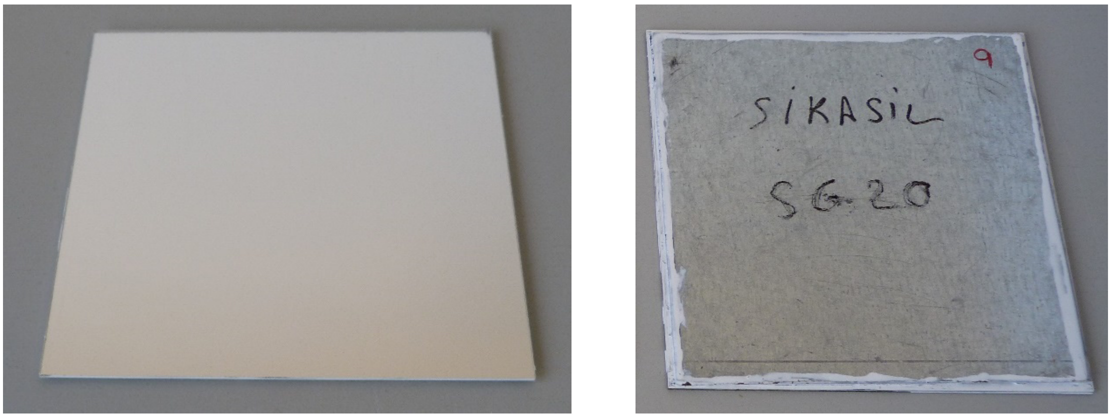


Figure 4. Picture of a SIKA S20 sample supplied, before accelerated aging testing. Left: front side (reflective side). Right: back side (reflector sample glued to a steel structure).

Table 1. Summary of accelerated ageing tests carried out in this study.

Accelerated aging test	**Standard**	**Test conditions**
Condensation	UNE 206016 Test 6.7 [5]	40°C with 100% relative humidity Total testing time = 480 hours
Thermal cycling + Humidity	UNE 206016 Test 6.8 A [5]	85°C and -40°C for 4 hours respectively at ambient humidity. Afterwards, the samples are exposed to high relative humidity of 97±3% during 16 hours at 40°C Number of cycles = 10; total testing time = 240 hours
Humidity freeze cycle	IEC 62108 Test 10.8 [6]	First step: 400 cycles from -40°C to 65°C. A dwell time of at least 10 min within ±3°C of the high and low temperatures Second step: 40 times to the humidity freeze cycle Total testing time ≈ 1500 hours.
UV + Humidity	UNE 206016 [5]	4 hours at 60°C to UV-radiation + 4 hours at 50°C to condensation (100% relative humidity without irradiation). Total testing time = 2000 hours
Damp heat	IEC 62108 Test 10.7 [6]	65°C with 85% relative humidity Total testing time = 2000 hours

The characterization of the samples was carried out before and after subjecting them to the different tests described in Table 1. The parameters used for the evaluation of the durability of the samples were the solar-weighted near-normal hemispherical reflectance (ρs,n,h), the monochromatic near-normal hemispherical reflectance (ρλ,n,h), and the monochromatic near-normal near-specular reflectance (ρλ,n,φ). The corresponding differences of the above mention reflectance parameters were obtained with the final and initial values, Δρs,n,h, Δρλ,n,h, and Δρλ,n,φ. In addition, a photographic inspection and an optical microscopy analysis was carried out. Reflectance measurements were performed according to the actual SolarPACES reflectance measurement guideline [7].

2.2.2 Results and conclusions

As example of the results, Table 2 shows the values of $\Delta\rho_{\lambda,n,h}$. In general, no remarkable degradation was seen in the new reflector materials designed by CIEMAT, with respect to silvered-glass reflector (REFERENCE) used as reference. The only exception are the materials made with adhesives B1 and B2 which present significant silver corrosion after the damp heat test, as can be observed in Table 2 and Figure 5. According to these results it seems that a chemical reaction happened with these two adhesives under the testing conditions of the damp heat test, see Table 1.

Table 2. Monochromatic near-normal near-specular reflectance differences, $\Delta\rho_{\lambda,n,h}$ (final – initial).

	A1	B1	B2	REFERENCE
Condensation	-0.002 ± 0.001	-0.002 ± 0.001	-0.003 ± 0.001	-0.002 ± 0.001
Thermal cycling + Humidity	-0.001 ± 0.001	-0.001 ± 0.001	-0.001 ± 0.000	0.000 ± 0.001
Humidity freeze cycle	-0.003 ± 0.001	-0.004 ± 0.001	-0.003 ± 0.001	-0.002 ± 0.001

UV + Humidity	-0.003 ± 0.002	-0.003 ± 0.001	-0.004 ± 0.002	-0.003 ± 0.001
Damp heat	-0.003 ± 0.002	-0.004 ± 0.002	-0.006 ± 0.005	-0.003 ± 0.001

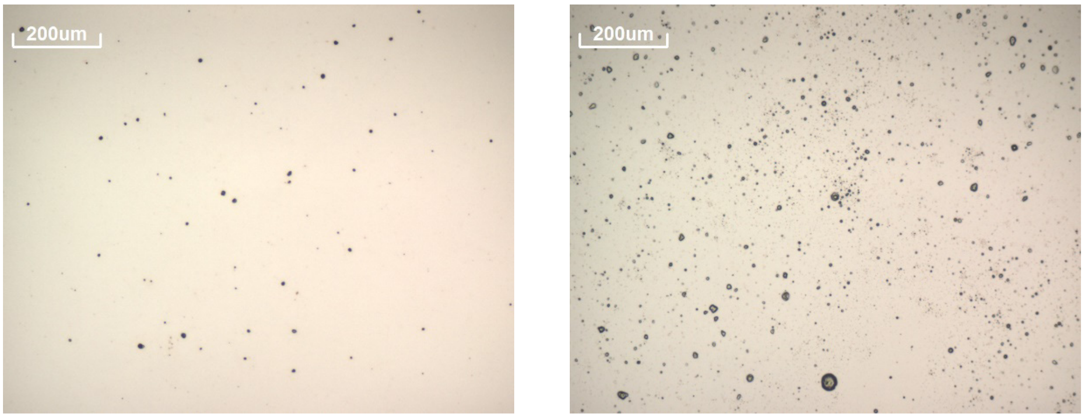


Figure 5. Picture of the B1 sample (left) and B2 sample (right) after both samples were subjected to 2000 h of the damp heat test.

Conclusions: i) the new reflector material manufactured by CIEMAT showed adequate durability under the testing conditions, ii) specially recommended the application of the adhesive SG20 by SIKA.

2.3 Installation of the self-aligned heliostat support structure in CESA-1 Heliostat Field (PSA), with only central facet assembly.

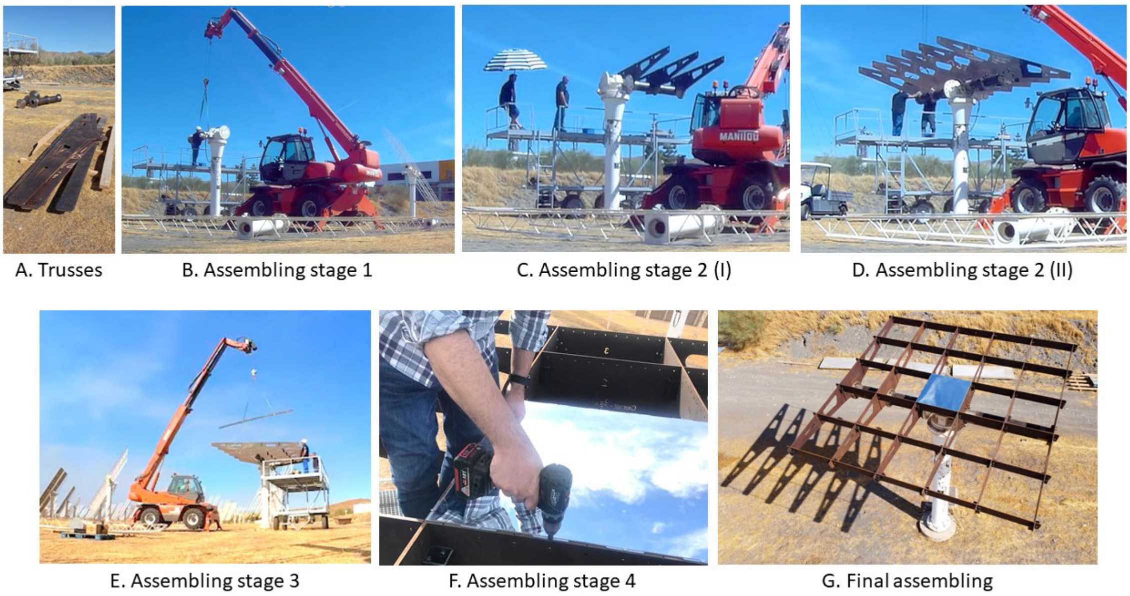
The milestone of the installation, i.e., assembly + self-canting of the heliostat in the CESA-1 field, is to demonstrate that this process can be performed under the following conditions:

i) Machinery: one crane and one work platform.

ii) Personnel: two mechanics, one crane operator.

iii) Tools: fixed or motorized torque key.

iv) Neither instrumentation nor qualified personnel shall be involved in the process.


A. Trusses B. Assembling stage 1 C. Assembling stage 2 (I) D. Assembling stage 2 (II)

E. Assembling stage 3 F. Assembling stage 4 G. Final assembling

Figures 6 A, B, C, D, E, F, G. Heliostat assembly sequence.

As already mentioned at the beginning of the article, once the heliostat support structure is assembled and the facets are screwed, the heliostat will be already focused and canted, without requiring any additional task for this process, so it is already an optical system ready to work in the solar plant. According to Figure 2A, Figures 6 A, B, C, D, E, F, G show now the real assembly process of the heliostat at the CESA-1 Heliostat Field on September 14, 2022.

Figure 7 shows the heliostat tracking on the CESA-1 target and the corresponding image of the reflected sun, unfortunately only by the central facet, due to logistical problems in the delivery of the rest of the material.

Figure 7. Self-aligned Heliostat on sun-track (left) and the reflected sun image from central facet (right).

At the time of publication of this article, no optical quality measurements of the central facet are available, only the confidence that the correct reflection of the solar disk allows us to conclude that at least the geometry of the facet reproduces our expectations and is not mechanically distorted. Our commitment for the year 2023 is to complete the assembly of the remaining facets and to proceed with the optical evaluation of this heliostat concept.

Conclusions and outlook

It has been experimentally demonstrated at PSA that it is possible to build and assemble the reflecting surface of a heliostat starting from a modular trusses structure, whose geometry and simple way of assembly lead to a heliostat whose facets need neither to be focused nor aligned. Moreover, neither instrumentation nor qualified personnel are required for this type of heliostat assembly process. The facets are very simple reflective elements, which adapt to the shape of the supporting structure to which they are screwed, in order to achieve both the geometry and alignment required in such kind of heliostat. Our PSA experience has shown us how much time is spent in building facets −that are themselves imaging systems−, packing and transporting them carefully, sorting them on site by focal length zones, mounting them on the heliostats and finally aligning them (canting), and all that just for our field of only 300 heliostats. We are here only talking about the *time* invested in the new heliostat optical set-up at the CESA-1 Heliostat Field, and how the so called *self-aligned* process reduces it, in a first approximation, by more than 50%. The advantage of this proven fact would apply immediately to a commercial solar tower power plant, not only in its construction phase, also in the successive campaigns to replace facets due to breakage and/or corrosion. All the effort in the development of this new heliostat design is not only aimed at reducing manufacturing and assembly time in the solar plant, but it must also have the objective of improving the optical quality of the heliostat. This is expected to be achieved in two ways: a) By eliminating the process of facet alignment (canting), an important source of error in the overall optical quality of the heliostat; b) With this concept, the focal length of each heliostat coincides with its slant range, which favors the optical quality of the field as all the heliostats are correctly focused.

As an outlook, we mention the remaining task of assembling the rest of the 24 facets pending of delivery for this prototype, as well as carrying out in 2023 an evaluation campaign regarding the optical quality that would be associated with this heliostat concept.

Author contributions

R. Monterreal: Conceptualization, Formal Analysis, Investigation, Visualization, Writing-Original Draft; **R. Enrique:** Conceptualization, Formal Analysis, Investigation; **G. Barrera:** Formal Analysis, Methodology; **R. Sánchez:** Formal Analysis, Funding Acquisition, Investigation, Resources; **T.J. Reche:** Formal Analysis, Investigation, Resources; **J. Rodriguez:** Methodology, Resources.

Competing interests

The authors declare that they have no competing interests.

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