# An Automated Model-Based Aim Point Distribution System for Solar Towers

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**Abstract.** Distribution of heliostat aim points is a major task during central receiver operation, as the flux distribution produced by the heliostats varies continuously with time. Known methods for aim point distribution are mostly based on simple aim point patterns and focus on control strategies to meet local temperature and flux limits of the receiver. Lowering the peak flux on the receiver to avoid hot spots and maximizing thermal output are obviously competing targets that call for a comprehensive optimization process. This paper presents a model-based method for online aim point optimization that includes the current heliostat field mirror quality derived through an automated deflectometric measurement process.

## INTRODUCTION

It is the intention of the solar power plant operator to make most efficient use of the cost-intensive collector field while meeting all technical restrictions of the receiver operation. The task of distributing the heliostat's aim points in the receiver aperture is complex, as the focal images vary with time and the desirable ideal flux distribution is unknown. Past work in literature on aim point distribution focused mainly on meeting the operational flux and temperature limits and was developed for specific receivers, like for the Solar Two molten salt receiver [1]. The simulations used there are mostly based on simple optical models for the heliostat field.

Today's computer technology and the available high resolution measurement techniques make it possible to use high precision fast ray tracing for model-based optimization of the distribution of aim points. This paper presents the background of both the high precision measurement technique for heliostat qualification and of the aim point optimization method that is going to be applied. Afterwards the development and implementation of automated software-based measurement and optimization systems is described. The systems are applied and tested at the Solar Tower Jülich, the German 1.5MW$_e$ research plant with more than 2150 heliostats and a 22 m² open volumetric receiver.

## BACKGROUND

### Measurement of Heliostat Slope using Deflectometry

A measurement principle called deflectometry for applications on specular surfaces is based on the reflection of regular patterns in the mirror surface and their distortions due to mirror surface slope deviations ([2]). The method was specifically optimized for the measurement of shape deviations of concentrating solar reflector panels like heliostat mirrors. For the deflectometry measurement at a solar power tower a stripe pattern is projected onto a white target at the tower at night. The reflection in the mirror is observed by a camera from the top of the tower. The deformations of the stripe pattern in the reflection are then used to evaluate the deviation of the local slope from its design value with a measurement precision <0.2mrad. The measurement setup is shown in Figure 1. This system was adapted to industrial requirements and validated by CSP Services during the SiBopS project.

The deflectometry method is originally prepared for quality assessment during commissioning of heliostat fields but its results are also a perfect basis for ray tracing calculations. The typical resolution of the surface data when used for ray tracing are several ten thousand points per square-meter (several points per square-centimeter).

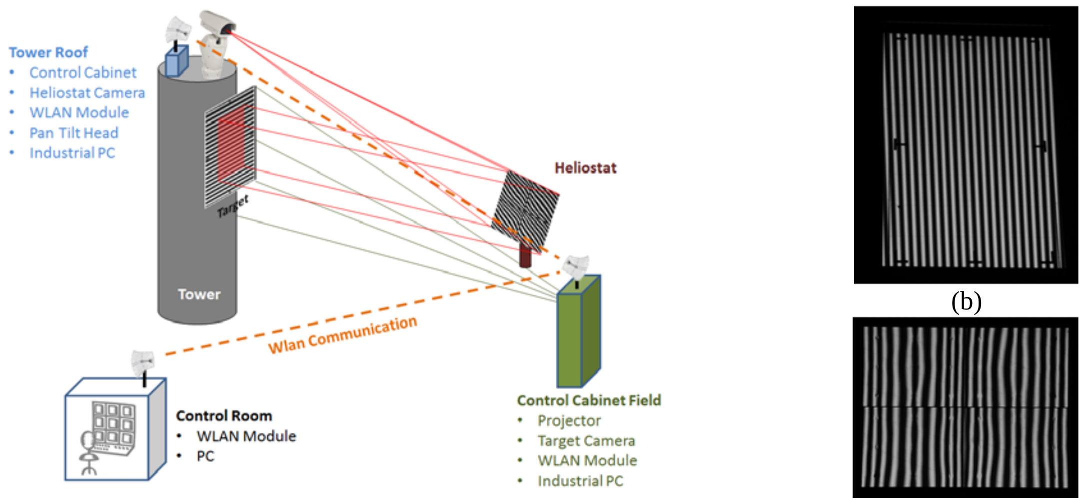


**FIGURE 1.** (a) Measurement setup for deflectometric shape measurement of a heliostat;
(b) Example image of a projected pattern on target and (c) reflected stripe pattern as seen in a heliostat mirror.

## Optimization of Heliostat-Aim Point Assignment

It is one of the objectives to use measured high resolution surface data as a basis for the precise calculation of the flux density distribution produced by single heliostats on the receiver surface. To be able to process this huge amount of data in an acceptable time, especially for optimization purposes, the new ray tracing code STRAL (solar tower ray tracing laboratory) was developed ([3]). It makes use of the capabilities of today's desktop CPUs (SIMD, multithreading) and efficient ray generation and processing to further improve the calculation speed. Accordingly, this code is able to process more than 60 million rays per second on an 8-core machine ([4]). The accuracy of the ray tracing calculations of STRAL based on deflectometry data was validated against direct flux density measurements successfully ([3]).

The optimization of the aim point of a single heliostat on the receiver surface is a continuous two-dimensional problem. Hence, for a field of $n_H$ heliostats the search space has $2\times n_H$ dimensions. Additionally, often non-linear constraints apply due to flux or temperature limitations. This hardly solvable problem can be mathematically modified if only a finite number of fixed aim point positions $n_Z$ are allowed ([5]). This restriction is justified when the realistic tracking accuracy of the heliostat's actuators (~0.5-1mrad) and the overall dimensions of the focal spots and the receiver are considered. The size of the solution space is then equal to $n_Z^{nH}$, and the exact solution of this problem remains unrealistic to find. But this formulation establishes the possibility to use heuristic methods for combinatorial optimization problems.

The optimization method applied here to this problem is the so-called ant-colony optimization meta-heuristic (ACO) that imitates the foraging of ants ([6]). This method is chosen due to its good performance regarding quality and calculation speed and the applicability to the problem ([7], [5]). The table of possible heliostat-aimpoint assignments is an $n_Z\times n_H$ matrix and each allowed combination (= solution) can be imagined as a path in the matrix (Figure 2 left). The probability to choose a certain combination *AiHj* is triggered by two factors: 1) a local factor, usually the specific intercept value of the heliostat *Hj* aiming at aim point *Ai*, and 2) a global factor, i.e. the quality value of the solutions, where *AiHj* is part of. As quality value various parameters like the total intercept factor, the intercept power, the thermal power or the thermal efficiency can be chosen (Figure 2 right). More details about the application of the ant-colony optimization meta-heuristic can be found in [7] and [5]. As a further advantage of the combinatorial treatment of the problem, the flux density of each single combination *AiHj* can be pre-calculated before the actual optimization. During the optimization process the flux images are used as partial results and superposed to save computation time.

This aim point optimization approach was applied to several simulation based test cases where it demonstrated its potential for plant operation improvement. In [5] it was applied to a small tower system with a concentrated photovoltaic receiver with strongly non-linear behavior. The aim point optimization found solutions with about 8% performance improvement compared to using only the central aim point and came as close as 99% to the theoretical maximum. In [8] the method was applied to an open volumetric receiver system with 1484 heliostats and a 85m² cylindrical receiver. The optimization was able to reach up to 5.8% increase in intercept and up to 8.7% increase in thermal power as compared to a manual aim point distribution, although only 15 aim points were used.

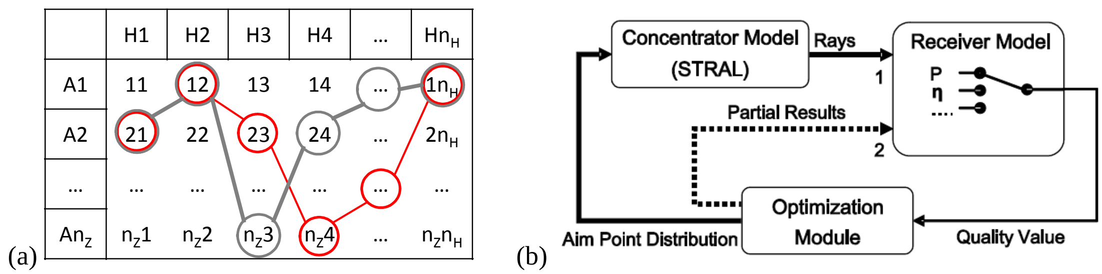


**FIGURE 2**. (a) Matrix of possible heliostat-aimpoint assignments.
(b) Visualization of the optimization loop with full ray tracing (1) and partial results (2) (from [5])

## LAYOUT AND IMPLEMENTATION OF AUTOMATED SYSTEMS

### Automated Deflectometry System

The developed automated deflectometry measurement system QDec-H consists of the sub-systems in the locations field (projection and target camera), on the tower roof (camera on pan-tilt-head) and in the control room (main control, connected by a wireless network (Figure 1).

For the measurement control and evaluation tasks CSPS' commercial QDec system and software was extended and adapted to the specific demands of heliostat field measurement. The software performs automatic camera movement and focusing of single or multiple heliostats and also runs the deflectometry measurement sequences and evaluation. Important system features are its simple operation, complete automation, short measurement time (about one minute per heliostat) and a post-processing specially adapted to solar concentrator specifications. The enhanced panel geometry definition allows application to any panel geometry and arrangement, any canting and many different curvatures.

### Automated Aim Point Distribution System

It was the objective to develop an automated software system that runs during real plant operation and regularly provides an optimized aim point assignment based on the latest available deflectometry data. The intended work flow is shown in Figure 3. Regularly, usually during the night before use, the flux images of each heliostat are pre-calculated and stored. During operation, in regular time steps, the aim point distribution system receives from the plant and field control systems the status information about the heliostat field, the actual DNI, the desired receiver power and, when indicated, the currently applicable operation restrictions of the receiver (flux or temperature limits, maximum gradients, etc.). Based on that, the optimization starts with the task to find an improved heliostat-aim-point assignment for the next time interval. Here, the nature of the ant-colony algorithm to find improved solutions very quickly is of great advantage. The intended time interval for a regular aim point distribution update is 15-60 minutes. But it is also possible to initiate an optimization run manually or triggered by external signals like expected cloud passages or changes in the operational restrictions.

The main basis for the flux calculation is the deflectometry measurement that provides maps of the local normal vector. The deflectometry measurements only have to be updated for new heliostats or those where changes have been applied to, like exchange of facets or structure elements, recalibration of facets, etc. The status information about the heliostat field covers the positions of the currently available heliostats, the actual reflectivity and the tracking accuracy. The reflectance can be an individual, group-averaged or field-averaged value that is attained through regular on-site reflectance measurements (usually of samples rather than the entire field). The tracking accuracy is a statistical value that is usually a by-product from the online track-correction process. It can also be available as individual or averaged value.

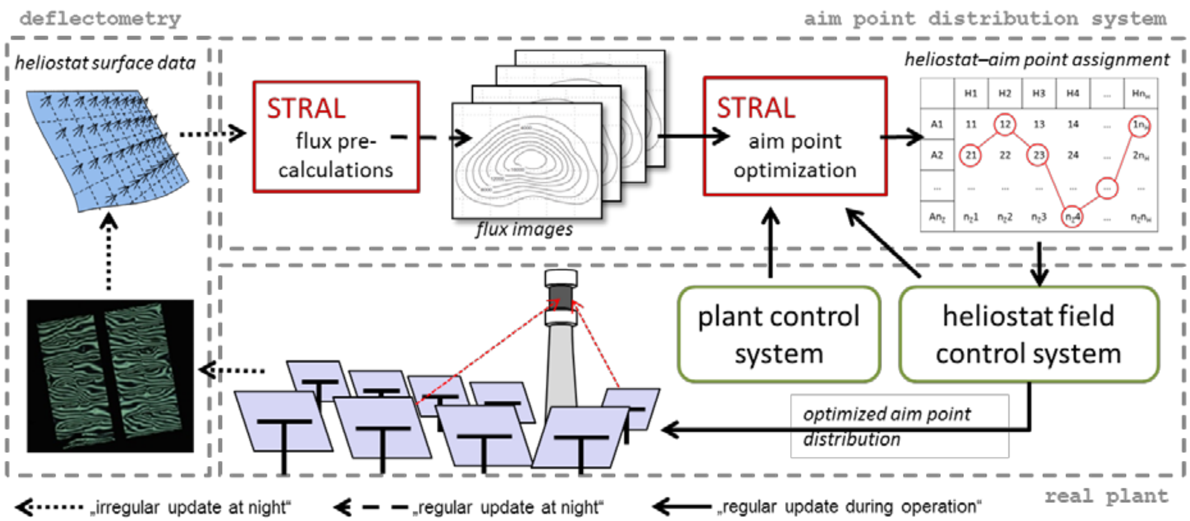


**FIGURE 3.** Basic work flow of automated system in real application.

To realize the intended work flow a basic control structure was designed and implemented as depicted in Figure 4. A central optimization control and survey tool is programmed in LabView®. This tool controls the pre-calculation process, initiates and stops the optimization run and handles the communication with the plant and field control system. The STRAL processes are controlled by the optimization control and survey tool via direct TCP/IP communication.

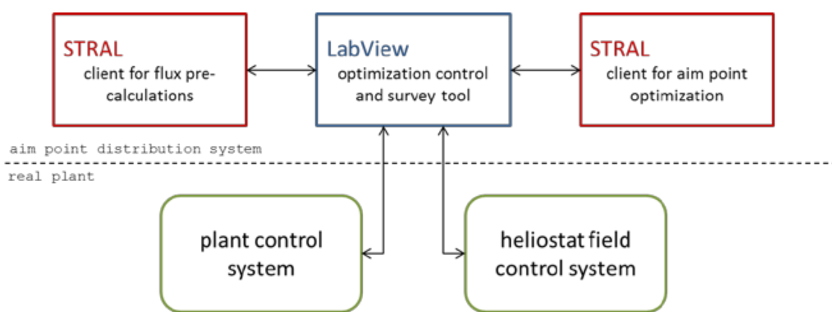


**FIGURE 4.** Basic control structure of applied aim point optimization system.

To pre-test the basic functionality and performance of the automated system a virtual testing environment was established where the side of the real plant in Figure 4 was simulated by a ray tracing model for the heliostat field (again STRAL) together with LabView® to emulate the control systems. The target was to get an updated aim point assignment every 15 minutes for the solar tower plant in Jülich with 2150 heliostats and a 22m² open volumetric receiver using 81 possible aim points. Therefore, the flux density of every heliostat aiming to every aim point was pre-calculated for each time point of the operation interval (the huge amount of data that is produced hereby can be reduced by grouping heliostats to aim at the same aim point and overlay their flux distribution in the pre-calculation). The pre-tests successfully demonstrated the basic functionality of the automated system and reached the goal of 15 minute update interval for a new aim point assignment. Additionally, it was revealed that a grid of 41 aim point positions is sufficient for this case.

For real testing the automated software system was implemented at the solar test plant in Jülich in 2014. Therefore, two workstations were installed: a “smaller” control station with a 12-core single-socket Xeon E5 CPU to host the control and survey tool and a more powerful workstation with a two-socket 24-core Xeon E5 CPU as the ray-tracing machine.

## TEST RESULTS

### Automated deflectometry system

With the automated deflectometry system a fast recurrent evaluation of the heliostat mirror shape for continuous quality control and up-to-date aim-point distributions is possible. The following figures show an example of the results of such automated deflectometry measurement.

Figure 5 shows the slope deviation of the mirror surface from the design geometry in horizontal (x) and vertical (y) direction of each mirror panel. The tilt of each mirror panel (facet) is calculated as the mean slope deviation of each panel and corresponds approximately to the canting error. In this example, the mean slope deviation of the complete heliostat is 0.69 mrad in x-direction (SDx) and 0.99 mrad in y-direction (SDy), representing very good heliostat geometry.

Figure 6 shows the integrated height deviation in millimeters from the ideal shape. With this z-deviation the tilt of each mirror panel (facet) is visible (canting). The 3D surface plot visualizes the height difference of the mirror panels from the design in exaggerated scale. In addition the height deviation at each of the mounting points is shown. This information can be used for the adjustment of the canting settings of the heliostat in the field. In this example, the panels show a negative height difference towards the center of the heliostat and a positive height difference towards the outer corners of the heliostat. This indicates that the heliostat has a slightly shorter focal length than desired, however with only little impact on the focus quality.

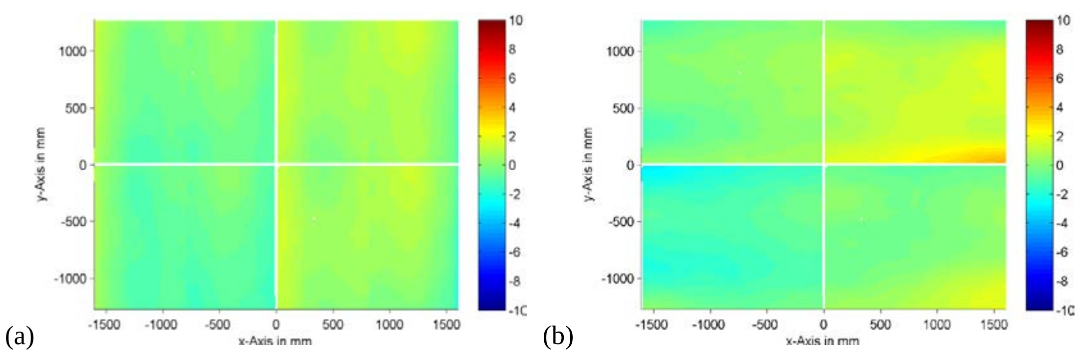


**FIGURE 5.** Heliostat slope deviation maps (in mrad)
in x-direction (a), and y-direction (b) for heliostat AX39 in the solar field of STJ Jülich

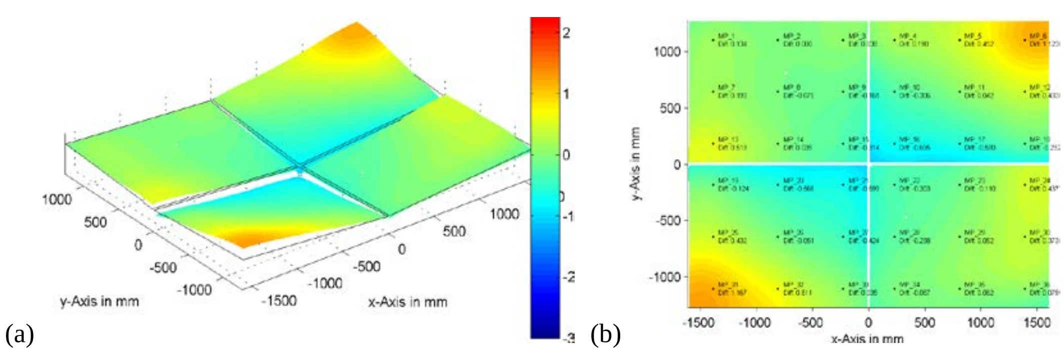


**FIGURE 6.** (a) Height difference of heliostat panels ideal shape (in mm);
(b) Height difference to ideal shape at mounting points (in mm)

## Aim point optimization system in virtual testing environment

First, the influence of grouping of heliostats (to aim at the same aim point) on the performance of the optimization was investigated and compared to the standard aim point assignment of the Jülich Tower (Figure 7). For the given time point (21st March, solar noon) the default aim point assignment resulted in an intercept power on the aperture of 10,500 kW. All optimization runs exceeded this value, the best being the configuration of 25 groups formed by four rows per group (labelled “25_4”) which showed an improvement of 1.5% after 15 minutes and 2.2% after two hours. The run without groups (each heliostat is optimized individually) performed slow compared to most others but was still showing progress after two hours. The group 25_4 was used for the further tests.

As a further test, the scenario of reducing the flux limit from 950kW/m² to 650kW/m² is considered. As reference it is assumed that without optimization the operator would send as many back rows of the heliostat field to the off-receiver position until the new flux restriction is met. The results are shown in Figure 8. Using the standard aim point assignment with defocused rows reduces the intercept power to 7,200 kW (-31%). The optimization delivers solutions with an intercept power above 9,500 kW after few minutes and about 10,000 kW after 15 minutes. No heliostat has to be defocused (set to off-receiver) and the loss due to increased spillage is only about 5%.

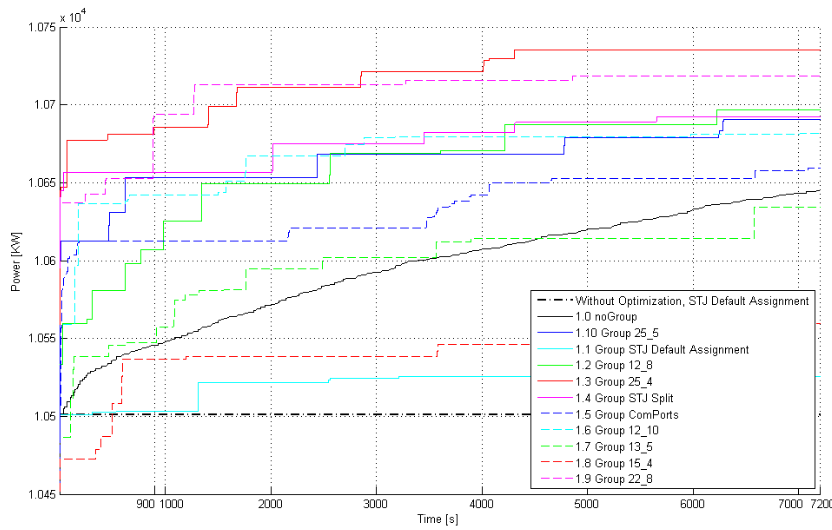


**FIGURE 7.** Progress of intercept power during optimization for various aiming groups, with flux limit of 950kW/m² applied

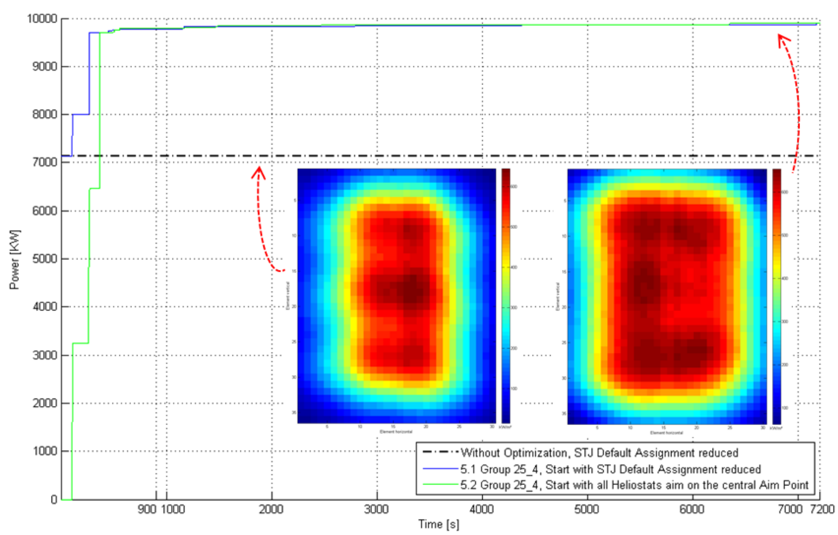


**FIGURE 8.** Optimization of aim point distribution for reduced flux limit of 650kW/m².
Flux density distribution for standard aim point assignment with reduced field (left), for optimization result (right).

## Aim point optimization in real application

Due to refurbishment of the heliostat field in Jülich, only a small number of heliostats were available in 2014 to test the automated aim point optimization system in real application. Therefore, only simple test cases that demonstrate the basic functionality could be made. One of the results is depicted in Figure 9, where initially 60 heliostats are equally assigned to the six standard aim points. Then the optimization is started to maximize the intercepted power with a flux limit of 850 kW/m² applied and aim point no. 3 blocked. As expected, the optimization directs all heliostats to aim point no. 4 and the execution in the real plant could be confirmed. The measured flux distribution in (c) shows the high tracking error of the heliostats.

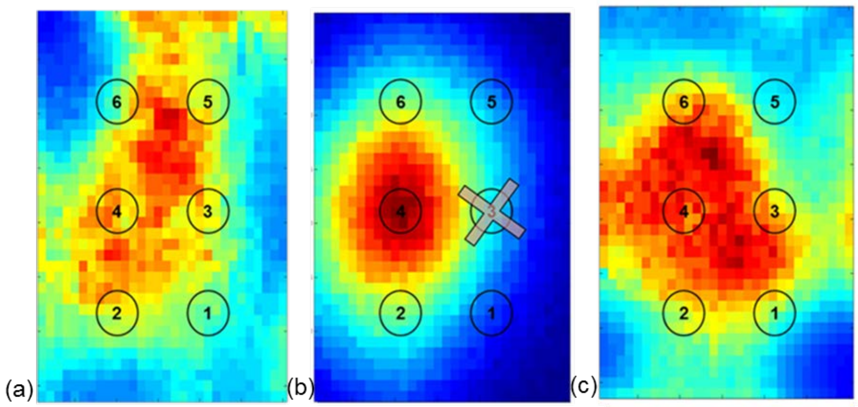


**FIGURE 9.** Measured flux profile before (a) and after the optimization: simulated (b) and measured (c) using 60 heliostats on 1st November 2014. (Measured flux profiles are not calibrated, only relative information)

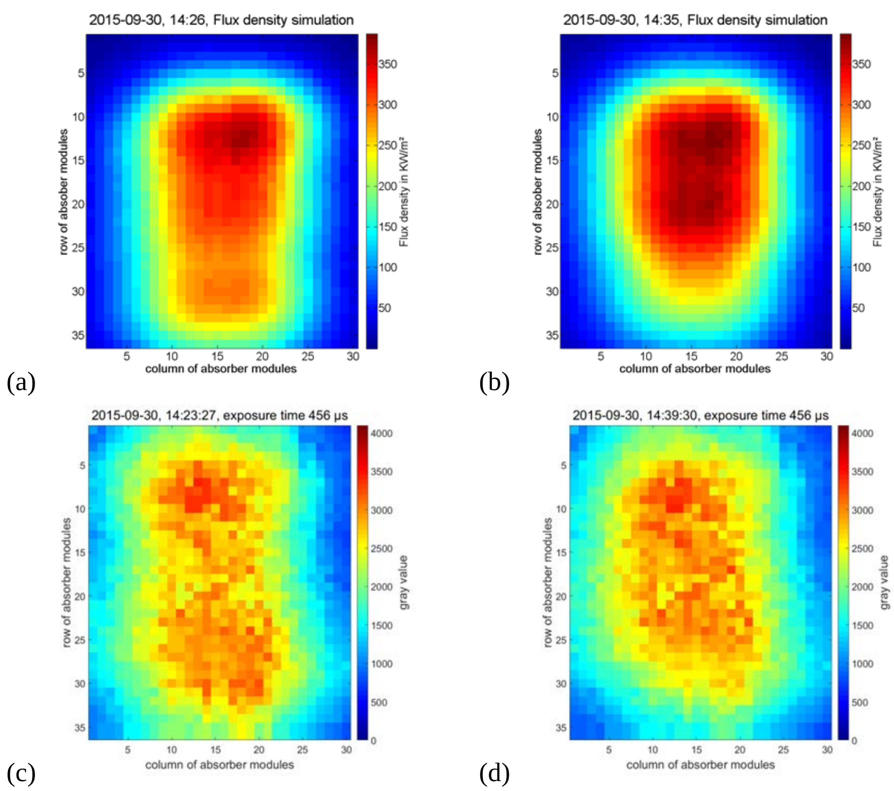


**FIGURE 10.** Flux profile before (left) and after the optimization (right) using 777 heliostats on 30th September 2015. (a) and (b) Simulated flux on target. (c) and (d) Measured flux profiles on target (not calibrated, only relative information).

In 2015 a larger number of heliostats were available and tracking accuracy was improved. Several real application tests could be performed, an example is shown in Figure 10. A group of 777 heliostats was used, distributed initially to the six standard aim points (Fig.10 (a) and (c)). The aim point optimization was started with the objective to improve the intercept, allowing to choose from 41 aim point positions on the target. The optimization result after only a couple of minutes is shown in Fig (b) as simulation and Fig. (d) as measured flux. The simulation shows an improvement in intercept of 2% and an increase of peak flux of 3.7%. The measured flux shows an increase of intercept and peak flux of 0.9% and 4.1%, respectively.

## SUMMARY AND OUTLOOK

An automated deflectometry measurement system for the quality control of mirror shape was developed and validated in the heliostat field of the Solar Tower Jülich. The system produces heliostat surface slope information at an accuracy <0.2mrad with a resolution >10,000 points per m² at a production rate of about 1 heliostat per minute. The industrial-suited design makes it applicable to large scale commercial power towers for quality assessment, e.g. during commissioning, or readjustment of mounted heliostats. The measurement data are a perfect basis for high precision ray tracing simulations of existing heliostat fields.

An automated model-based aim point distribution system was developed and tested in virtual and real testing applications. The system is based on high precision ray tracing simulation and uses the ant-colony-optimization algorithm to provide improved heliostat-aim-point assignments at an update interval of up to 15 minutes. The improvement in intercept power relative to manual operation was 2% and more depending on time point and boundary restrictions.

It is planned to continue application and testing of both systems at the solar tower Jülich. In a follow-up project, the aim point optimization system shall be extended to include online measurement data from the receiver into the optimization process.

## ACKNOWLEDGMENT

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