# Status update of the SolarPACES heliostat testing activities

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# Status Update of the SolarPACES Heliostat Testing Activities

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**Abstract.** Power tower or central receiver systems use hundreds to ten thousands of two-axis tracking mirrors, so called heliostats, which reflect and focus the sunlight onto a receiver on top of a tower during the day. As basis for a well performing heliostat field, a single heliostat has to perform "correctly". In order to describe and measure the performance of a single heliostat, the SolarPACES Guideline for Heliostat Performance Testing has been developed by a group of R&D and industry experts during the last years. However, at the end, the performance of the whole field, which means the superposition and interaction of all heliostats determines the energy collected in the aperture of a solar central receiver. For that reason, a second guideline is currently outlined, the SolarPACES Guideline for Heliostat Field Performance Testing. Both guidelines aim to be commonly agreed protocols between R&D centers and industry in the field of heliostat performance testing. Recently, a third guideline activity has been started to improve and unify heliostat wind load design methods. The once finalized guidelines (or their concepts) should be included in international standards (e.g. IEC) and used by national organizations like DKE, AENOR, ASME, ASTM. This paper gives an update of the state of the three guidelines being developed in the SolarPACES task III-heliostat working group.

## INTRODUCTION

SolarPACES is an international cooperative network bringing together teams of national experts from around the world to focus on the development and marketing of concentrating solar power systems, also known as solar thermal power systems. It is one of a number of collaborative programs, called Implementing Agreements, managed under the umbrella of the International Energy Agency to help find solutions to worldwide energy problems. Within SolarPACES, several international task-activities coordinate the work.

The objectives of task III "Solar Technology and Advanced Applications" is the advancement of the technical and economic viability of emerging solar thermal technologies and their validation with suitable tools by proper theoretical analyses and simulation codes as well as by experiments in special arrangements and adapted facilities. To this end, procedures and techniques are defined for the design, evaluation and use of the components and subsystems to optimize concentration, reception, transfer, storage and application of solar thermal energy. In essence, the goals are to investigate innovative multi-discipline advances needed for the further development of concentrating solar thermal systems.

Power tower or central receiver systems use hundreds to ten thousands of two-axis tracking mirrors, so called heliostats, which reflect and focus the sunlight onto a receiver on top of a tower during the day. The heliostat field represents almost 50% of the costs of a central receiver system and its performance is crucial to provide the concentrated solar radiation, the "fuel" of the solar power plant.

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Due to this importance, dedicated groups of R&D and industry experts has been working together in the framework of task III to work on the following heliostat guidelines:

- **Heliostat Performance Testing Guideline:** to measure the performance of single heliostat units (prototype validation & qualification, section 2)
- **Heliostat Field Performance Testing Guideline:** to measure the performance of industrial-sized heliostat fields (section 3)
- **Heliostat Wind Load Design Guideline:** to improve and unify heliostat wind load design methods as a basis for a heliostat specific engineering code (section 4)

Whereas the Heliostat Performance Guideline is in its final phase, the activities leading to the Heliostat Field Guideline and the Wind Load Design Guideline have only recently started. The status is shown in Fig. 1.

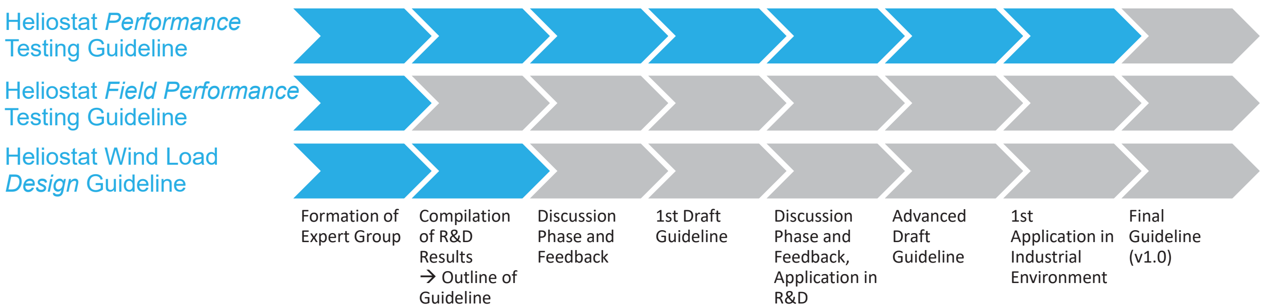



**FIGURE 1.** Status of the SolarPACES heliostat guidelines (year 2020)

## HELIOSTAT PERFORMANCE TESTING GUIDELINE

The (single) heliostat performance testing guideline was initiated in a national German framework in the year 2006 (SAPHIR project [1]) and then amplified, refined and discussed at European level (SFERA-II project [2]). From 2012 on, the discussion has been brought to the international framework of the SolarPACES task III-heliostat working group. Amongst others, the currently running German project HELIODOR has allowed its application to two industrial heliostat types. The experiences and lessons-learned from measurement service companies and manufacturers are currently being integrated.

### Content

The current version was disseminated to all stakeholders and contains the valuable feedback of experts from CIEMAT, CENER, CSP Services, CNRS-PROMES, CSIRO, DLR, Fraunhofer ISE, Heliokon, KAM, SANDIA, SBP and others. In its draft versions, it has been applied several times to characterize heliostats in research and industrial context. The guideline will be published as v1.0 in the next months on the SolarPACES homepage [3].

The guideline contains an internationally reviewed, concisely defined parameter list to describe heliostats and quantify and measure their performance. It focuses on the definition of parameters and performance testing of single heliostats during a limited time period. Measurement techniques or other techniques to derive the heliostat parameters are suggested. It aims to homogenize the content of test certificates of different qualification centers and facilitate the bankability of heliostats.

The guideline distinguishes between essential parameters (class-1), additional descriptive parameters (class-2) and beam parameters (class-3). The essential parameters (class-1) are mandatory to describe heliostat performance. In general, all these parameters must be given for comprehensive description of the heliostat performance. Additional descriptive parameters (class-2) as part of an extended list may deliver additional, but not essential information. They may be additionally given. Beam parameters (class-3) can be derived from class-1 parameters by raytracing, or are not easily measurable under defined conditions in industrial practice.

In each class, the heliostat parameters are grouped and accordingly named in the following subgroups:

- Heliostat configuration: Dimensions, geometry of concentrator, mirror panels, support, pedestal
- Optics: Reflectance, heliostat shape and beam properties
- Tracking: Tracking system, accuracy and security
- Control: Control system and power
- Limits & Tolerances: Limits of wind, temperature, hailstone resistance, lifetime, maximum inclinations, etc.
- Costs: Various cost parameters, installation time
- O&M: Power consumptions, consumables, maintenance frequency, etc.

The underlying philosophy to describe the performance bases on the measurement and documentation of essential (class-1) parameters only. Doing so, the heliostat configuration and reflective area, the slope deviation, the shape deviation with gravity, temperature (in future also with wind), the mirror reflectance, the tracking accuracy, and other parameters like power consumption and control-related properties are defined, see Fig. 2. With the information provided by these parameters and using a modern ray-tracer, the derived parameters (class-3 parameters), like beam quality, total beam dispersion or flux profiles can be generated under the specific conditions of use of the heliostat.

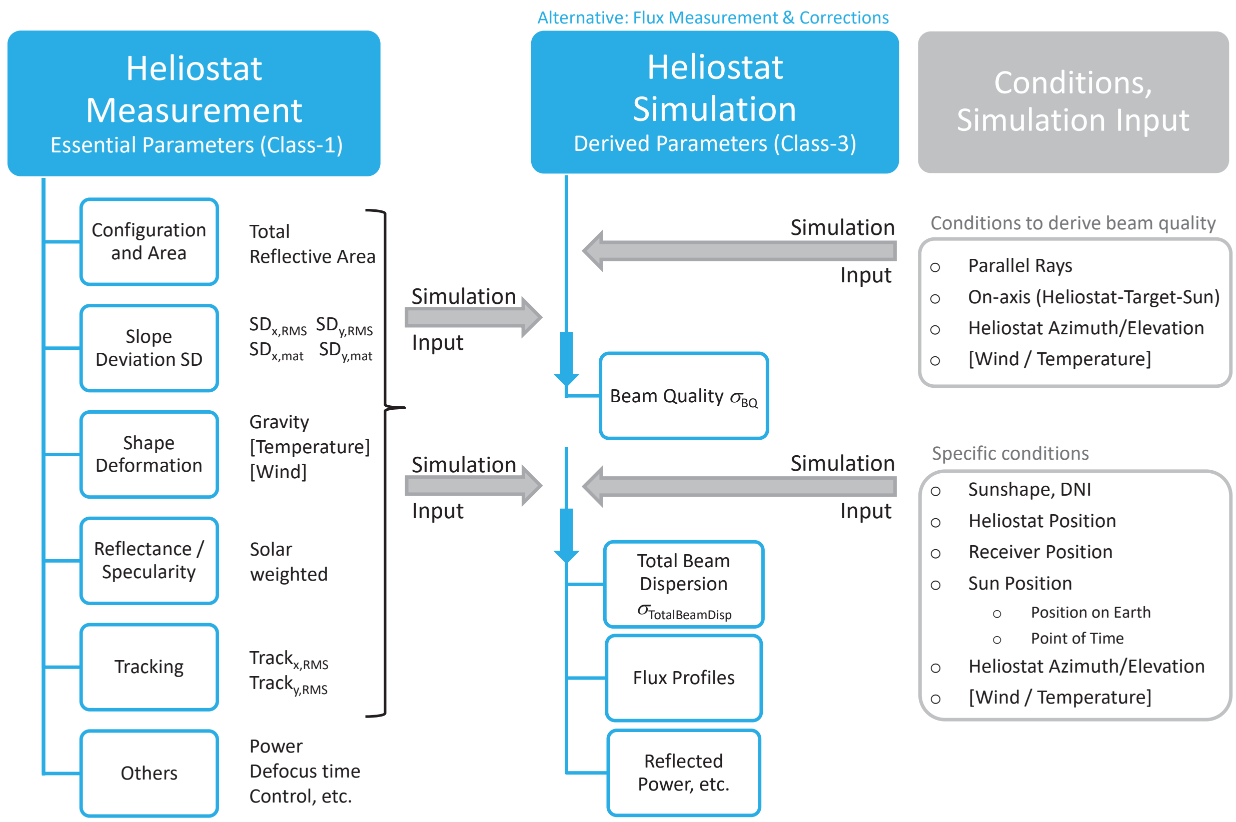



**FIGURE 2.** Overview of essential (class-1) parameters and calculation of beam (class-3) parameters by raytracing. Adapted from [4]

A template was prepared to facilitate the use of the guideline. It contains an exemplary report sheet of the Heliostat Performance Testing Guideline, shown in Fig. 3.

The current version of the guideline does not demand values for wind-induced errors in tracking and concentrator shape because of lack of suitable measurement techniques. For this reason, within the German project HELIODOR techniques to derive these values in practical tests are developed. First results are described in section 2.2.

| HELIOSTAT PERFORMANCE TEST | |
|---|---|
| Photo or simplified scheme of general heliostat configuration |  |
| Heliostat manufacturer name | HeliostatFactory |
| Name of heliostat model | FOCUS |
| Serial number(s) or other identifier(s) | PX5 |
| ⋮ | ⋮ |
| Reference to guideline version | SolarPACES Heliostat Performance Guideline v0.995 from 09.10.20 |
| Report format | This report and data CD |
| Date, signature and stamp of independant qualification organization/company | |

| n | Full Parameter Name (Symbol) | Value | Unit | Meas.Technique | Measurement Report |
|---|---|---|---|---|---|
| 1 | HelioConfig.CoordinateSys.HCS | see report | - | Laser dist.meter | Hel_Main.pdf |
| 2 | HelioConfig.CoordinateSys.CCS | see report | - | Laser dist.meter | Hel_Main.pdf |
| 3 | HelioConfig.CoordinateSys.ACS | see report | - | Laser dist.meter | Hel_Main.pdf |
| 4 | HelioConfig.General.Type | T-shape | - | Laser dist.meter | Hel_Main.pdf |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 27 | Optics.Conc.SDx /SDrad | RMS: 1.76 MEAN: 0.19 STD: 1.76 (100%) | mrad | Deflectometry | Hel_Shape.pdf |
| 28 | Optics.Conc.SDx* /SDrad* | RMS: 1.10 MEAN: 0.00 STD: 1.11 (98%) | mrad | Deflectometry | Hel_Shape.pdf |
| 29 | Optics.Conc.SDxHighFraction/ SDradHighFraction | RMS: 9.75 MEAN: 9.75 STD: 0.35 (2%) | mrad | Deflectometry | Hel_Shape.pdf |
| 30 | Optics.Conc.SDy /SDtan | RMS: 1.08 MEAN: -0.03 STD: 1.09 (100%) | mrad | Deflectometry | Hel_Shape.pdf |
| 31 | Optics.Conc.SDy* /SDtan* | RMS: 1.08 MEAN: -0.03 STD: 1.09 (100%) | mrad | Deflectometry | Hel_Shape.pdf |
| 32 | Optics.Conc.SDyHighFraction / SDtanHighFraction | RMS: - MEAN: - STD: - (0%) | mrad | Deflectometry | Hel_Shape.pdf |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 48 | Tracking.Accuracy.Track_2D | sR: 0.75 RMS: 1.06 | mrad | Beam on target | Hel_Track.pdf |
| 49 | Tracking.Accuracy.Track_x_HCS | RMS: 0.75 MEAN: 0.01 STD: 0.75 | mrad | Beam on target | Hel_Track.pdf |
| 50 | Tracking.Accuracy.Track_y_HCS | RMS: 0.75 MEAN: 0.00 STD: 0.75 | mrad | Beam on target | Hel_Track.pdf |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 62 | LimitsTol.WindSpeed.NormalOperation | 8 | m/s | - | |
| 63 | LimitsTol.WindSpeed.ReducedOperation | 20 | m/s | - | |
| 64 | LimitsTol.WindSpeed.GustSurvival | 40 | m/s | - | |
| 65 | LimitsTol..OperatingTemp | [-20;50] | °C | - | |
| 66 | Cost..Total | 1'900 (Morocco) | € | - | |
| 67 | Cost..SpecificWithoutFoundation | 120 | €/m² | - | |

**FIGURE 3.** Extract of an exemplary report sheet of the Heliostat Performance Testing Guideline (v0.995), using 67 essential (class-1) parameters.

## Current Work Regarding Wind-Induced Errors

Usually, tracking tests are done at low wind speeds. But how does the guideline address measuring the tracking accuracy for heliostat prototypes under higher wind speeds? And how is the concentrator shape itself affected by wind? Waiting for the correct wind conditions and tracking the heliostat on a white target is tedious and not practical. In the current version, no performance test under wind load was available. For that reason, an acceptance test is currently under development to determine performance indicators for single heliostats under wind load.

The development of the acceptance test is based on two main conditions, i.e. (1) tests shall be conducted on the real scale heliostat and (2) the heliostat shall be artificially excited as waiting for suitable wind conditions is neither practical nor is the wind reproducible. Furthermore, the basic concept of the acceptance test is that reference wind and ambient conditions as well as a reference setup is prescribed for which the performance indicators will be valid and which must be identical when comparing performance indicators of two different kinds of heliostats. The reference conditions and setup comprise the heliostat elevation angle $\gamma$, the wind angle of attack $\beta$, the air density $\rho$, the terrain roughness length $z_0$ and the mean wind speed $\bar{u}(h, z_0)$ and turbulence intensity $Tu(h, z_0)$ which in turn are both a function of the terrain roughness length as well as of the heliostat elevation axis height $h$.

One of the major development processes of the acceptance test is to define a suitable artificial excitation method. This step requires to understand and investigate the true wind-induced behavior of different kinds of heliostats at first. Therefore, dynamic photogrammetry measurements have been conducted on a Stellio heliostat (SBP) and are currently conducted on a HelFer heliostat (KAM). More information about the dynamic photogrammetry measurement technique applied to heliostats is found in [5]. Figure 4(a) shows a snapshot of the Stellio shape as it was captured with dynamic photogrammetry while the concentrator was subject to wind load. As visualized in Fig. 4(a), deviations of the entire concentrator as well as local deformations, leading to tracking and slope deviations respectively, can be determined and evaluated by means of dynamic photogrammetry measurements. While the final acceptance test shall include performance indicators for both the wind-induced tracking and slope deviation, this paper will focus on the tracking deviation solely and will present a draft procedure of a corresponding acceptance test.

The wind-induced tracking deviations of the Stellio are evaluated in the frequency domain, see Fig. 4(b). The frequency range below 2 Hz corresponds to the mean and background response of the Stellio which, according to [6], is characterized by slow oscillations that follow the course of the wind load. On the other hand, the frequency range above 2 Hz corresponds to the resonant response which is caused by an excitation of eigenfrequencies and is superimposed to the mean and background response.

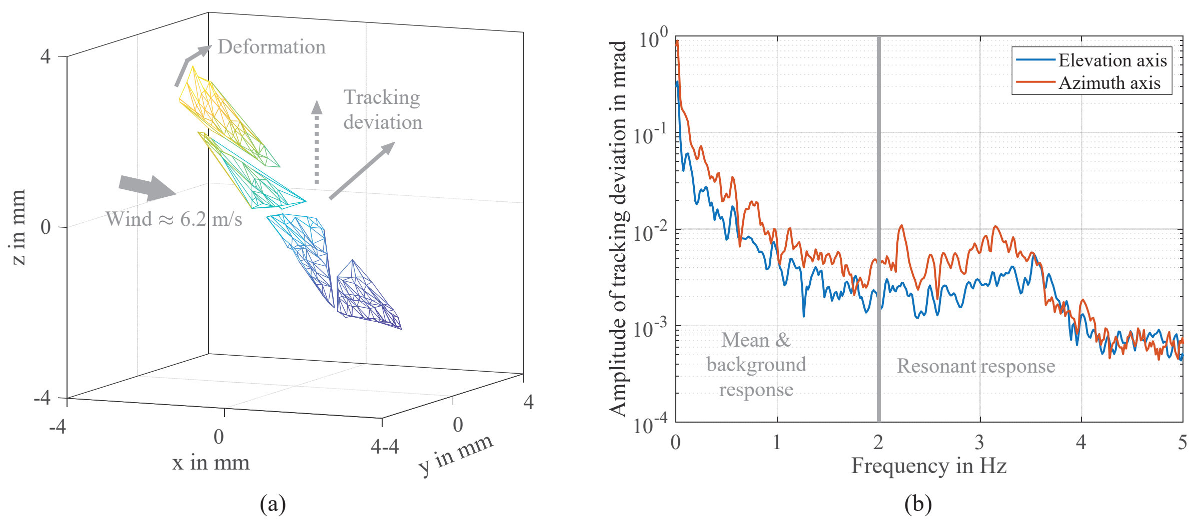



**FIGURE 4.** (a) Snapshot of the Stellio concentrator while it is deviated and deformed by wind load, captured with dynamic photogrammetry. Note that due to the scaling of the axes, the tracking deviation appears much higher than it actually is (order of magnitude of tracking deviation is mrad). (b) Amplitude spectrum of wind-induced tracking deviations of the Stellio heliostat, determined from dynamic photogrammetry measurements.

Figure 4(b) demonstrates that in case of the Stellio heliostat, the amplitudes corresponding to the resonant response are negligible compared to those corresponding to the mean and background response. This finding firstly implies that the artificial excitation method does not need to be of dynamic nature and secondly that the wind-induced tracking deviations follow the course of the wind load and can be approximated as

$$\Delta Track_{wind} = k_M * M_{aero} \tag{1}$$

where $k$ is the stiffness of the heliostat and $M$ is the moment of force due to wind load.

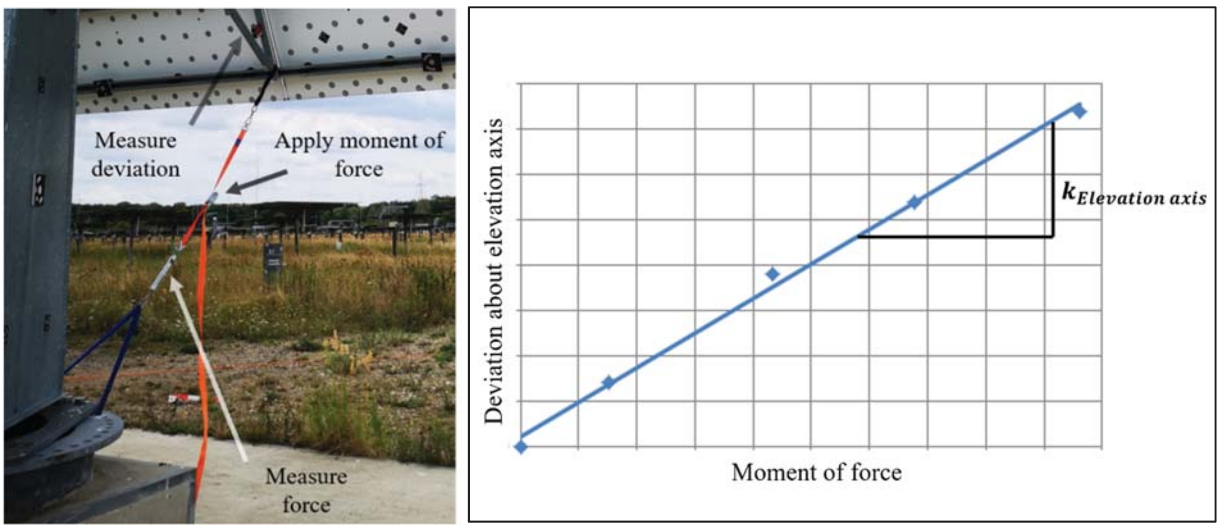
As the aforementioned procedure would underestimate the tracking performance indicator of heliostats with a non-negligible resonant response, an extended procedure is currently under development to account for an additional resonant response component.

The stiffness $k$ of Eq. 1 is to be determined through the artificial excitation test which, according to the current stage of development, will be a pulling test. Figure 5(a) shows an exemplary setup of the pulling test applied to the Stellio heliostat.

From the pulling test, the stiffness $k$ can for example be determined by a graphical analysis, as shown in Figure 5(b), and can then be used to finally determine the tracking performance indicator (separated by the elevation and azimuth axis) as follows:

$$\Delta Track_{wind,ax} = k_{ax} * M_{aero} = k_{ax} * c_M \frac{\rho}{2} \bar{u}(h, z_0)^2 A\, l \qquad \text{with } ax = El, Az \tag{2}$$

The aerodynamic moment in Eq. 2 is described by means of the non-dimensional moment coefficient $c_M$ which takes the prescribed reference wind conditions (turbulence intensity $Tu$, angle of attack $\beta$) and the reference setup (elevation angle $\gamma$) into account. The moment coefficient is planned either to be taken from existing wind tunnel studies or to be determined through a field measurement campaign taking dynamic pressure measurements.
Furthermore, the mean wind speed and air density in Eq. 2 are prescribed by the acceptance test, according to the reference conditions. Lastly, the area of the heliostat $A$ and the characteristic length $l$ are heliostat specific properties that can be measured for each individual heliostat. With all prescribed and measured parameters, the tracking performance indicator can finally be calculated.




(a) (b)

**FIGURE 5.** (a) Exemplary setup of a pulling test applied to the Stellio heliostat. (b) Determination of heliostat stiffnes by graphical analysis from results of a pulling test.

The presented draft procedure of the tracking acceptance test is currently continuously improved and will be validated by further dynamic photogrammetry measurements in the future to prove that the determined performance indicators reflect the true impact of wind load on single heliostats.

## HELIOSTAT *FIELD* PERFORMANCE TESTING GUIDELINE

In power plant projects, the heliostat field and tower system can be provided by different suppliers and thus each part represents an independent performance unit. However, there have been no standardized methods for testing and specifying the performance of a heliostat field. Existing Guidelines [7, 8] do not distinguish between heliostat field and tower performance in the acceptance test procedure which leads to a dilemma, because provider and costumer are unable to validate the contractually agreed performance requirements. To address this problem, it is essential to develop an acceptance test for heliostat fields, which defines the system boundaries only around the heliostat field.

The aspects of interaction of the heliostats in a solar field (blocking/shading effects) and the conditions of operation (e.g. cosine effect, atmospheric conditions, soiling, aim pointing) impedes simply multiplying single heliostat performance by the number of heliostats. Beyond that, the heliostat fields and distances are much larger and the number of heliostats is enormous. How do we proof and measure the performance of a whole heliostat field as designed and built? How could an acceptance test look like? Procedures to answer these questions will be defined in the SolarPACES Guideline for Heliostat *Field* Performance Testing.

## Basic Principles

In the German project HELIODOR, a procedure as basis how to cope with the immense number of heliostats has been developed for heliostat field acceptance testing. A statistically chosen, limited number of heliostats can be characterized by the measurement methods being developed in the different R&D centers or by methods mentioned in the (single) heliostat performance testing guideline. The measured performance parameters of individual heliostats are used to model a virtual copy of the solar field in a ray tracer. Afterwards, the ray tracer result has to be proofed with a validation measurement.

A statistically chosen, limited number of heliostats (sample size) can be estimated by using the Slowin's formula:

$$n = \frac{\frac{z^2 * p(1-p)}{e^2}}{1+(\frac{z^2 x p(1-p)}{e^2 N})} \quad (3)$$

where $n$ is the sample size of heliostats to be measured, $z$ the z-score, $p$ the standard deviation, $e$ the margin of error and $N$ the population size, i.e. the total number of heliostats in the field. For every heliostat performance parameter, a different sample size can be calculated.

Figure 6 shows the number of heliostats to be characterized to be representative for the slope deviation quality of the heliostat field for three different error margins. Regardless of the error margin, the required sample size becomes almost static for solar plants with more than 2000 heliostats. Nevertheless, with a need of a lower error margin, the number of necessary measurements (samples) is growing rapidly. As a consequence, depending on the impact of the performance parameter, a different error margin is suggested. The selection process of heliostat samples to be measured is completely random.

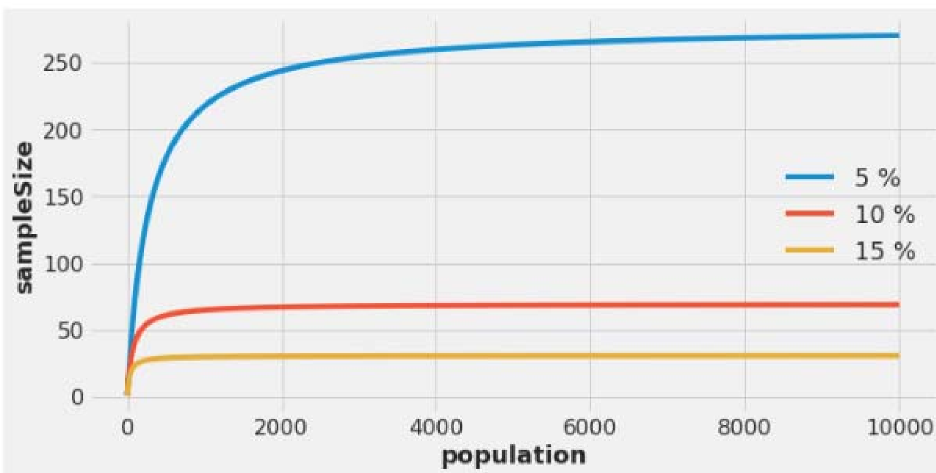
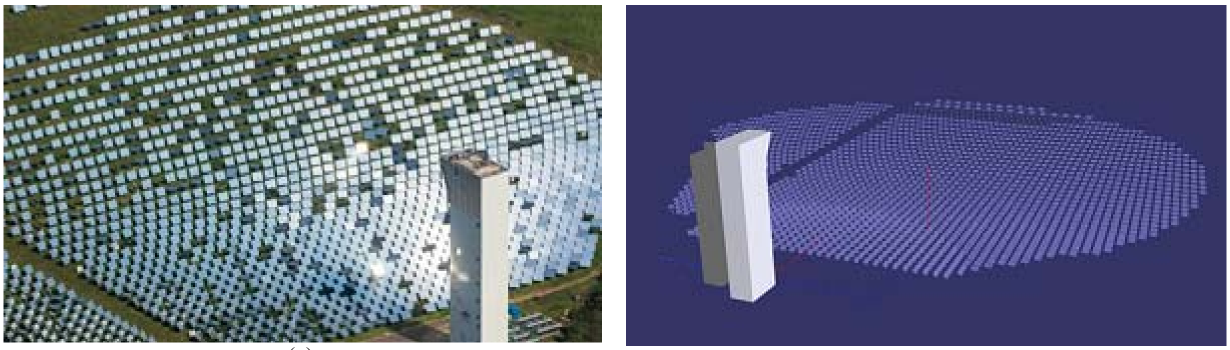



**FIGURE 6.** Number of heliostats to be characterized to be representative for the heliostat field quality. Curves are plotted for the error margins 5%,10% and 15%.

After measuring the performance parameters of the heliostat samples, the generated dataset is analyzed. During this step of data exploration, clusters and anomalies are getting detected. If local abnormalities or clusters occur, more samples in those areas will be taken. This procedure is carried out for each performance parameter individually. Afterwards the distribution function of each sampled performance parameter (e.g. slope deviation) is approximately the same as the unknown distribution function of entire heliostat field. This allows to generate synthetic data from the distribution function for each performance parameter for the non-sampled heliostats, but only under the condition that the distribution function does not change while generating data. By using the kernel density estimation, it is possible to generate the missing performance parameters for the unmeasured heliostats while keeping the distribution function constant and create a dataset of unassigned performance parameters for the total number of the heliostats in the power plant (population size).

In the last step, the virtual heliostat field has to be created and performance parameters assigned (Fig. 7). The assignment of a performance parameter to an individual heliostat depends on detected local anomalies and clusters for this performance parameter, but also historic data (e.g. construction order or wash frequency) can be considered. The generated virtual heliostat field model allows to calculate nominal hourly or yearly efficiencies of the manufactured heliostat field. The simulated power can be validated by flux measurements of individual heliostats or groups. Other important heliostat field properties that do not have a direct impact on the nominal efficiency, like the total power consumption or system defocus are measured separately.

The described procedure for heliostat fields and their acceptance testing can also be applied to already operating heliostat fields with the objective to maximize their performance. The international CSP community of both research and industry has applied for a SolarPACES grant which addresses to review, compare, and discuss the advantages and disadvantages of heliostat evaluation methodologies, which are either currently developed or in being developed.



(a) (b)

**FIGURE 7.** (a) Heliostat field at Juelich research facility. (b) High resolution ray tracer model (STRAL) of the heliostat field.

## HELIOSTAT WIND LOAD DESIGN GUIDELINE

The interaction with wind is a major factor in a heliostat's design, however there is no wind load design code appropriate for such structures. Heliostats have a non-standard shape that does not conform to conventional shapes of buildings, billboards or solar PV structures, and, the shape changes with tracking position. The heliostat size ranges between 1-150m$^2$ and they are installed in a range of terrains, therefore they experience a wide range of windspeed and turbulence conditions depending on the incoming boundary layer [9].

Several wind tunnel measurement campaigns and numerical studies have been conducted on isolated heliostats to determine wind load coefficients and study their dependence on different wind conditions, e.g. [9-13]. Being more complex, studies on the wind effect on the optical performance on real scale heliostats are less frequent, e.g. [5, 14, 15].

Although fundamental work on heliostat wind load design methods were published almost 30 years ago [10] no progress has been made to improve or unify the wind load design methods despite significant commercial deployment of heliostats internationally. Many heliostat designers have to complete expensive experimental work and take significant commercial risk on a design. Drawing together research groups who are working on wind tunnel and outdoor testing (SNL, University of Adelaide, CSIRO, CENER, DLR), and through engagement with industry stakeholders, the SolarPACES task III working group aims to draft a heliostat wind load design guideline which could be a basis for a heliostat specific engineering code. This activity aims to simplify and reduce duplication of wind engineering of heliostats for industry, de-risk heliostat structure and component designs and reduce the cost of heliostat fields.

Load coefficients from state-of-the-art wind tunnel testing have been recompiled and an 8-step wind load calculation process has been proposed at the SolarPACES 2019 so far. A spreadsheet for wind load calculations based on wind tunnel testing has been made public [16]. Wind field measurement data inside a real-sized heliostat field will be generated in German-Spanish project starting in 2021.

## CONCLUSIONS

SolarPACES, an IEA Implementing Agreement, is an international cooperative network bringing together teams of national experts from around the world to focus on the development and marketing of concentrating solar power systems. As part of the SolarPACES task III, since 2012, a dedicated group of R&D and industry experts on heliostats has been collaborating in the heliostat working group. Three activities have been launched, all aiming to de-risk heliostat fields and reduce their costs: The Heliostat Performance Testing Guideline (single heliostats), the Heliostat *Field* Performance Testing Guideline, and the Heliostat Wind Load Design Guideline.

The (single) Heliostat Performance Testing Guideline focuses on a protocol to test and qualify prototypes and individual heliostats. The Heliostat *Field* Performance Testing Guideline identifies solutions to estimate the performance of an industrial-sized heliostat field on an objective, scientific, but practical level as a basis for performance acceptance testing. Both guidelines aim to increase confidence between stakeholders of commercial CSP projects by offering accepted protocols to prove compliance with their contractual agreements in a standardized manner. The wind load design guideline should improve and unify heliostat wind load design methods and could be a basis for a heliostat specific engineering code.

Whereas the Heliostat Performance Guideline is in its final phase and has been applied several times, the activities leading to the Heliostat *Field* Guideline and the Wind Load Design Guideline have only recently started. The once finalized guidelines (or their concepts) should be included in international standards (e.g. IEC) and used by national organizations like DKE, AENOR, ASME, ASTM.

## ACKNOWLEDGMENTS

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