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Heliostat Testing According to SolarPACES Task III Guideline

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Abstract. The SolarPACES Guideline for Heliostat Performace Testing finally provides a solid base for standardized testing and comparison as well as the definitions of essential heliostat parameters such as slope and tracking errors. SBPS is running an extensive test program for their 4 Stellio preseries heliostats at the DLR Solar Tower in Juelich, Germany until summer 2019. Additional objective is to accumulate operating hours and evaluate long-term effects on the Stellio performance quality. Slope error measurement has been performed by CSPS and is repeated every 3 months. First results show 1D slope errors of 0.7 to 1.2 mrad. Tracking performance could not have been concluded so far due to missing final measurements of the kinematic system of each heliostat necessary for calibration. However, beam centroid evaluation software has been tested with first uncalibrated tracking hours and is prepared for normal operation. First photogrammetric measurements have been performed to characterize the dead weight deflection of the heliostat in 15 different azimuth and elevation combinations. This has been prepared and implemented in Rhino CAD. Adaptions may be necessary to include pylon deflection as well.

INTRODUCTION

Numerous different heliostat systems are available within the CSP industry. In every tender phase there is a huge effort for the owners/investors to compare and select but also for the bidders to underline their cost effectiveness. Technology provider often use proprietary test methods (and definitions of parameters), making any comparison difficult or even impossible. As in every other industry, there is high need for standardization in evaluating the different systems. There was no general code available until now. The author welcomes the initiative to establish a standard to have fair and efficient tender phases and save considerable time and money in its process while improving the result. The lessons learned from this first test program shall be made available and used to further push and improve the application of the "SolarPACES Guideline for Heliostat Performance Testing", in the following referred to as the "guideline" [1]. This paper describes the two optical tests for determining slope and tracking error as well as one mechanical test for characterizing self-weight deflection and beam quality during tracking which have been performed.

GUIDELINE

Within the scope of the SolarPACES Task III activities, Röger et. al. developed the guideline in cooperation with several industry leaders and research institutes such as to make heliostat performances comparable. Definition of parameters and measuring them is described extensively. The most prominent example and recurring source of misunderstandings is the definition of the optical quality of heliostats which includes both the mirror surface quality as well as the tracking accuracy of every heliostat. E.g. two parties speak about a normally distributed slope error, yet

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one defines it to be a mean one-dimensional error, the other to be a two-dimensional value derived through convolution of one-dimensional errors in their respective planes rectangular to each other. Naturally, this results in misguided decisions during tender phase or numerous discussions about the definition of errors at best.

In the guideline, so-called class-1 parameters are used to describe the most important quality parameters of the system without relying on environmental circumstances (such as sunshape) and their different definitions and measurements. The parameters are used as input for raytracing simulations to ultimately derive class-3 parameters such as beam quality or the total beam dispersion. Class-2 parameters are further descriptive values which are not primarily needed for the initial heliostat characterization (e.g. weight, materials used or deformation of the concentrator under dynamic wind loads). They deliver additional, but not essential information. Validations by Ulmer et al [2] have shown, that the currently available raytracing tools have reached an excellent simulation quality compared with real world data based on deflectometry measurements. The only class-1 parameter which currently still relies on environmental circumstances like attenuation, shading of the tower or non-ideal Lambertian targets for measuring is the pointing accuracy on a test target. This roots in the lack of a practicable and accurate holistic model containing parameters such as drive characteristics, drive triggering and dynamic behavior under wind loads.

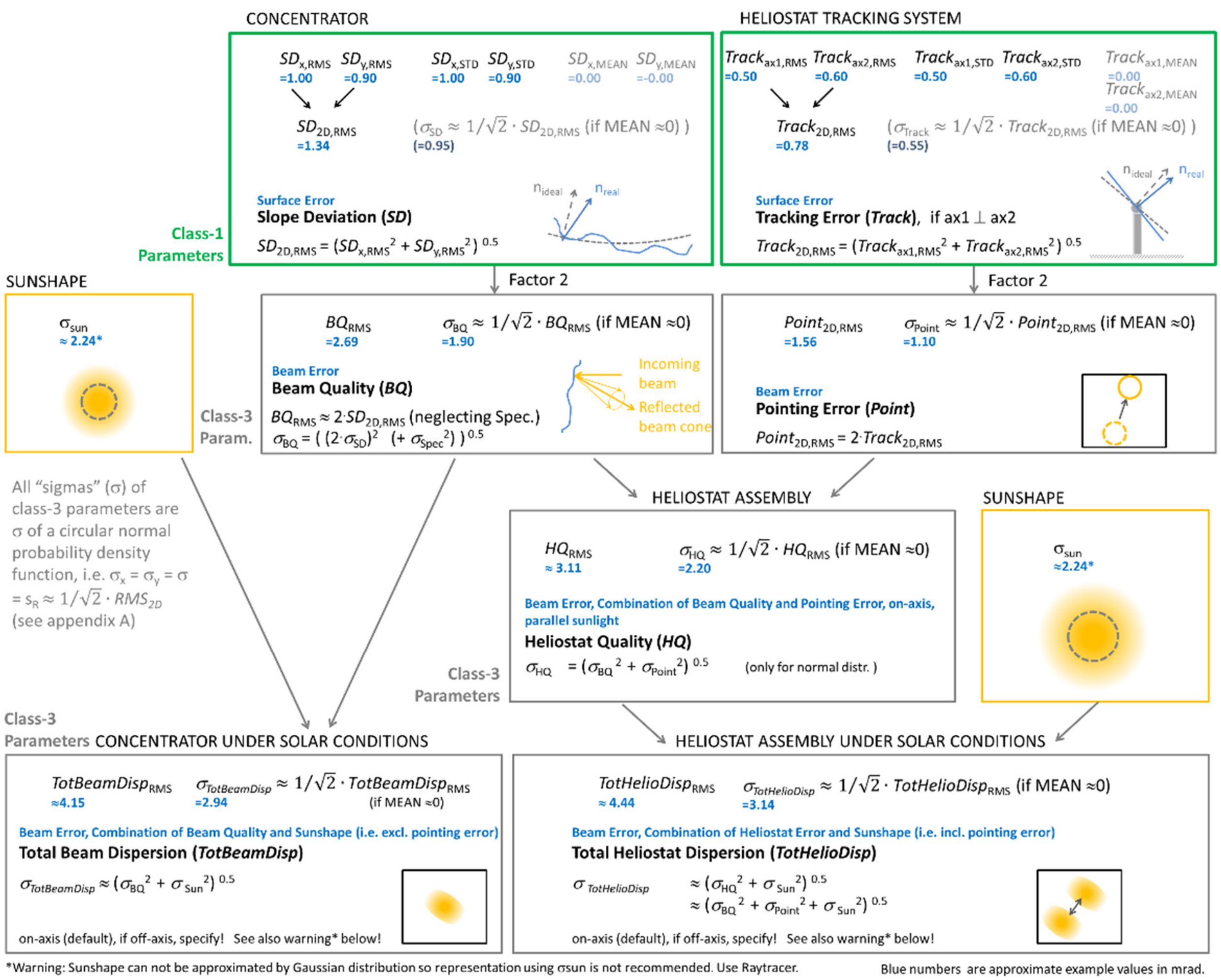


FIGURE 1. Convolution of optical errors from one-dimensional surface or tracking errors to the total heliostat error with exemplary values in blue [1]

TESTING

Setup Juelich

For the testing of the four pre-series Stellio heliostats at the Solar Tower Juelich, SBPS has been eager to use and apply this new standard and, together with partners CSPS and DLR, arranged the test program accordingly. One heliostat has been mounted on the universal heliostat testing platform of DLR (HeliTep) and equipped with strain gauges to measure drive forces as well as inclinometers to measure pylon and concentrator inclinations during different azimuth and elevation settings. Additionally, this heliostat is analyzed through static and dynamic photogrammetry to further validate or, if required, improve the FEA model as well as compare wind tunnel testing commissioned previously by SBPS with a representation to scale. This includes approx. 2000 reflective targets on the concentrator and on the pylon structure. The setup is complemented by two additional heliostats in the North of the HeliTep and one in a Western position to get experience with the foundations and the general assembly in the field (**FIGURE 2**).

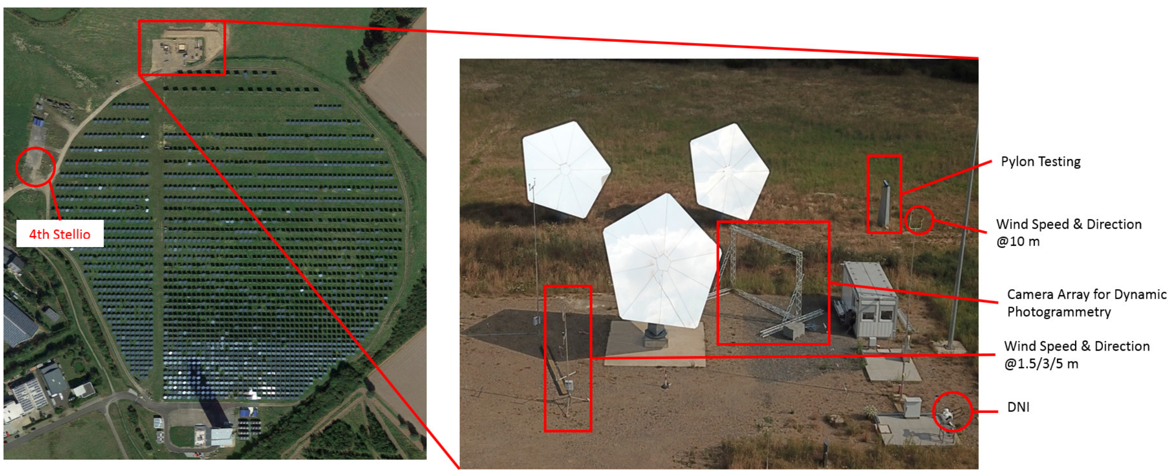


FIGURE 2. Juelich Solar Field with heliostat testing platform (Helitep, left). Equipped with one Stellio (in the front), two additional ones with designated foundations (in the back) and a 4th heliostat in Western location for different main angle setup.

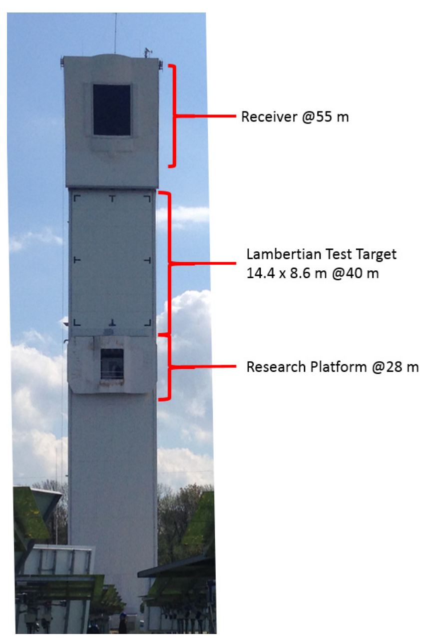


FIGURE 3. Tower of the DLR solar testing facility in Jülich, Germany.

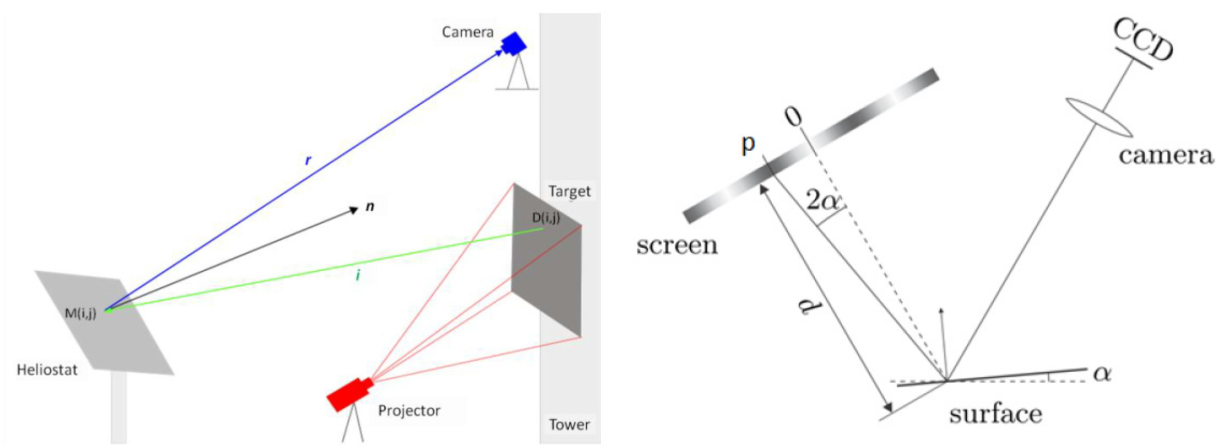
All heliostats are kept in tracking mode on a virtual aimpoint beside the tower to generate operating hours and get advanced experience with long-term behavior. The Solar Tower Julich is equipped with a Lambertian target of 14.4 m x 8.6 m (**FIGURE 3**) and a camera system able to verify tracking tests conducted by SBPS on a weekly basis for every heliostat to see any possible shifts of the average beam position. Depending on target availability and DNI, tracking is done for complete days including morning and afternoon hours.

Definitions

The global coordinate system (GCS) used is a right-handed coordinate system with x oriented east, y oriented north and z results as the vertical axis. The origin is at the bottom of the tower, being a projection of the center of the receiver of the Solar Tower Juelich on the ground. The more challenging task was to define a proper coordinate system for the Stellio concentrator (HCS). Being a slope drive heliostat with tilted main axis and a non-zero universal joint connecting primary and secondary rotation axis. This also leads to a rolling movement of the concentrator through different azimuthal positions which is not the case for common azimuth-elevation heliostats with pedestal mount. As a result, this needs a transformation including rotation as well as translation.

Slope Error Measurement

Deflectometry measurement was performed with CSPS's QDec-H system, permanently installed at the Solar Tower Juelich, with an adaptation to the unique pentagonal Stellio design (**FIGURE 4**). The measurement was done in compliance with the guideline's appendix C for techniques for derivation of parameters. Parameter "Optics.Conc.SD_2D" is required to be measured with at least 100 data points per m² for photogrammetry. The QDec-H system achieves a 150x higher resolution and thus gives a very detailed measurement result for complete characterization and optimization of all effects on surface slope. **FIGURE 4** shows the common setup for field testing the mirror surface quality. Sinusoidal stripe patterns of different sizes and orientations are projected onto a tower target and their reflection in a heliostat is recorded with a camera on top of the tower. As a condition, this kind of deflectometry setup requires fixed azimuth-elevation settings for the measurements which are dependent on heliostat position and target height. Due to the higher self-weight deflection towards high elevation positions of the concentrator (with the surface normal approximating vertical), heliostats close to the tower experience a higher deformation during measurement and heliostats towards the outer rim of a field tend to have almost no additional deformation from this effect. See also chapter "Photogrammetric Measurement of Self-Weight Deflection" in this paper.



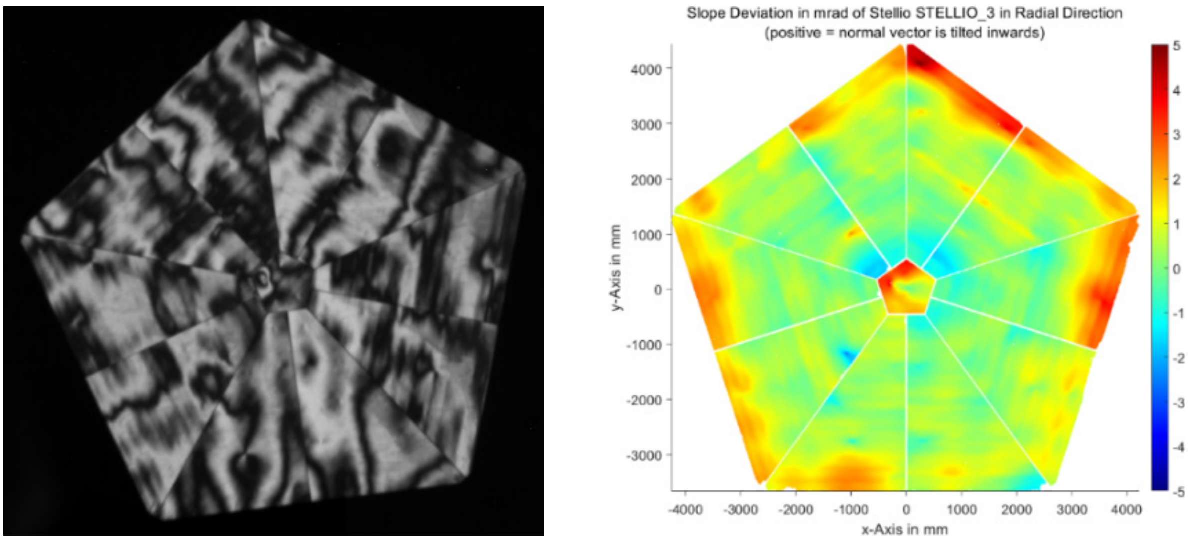
(a) (b)

FIGURE 4. QDec-H measurement setup [2] (a) and principle of phase measuring deflectometry [3] (b).

The local normal vectors $\vec{n_i}$ of the mirror surface and their deviations α_i from the nominal surface in one plane can now be determined:

$$\alpha_i = \frac{1}{2} * arctan\left(\frac{p_i}{d}\right) \quad (1)$$

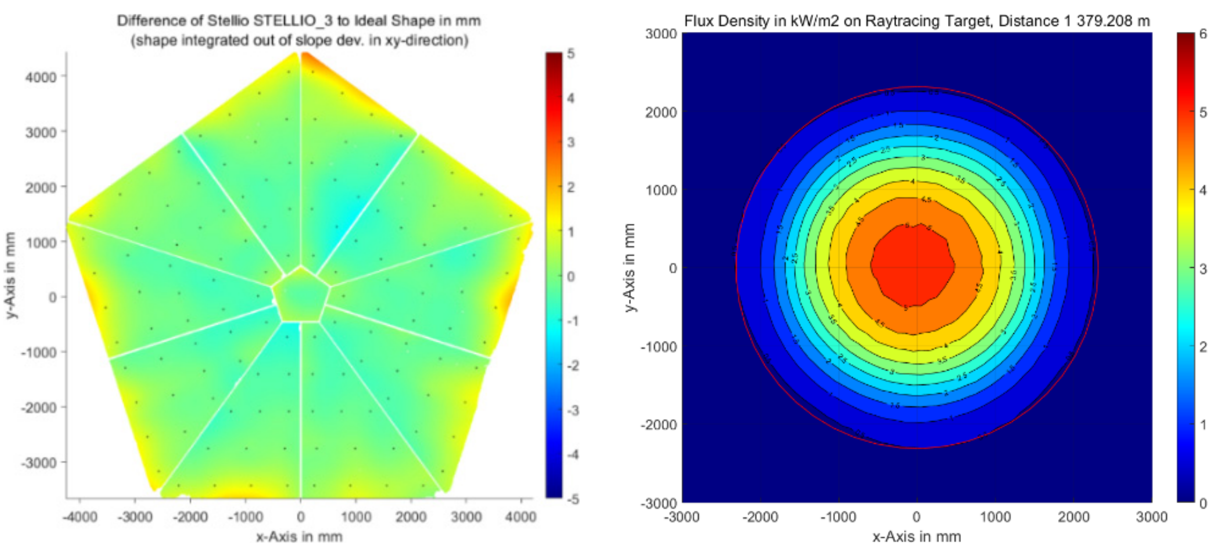
Through combination with measurements of both horizontal and vertical patterns, it is possible to also calculate 2D slope deviations as well as radial and tangential portions which are especially useful for describing the rotation-symmetric design of the Stellio concentrator. **FIGURE 5** shows the distortions of the patterns and the result gained from the evaluation of QDec-H.



(a) (b)

FIGURE 5. Measurement pictures of reflected stripe pattern seen in mirror of heliostat (a) and visualization of measured slope deviation in radial direction in mrad (b)

The heliostat facets show a mean slope deviation of 0.8-1.1 mrad in radial direction (SDrad) and 0.7 – 1.2 mrad in tangential direction (SDtan). The guideline requires measurement uncertainties of < 0.5 mrad for local spots and 0.2 mrad for the complete surface. The QDec-H system is specified with < 0.3 mrad for local spots and < 0.1 mrad for the complete surface. **FIGURE 6** shows the height deviation of the facets from the ideal shape in z-direction. In addition to that, the theoretical flux density on a flat target, referring to an implemented raytracing model, is stated.



(a) (b)

FIGURE 6. Height difference to ideal shape (a) and resulting simulated flux density on target (b).

Tracking Error Measurement

The tracking accuracy for the Stellio heliostats is determined by beam centroid evaluation with target images from the Juelich Solar Tower taken by a dedicated industrial camera system using the Sony IMX174 CMOS sensor which allows for precise settings of e.g. exposure time and delivers a detailed histogram of the current frequency distribution of the brightness. This allows for adjusting to a fixed exposure setting and avoids saturation of the beam images which would lead to distorted centroid. Other hardware requirements involve a solid camera mounting which is not stimulated easily by wind as this leads to a moving field of view and falsifies the calculation by assuming the wrong target dimensions and position. To reduce the calculation time needed for finding the corner of the target, the camera is mounted directly to the office container.

For the first tests with the new system, images were taken every second and evaluated later by a Matlab script. The script matches a template for the upper left corner and searches through the image by normalized cross-correlation to find the corner of the target in the green channel image. Since the camera position relative to the target is fixed, the remaining three corners can now be determined by simply adding the relative pixel coordinates to the first corner. The tetragon is used as a mask to crop and rectify the distorted green channel image.

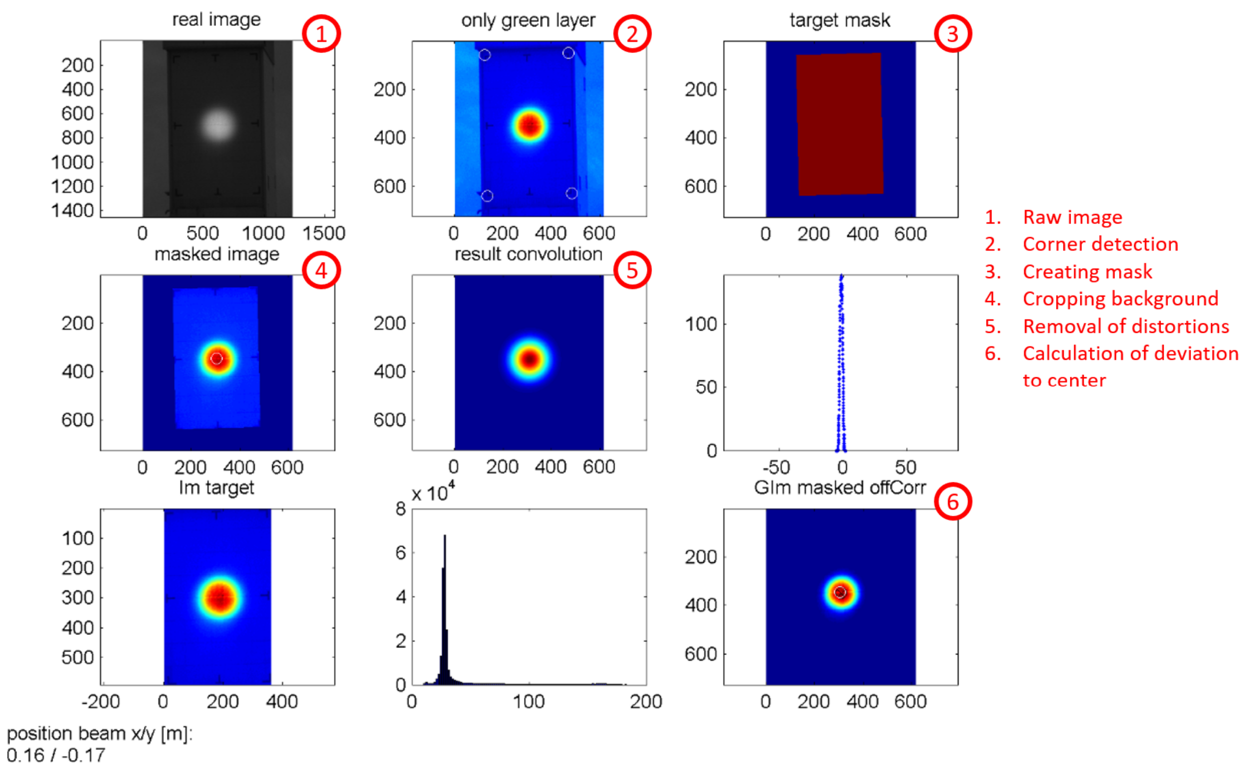


FIGURE 7. Steps of beam centroid calculation from raw image to rectified and cropped target image with detected beam centroid. Exemplary result in lower left corner.

The goal is, that the whole image acquisition, processing and evaluation process as shown in **FIGURE 7** takes less than one second. The actual centroid deviation can be seen between the center of the beam and the center of the target (marked with a circle). This is far quicker than required to achieve the 60 images per hour required by the guideline. However, to see wind influences, one should at least have a resolution of one second – or even less, since gust wind speeds are averaged over 3 second intervals. Nowadays, this should not cause substantial calculation time with current hardware.

Photogrammetric Measurement of Self-Weight Deflection

There are usually two forms of self-weight deflection: The deflection of the concentrator itself, influencing the mirror surface, mirror panel position and, in the end, beam quality on the receiver. This form cannot be compensated by the drives and is subject to a techno-economic optimization of stiffness, steel mass, which drives costs up, and optical quality.

The other form of deflection is the elastic deformation of the heliostat pylon and any support structure mounting the concentrator. It leads to the concentrator bowing down (α_{SD}), effectively positioning the concentrator normal lower than required. For any common azimuth-elevation heliostat, this can easily be compensated by properly controlling the elevation drive stroke length and pulling the concentrator back in the desired position (**FIGURE 8**).

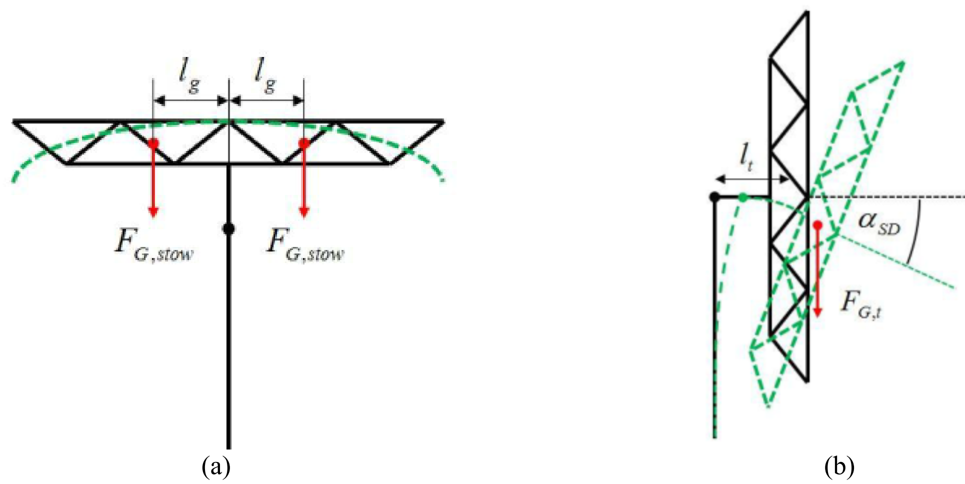


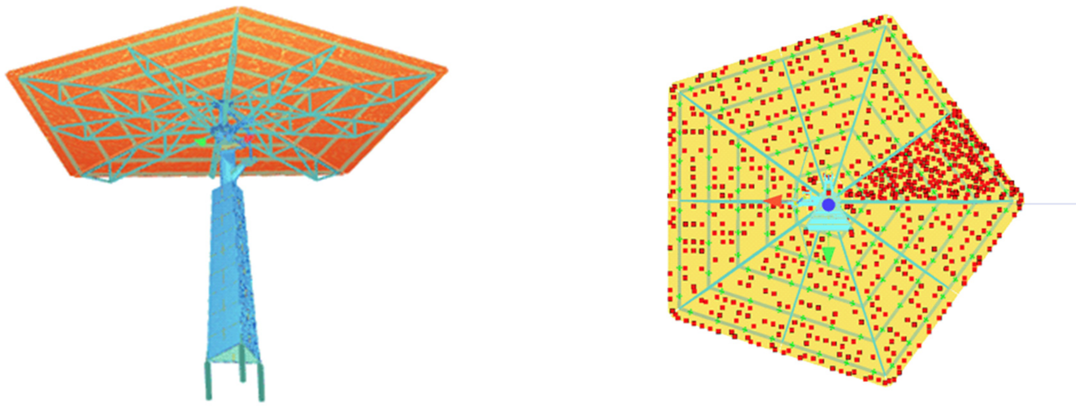
FIGURE 8. Self-weight deflection of the concentrator itself (a) and deflection of the pylon including steel structure elements of the kinematic assembly (b). Ideal shape in black, real shape exaggerated in green [4].

The slope drive setup in combination with the non-axisymmetric pylon and drive design of Stellio make it a necessity to have a more sophisticated correction algorithm for the drives to counteract the varying deflection depending on main and secondary axes angles, depending on both elevation and azimuth orientation currently prevailing.

The measurement with a dense grid of reflective targets also allows for best-fitting a mirror surface and raytracing simulations to get results on beam quality during tracking. The heliostat measured in Juelich is equipped with approx. 2000 reflective targets from which 1500 are placed on the backside of the mirror surface of the concentrator. With a mirror surface of 48 m², this equals 31 targets / m², although one facet has been equipped with double the target density. The guideline however suggests measuring with at least 100 targets per m² (parameter "Optics.Conc.DefGravity_deltaSDmat"). Considering the effort to put the targets on this medium-sized heliostat, larger mirror surfaces would be even more time consuming. The photogrammetric measurement requires a lot more effort when using more targets to take more pictures and being able to see as much targets as possible during one campaign. To check the methodology, one measurement in stow position was evaluated and compared with the predictions of the FE analysis done in Sofistik [5] to check the feasability of the process.

This is important because the test matrix involved 3 different elevational and 5 azimuthal positions resulting in 15 positions each consuming half a day of field measurement.

The raw xyz-coordinates were used for post-processing in the CAD program Rhino in combination with the Grasshopper-Plugin. This was necessary to generate best-fit surfaces and derive the reference geometries to compare the point cloud with the FE model. Both point clouds were aligned in the X/Y coordinates and then projected onto a best fit plane to define them as fixed nodes in Sofistik (**FIGURE 9**).



(a) (b)

FIGURE 9. FE model from Sofistik (a) and projected nodes on the mirror surface (b)

It turned out, that Sofistik could not handle more than 750 data points and larger amounts led to a meshing problem.

After reduction of the nodes, the model deformation was calculated and the deviation of the nodes from their position in the unloaded state could be determined as vector.

The evaluation showed that the FE model underestimated the actual deformation by a factor of 4 (average over mirror surface). It has yet to be determined, which characteristics of the model need adjustments. Also, the comparison described needs to be doublechecked with a second measurement to avoid any misleading conclusions.

RESULTS / OUTCOME OF TESTING ACCORDING TO GUIDELINE

The test program for Stellio was designed according to the guideline from the very beginning. This avoids several test iterations to reach the guideline requirements. The Stellio tests are also repeated during different times of the year to include all seasons. The testing of the Stellio preseries will be concluded in June next year.

The experience from conducted tests has been mainly positive. The deflectometry system of CSPS has been adapted to the Stellio kinematic with few efforts and is working without any problems. Regarding photogrammetry, the effort for placing around 30 targets per square meter is already high for a mid-sized-heliostat. The value of 100 per square meter is not practical from the authors point of view for covering the complete concentrator with it. An exception may be fractions of the mirror surface where a more detailed investigation outweighs the effort. As mentioned earlier, SBPS will publish the lessons learned from this initial test program according to the guideline after the testing campaign is concluded.

ACKKNOWLEDGMENTS

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