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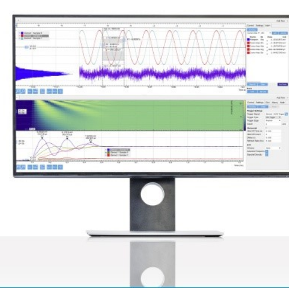

# Optimization of Robust Aiming Strategies in Solar Tower Power Plants

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**Abstract.** In solar tower power plants aiming strategies are used to distribute the heat flux on the receiver surface. An optimal strategy maximizes the mass flow while avoiding thermal overloading to prevent the risk of damage to receiver components. This problem has been modeled as an integer program (IP) to provide deterministic solutions. To consider disturbances caused by the tracking error, the aiming strategy is extended to ensure a robust solution.

## INTRODUCTION

A promising option for using concentrated solar power are solar tower power plants as they provide energy in a highly scalable way. To further increase their efficiency and the life span of the receiver, the aiming strategy should be as optimal as possible. For industrial use, a fast and accurate optimization routine in real-time is needed. Furthermore, the aiming strategy should ensure that safety constraints do not get violated and thermal stresses are minimized. Additionally, uncertain effects such as local heat fluxes should be considered which can occur due to cloud movements or tracking errors.

There already exist different approaches to find an optimal aiming strategy: Belhomme et al. [1] propose a solution based on the ant colony optimization metaheuristic, Astolfi et al. [2] offer fixed approaches for aiming strategies, Besarati et al. [3] use a genetic algorithm, and Ashley et al. [4] use integer linear programming to determine an optimal solution.

While a good solution can be sufficient – especially when it can be computed fast – an optimal solution is preferable when it can be computed in a similar amount of time. While [1], [2], and [3] are heuristics, they do not necessarily find an optimal solution. Just [4] presents an optimal solution to the given problem, however they do not consider heat flux gradients at the receiver. Furthermore, there is no work which considers uncertainties that can lead to deviation of heliostat heat flux distributions. As these effects can cause violations of safety constraints at the receiver, it is important to consider them when developing an optimal aiming strategy.

In this paper, robust aiming strategies are developed which find the global optimal aiming strategy for arbitrary receiver geometries.

## OPTICAL MODEL

The receiver is discretized by a number of aim points which can be adjusted to control the accuracy of the aim point resolution on the receiver surface. Besides the aim points, the receiver is also discretized by so-called measurement points. On these points, the intensity of the irradiation reflected by a heliostat on the receiver surface is evaluated. The number of measurement points and thus the measurement point resolution of the receiver surface can be adjusted as well. Usually the number of measurement points is greater or equal than the number of aim points.

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An optical model is used to provide the projected heat flux distributions for all heliostats aiming on each aim point on the surface of the receiver. As in [4] and [5] we assume the heliostat images to be modelled by a Gaussian distribution. Additionally, we distort the images in dependency of the incident angles and the outer receiver shape. Every receiver type is allowed. For a given sun position and for each aim point the flux distributions of every heliostat are pre-computed. This approach will later shorten the running time of the optimization finding an optimal aim point configuration. Besides, this practice allows us to replace the pre-computed heliostat images by measured data if desired.

## THERMODYNAMIC CONSTRAINTS

For a given sun position and its direct normal irradiation, the maximum possible optical power can be computed by summing up the maximum heat flux distributions of each heliostat provided by the optical model. Then by using a thermodynamic receiver model, a desired flux distribution (DFD) can be found which maximizes the mass flow in the receiver and complies with the allowed flux distribution (AFD) [8]. The DFD simply distributes the maximum possible optical power on each measurement point on the receiver surface. The search for a DFD is an optimization itself which for example can simply be a homogeneous distribution as in [4].

Once this DFD map is found, the aiming strategy corresponds to the search of an assignment of heliostats onto aim points, such that the maximum possible flux is transferred to the receiver for the resulting heliostat flux distribution (HFD) without violating the AFD which is used as upper bound. Additionally, we constrain flux gradients at the receiver. This optimization problem is solved using integer linear programming. The results of the optimization model are shown in the following.

## AIMING STRATEGY CONSIDERING GRADIENTS

The desired flux distribution and the maximum allowed flux distribution for a coarse resolution and a fine resolution of the measurement points on the receiver surface are shown in Fig. 1 and Fig. 2. The heat protective shield is considered by limiting the heat flux around the receiver. For this test scenario, the DFD and AFD are chosen to be equal. Thus, the resulting heliostat flux distribution should be as close as possible to the DFD, but never exceed it. Besides constraining the maximum flux at each measurement point, we furthermore bound the maximum gradient between two measurement points vertically and horizontally. As in [5] we use integer linear programming to select the optimal aim point for each heliostat to reach this goal. For the set of measurement points M, aim points A and heliostats H the deterministic optimization model is given by

- **Local receiver heat flux:**

$$Q_m^{\text{receiver}} = \sum_{h \in H} \sum_{a \in A} Q_m^{h,a} \cdot x^{h,a}$$

- **Objective function:**

$$\max Q^{\text{total}} = \max \sum_{m \in M} Q_m^{\text{receiver}}$$

- **Decision variables:**

$$x^{h,a} \in \{0,1\} \quad \forall\, h \in H \quad \forall\, a \in A$$

- **At most one aim point per heliostat:**

$$\sum_{a \in A} x^{h,a} \leq 1 \quad \forall\, h \in H$$

- **Comply HFD with AFD:**

$$Q_m^{\text{receiver}} \leq Q_m^{\max} \quad \forall\, m \in M$$

- **Constrain heat flux gradients:**

$$Q_{i,j}^{\text{receiver}} - Q_{i-1,j}^{\text{receiver}} \leq G_{i-1,j}^{\text{max,horizontal}}$$
$$Q_{i-1,j}^{\text{receiver}} - Q_{i,j}^{\text{receiver}} \leq G_{i-1,j}^{\text{max,horizontal}}$$

$$\forall\, i \in \{2, ..., n_{m,x}\} \quad \forall\, j \in \{1, ..., n_{m,y}\}$$

$$Q_{i,j}^{\text{receiver}} - Q_{i,j-1}^{\text{receiver}} \leq G_{i,j-1}^{\text{max,vertical}}$$
$$Q_{i,j-1}^{\text{receiver}} - Q_{i,j}^{\text{receiver}} \leq G_{i,j-1}^{\text{max,vertical}}$$

$$\forall\, i \in \{1, ..., n_{m,x}\} \quad \forall\, j \in \{2, ..., n_{m,y}\}$$

As heliostat positions and receiver properties, the settings from the PS10 power plant in Spain are used. The resulting heliostat flux distribution is shown in Fig. 3 and Fig. 4, and the allocations are drawn in Fig. 5 and Fig. 6. For a run-time of 60 seconds on a standard computer using a single core, more than 99.8% of the available thermal energy are transferred to the receiver for the given HFD solution maps.

However, typical tracking adjustment times are shorter than 60 seconds, on the order of 10 seconds. To reach this time either a multi-core processor should be used (mixed integer linear programs are predestined for parallelization), or the number of aim points per heliostats should be reduced (e.g. the heliostats far in the back are just allowed to aim on the central aim points to reduce the spillage losses).

From Fig. 5 and Fig. 6 it can be seen that heliostats with large incidence angles and thus with strongly distorted images target the center of the receiver, such that spillage losses are minimized. Heliostats with small incidence angles target the aim points for which the cosine losses at the heliostats are minimized to reflect the highest possible thermal energy.

It is not desirable for the heliostats to target the heat protective shield as the thermal energy hitting it is not transferred to the heat carrying medium. For this reason, the heat fluxes at the heat shield are very small. They are induced by the sun shape error and by optical errors of heliostats, which both cause the Gaussian distribution used to model the heat flux density of heliostats to enlarge.

Clouds can be considered by defining the heliostat flux distribution on the receiver surface as zero for all shaded areas of the heliostats. This effectively reduces the size of the problem and is beneficial to the run time of the optimization in most cases.

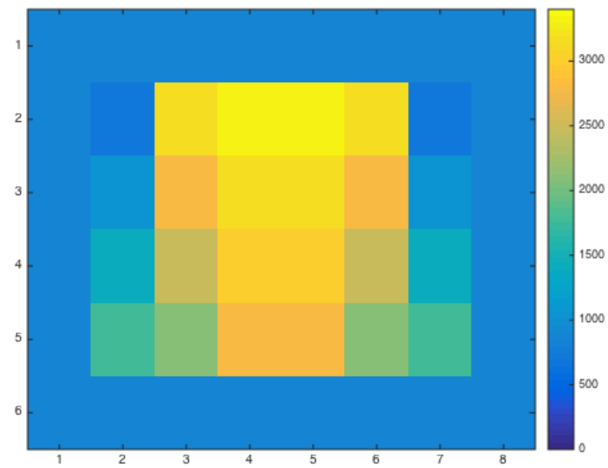


**FIGURE 1.** Allowed flux distribution (AFD) and desired flux distribution (DFD) on the receiver surface for a coarse resolution.

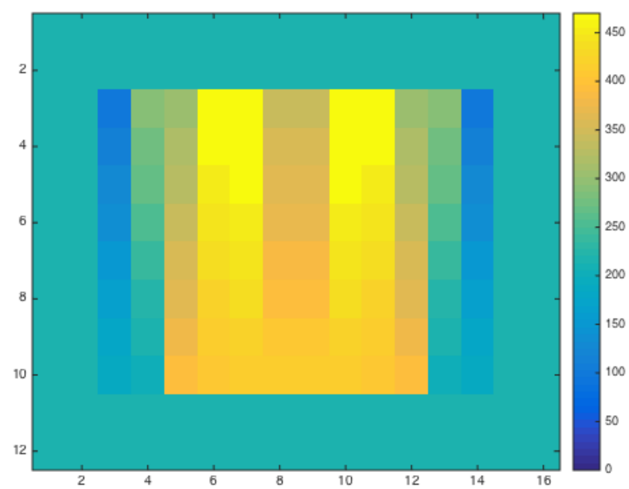


**FIGURE 2.** Allowed flux distribution (AFD) and desired flux distribution (DFD) on the receiver surface for a fine resolution.

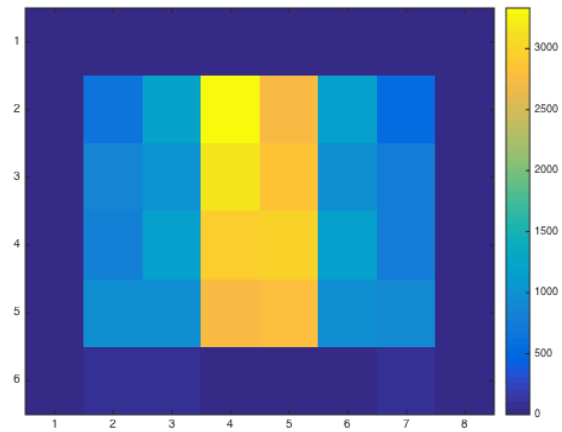

**FIGURE 3.** Resulting heliostat flux distribution (HFD) on the receiver surface for the coarse resolution test case.

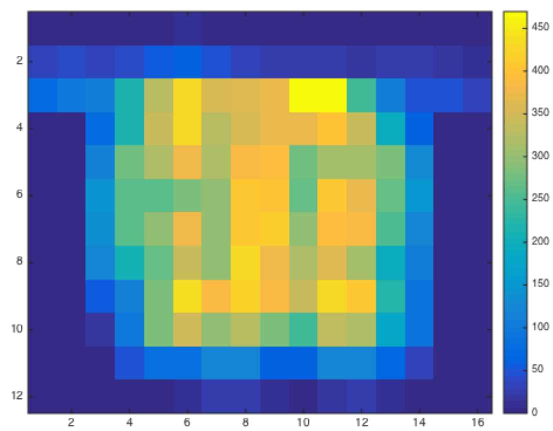

**FIGURE 4.** Resulting heliostat flux distribution (HFD) on the receiver surface for the fine resolution test case.

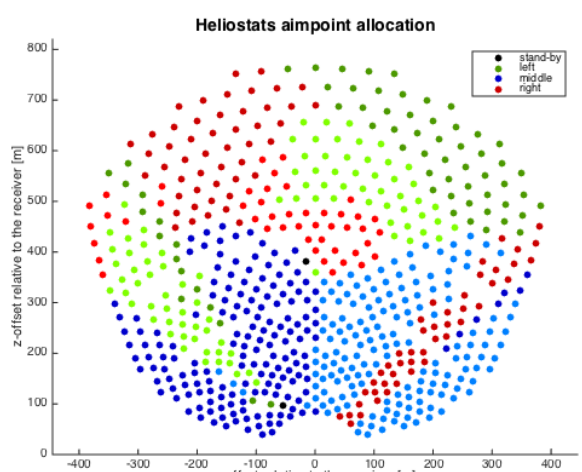


**FIGURE 5.** Aim point allocation of the heliostats for the coarse resolution test case.

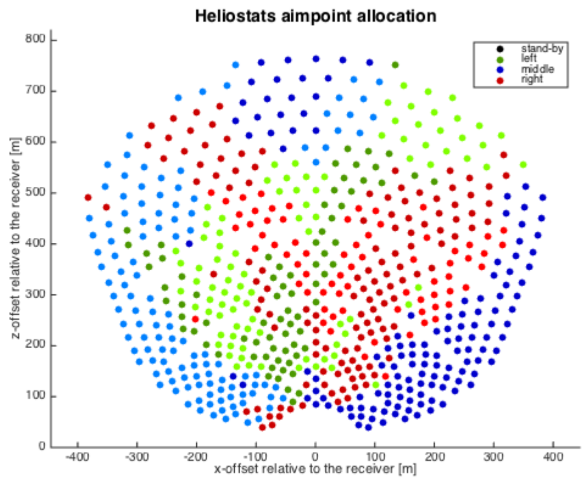


**FIGURE 6.** Aim point allocation of the heliostats for the fine resolution test case.

## ROBUST AIMING STRATEGY CONSIDERING UNCERTAINTIES

While operating a solar tower power plant there are several uncertain parameters which influence the process. Here especially the tracking errors of heliostats are important, as they can cause a whole heliostat image to deviate to a different location than intended. This behavior is probabilistic and can potentially violate given safety constraints. Thus, it is of great importance to consider tracking errors as uncertainties; especially for very critical safety constraints or for heliostats in solar tower power plants that are prone to the effects leading to tracking errors.

Examples for these effects are inaccuracies of the motor aligning the heliostats, dirt or wear at the joints of the tracking axes or imperfections in the construction of the heliostat. The results of tracking errors on different heliostats with respect to the total heat flux distribution at the receiver do not cancel each other out, as they behave in a non-Gaussian way [6]. For this reason, we have to consider them as uncertainties and cannot simply consider them by enlarging the Gaussian distribution of the heliostat images.

We model tracking errors by using a robust optimization approach called Gamma robustness [7], i.e. we allow a previously determined number of heliostats to deviate. We extend the previous aiming strategy, but neglect heat flux gradients, as the problem would become too large otherwise. If a heliostat deviates from its intended aim point, its image can be moved. We assume that the heliostat is tracked biaxially, which means that the heliostat image can be moved in horizontal and vertical direction.

When constraining the maximum heat fluxes, we have to make sure that they are not violated for every possible deviation caused by the tracking errors. We introduce a new term to the maximum heat flux constraints that represents the additional heat flux hitting a measurement point when a heliostat deviates towards it from its original aim point. To obtain a solution feasible for every possible additional heat flux, we have to determine its maximum, which means that we have to solve a nested optimization problem inside the original optimization problem.

To be able to solve the optimization problem as a whole directly, we dualize the nested optimization problem and reformulate the maximum heat flux constraint. As a result, we obtain an optimization model directly solvable by using mixed integer linear programming (MILP). For the set of measurement points M, aim points A and heliostats H the robust optimization model is given by

- **Deterministic local receiver heat flux:**

$$Q_m^{\text{receiver}} = \sum_{h \in H} \sum_{a \in A} Q_m^{h,a} \cdot x^{h,a}$$

- **Additional local receiver heat flux:**

$$\hat{Q}_m^{h,a} = Q_{\text{worst},m}^{h,a} - Q_m^{h,a}$$

- **Objective function:**

$$\max Q^{\text{total}} = \sum_{m \in M} Q_m^{\text{receiver}}$$

- **Decision variables:**

$$x^{h,a} \in \{0,1\} \quad \forall h \in H \quad \forall a \in A$$
$$u_m \in \mathbb{R}_0^+ \quad \forall m \in M$$
$$v_m^h \in \mathbb{R}_0^+ \quad \forall h \in H \quad \forall m \in M$$

- **At most one aim point per heliostat:**

$$\sum_{a \in A} x^{h,a} \leq 1 \quad \forall h \in H$$

- **Comply HFD with AFD (1):**

$$\sum_{h \in H} \sum_{a \in A} Q_m^{h,a} \cdot x^{h,a} + \Gamma \cdot u_m + \sum_{h \in H} v_m^h \leq Q_m^{\max} \quad \forall m \in M$$

- **Comply HFD with AFD (2):**

$$u_m + v_m^h \geq \sum_{a \in A} \hat{Q}_m^{h,a} \cdot x^{h,a} \quad \forall h \in H \quad \forall m \in M$$

When applying the robust aiming strategy to the PS10 solar tower power plant with the maximum allowed relative flux distribution given in Fig. 7, the results shown in Fig. 8 and Fig. 9 are obtained for up to 30 of 624 heliostats deviating.

Comparing Fig. 5 and Fig. 9 as they use the same measurement distribution at the receiver shows, that less heliostats than before aimed onto the center of the receiver now aim more to the left or right side of the receiver. The reason for this is that the robust aiming strategy is more conservative than the first aiming strategy as heat fluxes violating maximum heat flux constraints have to be prevented. The heat flux distribution at the receiver is spread out over a wider area.

Another consequence is that the obtained heat flux distribution at the receiver does not come as close to the maximum allowed one as the first aiming strategy did, while transferring a smaller amount of thermal energy to the receiver. For these reasons this aiming strategy can be used when it is of exceptional importance that certain heat flux values are not exceed. The first aiming strategy, however, can be used when heat flux gradients need to be considered and/or when a certain heat flux distribution shall be obtained.

It is noticeable that the optimal solution of this optimization problem was found in 60.2 seconds even though the size of the problem is much larger than for the first aiming strategy.

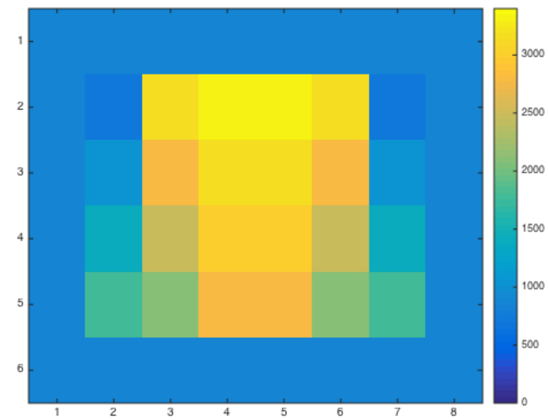

**FIGURE 7.** Allowed flux distribution (AFD) and desired flux distribution (DFD) on the receiver surface for a coarse resolution.

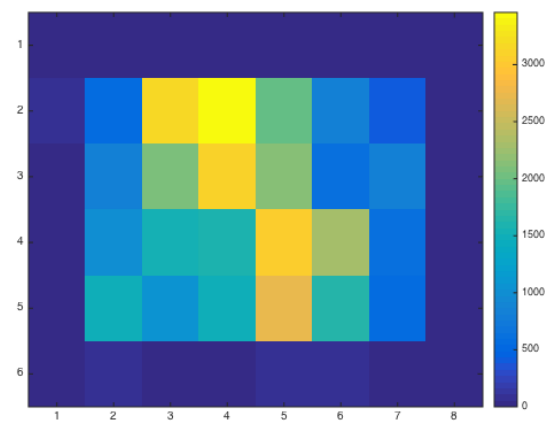

**FIGURE 8.** Resulting heliostat flux distribution (HFD) on the receiver surface considering uncertainties.

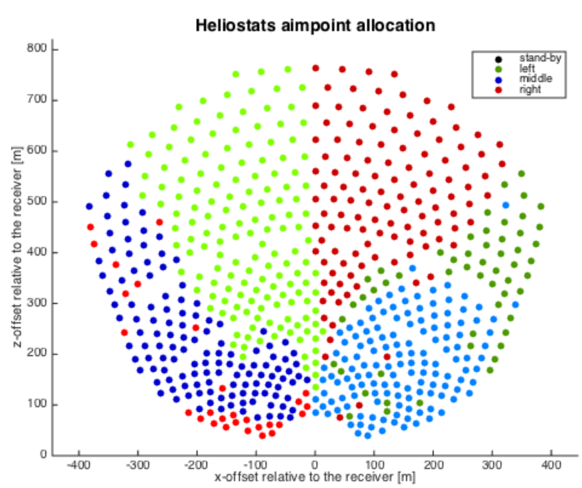


**FIGURE 9.** Allowed flux distribution (AFD) and desired flux distribution (DFD) on the receiver surface for a coarse resolution.

## CONCLUSION

For industrial use aiming strategies have to be applicable to solar tower power plants in real-time. The obtained solutions shall transfer the largest possible amounts of thermal energy to the receiver while simultaneously reducing thermal stresses such that a long lifetime of the receiver can be ensured. We developed two aiming strategies that obtain solutions which satisfy these requirements. The first aiming strategy constrains maximum heat fluxes and maximum heat flux gradients at the receiver, the second one constrains maximum heat fluxes and considers tracking errors as uncertainties. Within a case study both aiming strategies were applied to the solar tower power plant PS10 in Spain.

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