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Building a 5D Database of Heliostats Flux Distributions: Toward High Flexibility High Accuracy Flux Control for Odeillo's Big Solar Furnace

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Abstract. In order to increase the flexibility and the control of the concentrated solar flux provided to test processes and materials at the big solar furnace in Odeillo (up to 1000 kW and 10000 KW/m^2), extensive and accurate knowledge of the individual contribution of each of the heliostats is required, for all their aiming points. For a solar furnace, with double mirror reflection and heavily changing shadow of the solar beams, this would require too much experimental time to record this behaviour systematically, either directly (flux measurements of all the configurations) or indirectly (simulation by ray tracing based on the real optical configuration measured, both at macroscopic and microscopic scale). This work here presents a trade-off method based on real flux measurement, but at sampled configurations, then interpolated to fill in missing data. 5 dimensions have been sampled: heliostats (1D) + aiming directions (2D) + flux distributions (2D). An evaluation of the method is presented based on actual experimental data, with a discussion of the experience.

Keywords: Solar Furnace, Flux Measurements, Camera, Radiometer, Data Interpolation, Heliostats, Aiming Strategies, Big Data, Data Processing, Solar Receiver, Cavity

Figure 1. Overall view of the Big Solar Furnace and heliostats in Font Romeu Odeillo, Eastern Pyrénées, France, operated by the PROMES-CNRS laboratory since 1968.

1. Introduction: work motivation

For a research facility, the capacity to control and simulate the widest range of operating conditions is key to evaluate and qualify the hosted processes. Work has been conducted for solar tower plants (STP) in order to develop heliostat aiming strategy to tailor flux distribution for the targeted needs, either in simulation, experimental or operational scale, but nearly none for solar furnaces with their double reflection, despite their capability to investigate a much larger flux range.

1.1 Objectives of the supporting project CLÉ-DE-SOL

The work presented here, partially funded by the European ERDF project CLÉ-DE-SOL, has allowed to greatly enhance flux control for Odeillo's Big Solar Furnace operated by the PROMES-CNRS laboratory: both spatial and dynamic control of incoming power on the tested solar receivers.

- Firstly, flux measurement methods and heliostats upgrades have allowed to build an accurate heliostats flux database, presented here.
- Secondly, we have developed an optimization algorithm based on genetic heuristics in order to determine where each heliostat should aim, based on the flux distribution from the heliostats flux database, in order to reach together the required flux distribution. This second step is presented separately.

The operational test case involved 25 heliostats (out of 63) and a 23cm deep convex cavity with a 100x10 cm flat solar receiver, related to a tubular particles receiver testing scenario.

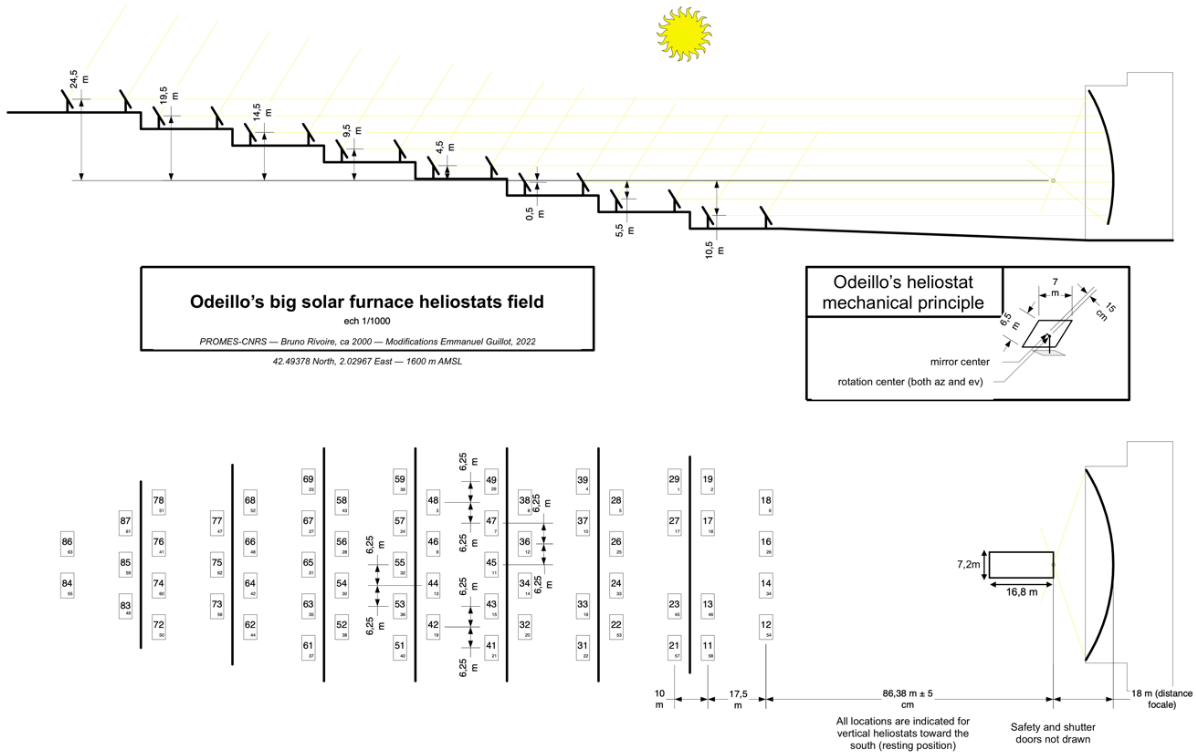

Figure 2. General layout of the heliostats field of the big solar furnace and its parabola. Not displayed: the doors in front of the solar tower which are used both for safety and to regulate concentrated solar power.

2. Odeillo’s Big Solar Furnace

The PROMES-CNRS laboratory has been operating the 1000 kW Big Solar Furnace since 1968 in Font Romeu Odeillo, France. This facility allows to investigate processes to harness the solar energy (production of electricity and solar fuels, thermochemistry) but also to study materials up to 3500°C on a surface up to 1 m wide, by collecting the solar energy thanks to 63 heliostats (2835m^2 total surface of mirrors) and then concentrating it with a parabolic mirror with 9000 facets (1830 m^2 aperture area) inside a tower which hosts the experimental setup and the control room [1][Fig. 1][Fig. 2]. This facility has only one rival in the world, built by the USSR in Parkent, Uzbekistan, commissioned in 1987.

The extensive capability of the CNRS solar furnace is due on one hand to its optics quality and on the other hand to the control system of the 63 heliostats field: the tracking performance including during cloudy (automatic switch between open and close loop tracking) or windy conditions, the flexibility of the available aiming strategies, all beyond current performance of towers heliostats fields thanks to a recent rejuvenation of the control system, leading to high accuracy heliostats with high dynamic [2].

3. Heliostats flux database building for solar furnaces

The heliostats flux database is a dataset allowing one to know what is the contribution of each heliostat with any aiming offset point: indeed, due to the optical configuration of a solar furnace, contrary to STP, even with small offset compared to the focal length, the flux distribution quickly changes and should be evaluated for each offset location (each aiming point). In addition, non-linearities are present due to shadowing effects from the tower building, safety doors, or the cavity itself. Therefore, it is required to estimate separately the flux distribution for each considered aiming direction: we cannot rely on spatial invariance like for STP.

Two options have been considered to build such a database: simulation, based on ray-tracing, or flux measurements. Simulation has been discarded as requiring a very accurate optical model of the ~15000 involved mirrors, which would have been too costly (deflectometry or photogrammetry required at a large scale on both flat heliostats and a very large parabola). In both cases, spatial interpolation is required to limit the number of configurations to be simulated or to be measured.

Figure 3. (left) General view of the cavity inside the aluminum water-cooled shield, with at it center the 10x100 cm flat white lambertian target and the dark radiometer at its own center. (right) Closeup on the Captec water-cooled radiometer. Notice the vertical black and silver strips used to compensate for the convection bias.

3.1 Flux measurement method

In order to get flux distribution at the focal plane of the big solar furnace, several components are used [Fig. 4]:

- **A white Lambertian target**. For this setup, the test case cavity has been built in high temperature high flux foam covered with magnesium oxide to improve both its resilience and its optical properties (reflectivity and angular behavior) [Figure 3].
- **A camera to record brightness levels** on the target. An AVT Manta 125C camera is used: Sony ICX445 1/3" CMOS sensor with 1292x964 pixels, full control of the radiometric chain. Custom C software is used to record the images at full rate (30 fps) without any degradation such as lossy compression (TIFF files).
- **A radiometer to calibrate the camera+target** system. A radiative flux sensor manufactured by Captec is used [3]. These sensors, physical cousins of the Gardon gages and Schmidt Boelter sensors, also use thermocouples and temperature differences in a thermally known material to measure thermal flux. The main advantage: they are not sensitive to convection and ambient temperature, contrary to the Gardon gages. However, due to their manufacturing process, they are limited to low flux: up to 500 kW/m2 depending on the model. Here, the 15mm diameter watercooled sensor is limited to 350 kW/m2. The acquisition system for the voltage of the sensor (0-500 mV) is an eDAM ModBus voltmeter, manually periodically compared during the experiments to a high accuracy Gantner A4 or a Keithley 2400 voltmeter, depending on their availability.

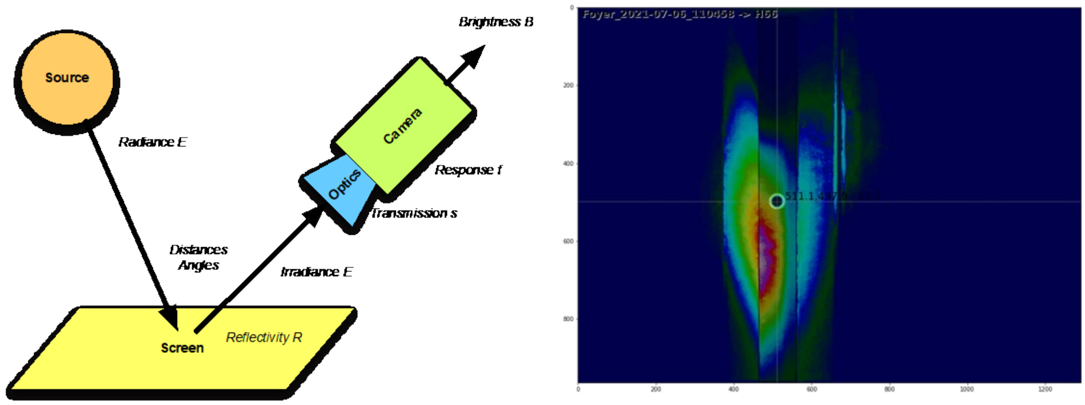

Figure 4. (left) Camera based flux measurement principle.
(right) Raw camera flux image in false colors with automatic detection of the radiometer location in its center. The white rectangular central target is 10x100 cm.

For this setup, the radiometer was integrated inside the white target: with this configuration, the recording of the reference flux is permanent. However, there is no camera measurement at the radiometer location: this mean gray levels must be interpolated based on the value immediately around the radiometer. The quality of this interpolation depends on the flux gradient conditions. Calibration of the system gray level <-> flux, was only performed under low flux gradient. A python program was developed using OpenCV to achieve this image processing step and evaluation [Fig. 4].

4. Building the 5D flux heliostats database

4.1 Experimental campaign (2021)

In order to deliver flux onto the 100x10 cm solar receiver (practical test case for this work), the area of interest for the aiming points is about 200x100 cm, depending on the beam incoming angle of each heliostat. To speed up data recording and limit solar position impact, the camera+radiometer based flux measurement was done at 30Hz during each heliostat controlled trajectory on this area, after upgrade of the control software to allow high speed high accuracy and reproductible trajectories (heliostat movement with close-loop cameras [2]).

For 25 heliostats, one dataset requires about one hour of automatic recording: about 100 000 14bits images (~35 GB), plus heliostat trajectories, pyrheliometer measurements and calibration radiometer data, each 1D datasets. Each run is completely autonomous and can safely be achieved without human supervision: random heliostat choice, adapted trajectory determination and control, data recording of all required sensors.

Full measurements have been conducted a dozen times in autumn 2021, in addition to all the uncomplete runs during the method implantation.

4.2 Data interpolation and database assembly

To build the final dataset, for each experimental recording, all this data has been first supersampled at 1 kHz then synchronized with custom Python code relying mostly on numpy and scipy functions. Then, the data has been spatially interpolated (linear metric) and supersampled regarding the aiming location of the heliostats: their trajectories were programmed every 10cm, but were oversampled every 5cm, the minimal meaningful resolution. Flux measurement data resolution was kept as from camera: 1mm per pixel.

At the end, for each full experimental dataset, 5D databases calibrated in flux (kW/m2) were built:

- 1D to choose the heliostat,
- 2D for heliostat aiming locations (x-y position on the focal plane),
- 2D for flux data on the test case receiver and cavity (x-y flux distribution on the focal plane).

It should be noted that more parameters could be added for such a large solar furnace to be complete:

- 1D for the main shutter aperture (large vertical doors),
- 1D for the secondary shutter aperture (vertical triangular door),
- 1D for Z-axis scanning along the optical axis (which would allow full tomographic analysis of the focal volume, in any plane, with a method already experimented on the smaller solar furnaces available in Odeillo in a separate work).

Once a 5D database available, a python code was developed in order to provide the flux distribution for any heliostat at any location on the receiver, for any aiming point, even above the 5cm resolution: another interpolation code was designed and tested for this last processing step.

4.3 Database visualization and exploitation

A client for web browsers was designed to display the interpolated flux distribution in real time for the facility operator (HTML+vanilla javascript frontend, flask python-based backend) [Figure 5 left]. This tool also allowed to select the best 5D database by visually comparing the quality of the interpolations, which has been used to run a specially developed genetic algorithm to determine heliostats aiming configuration to deliver homogenous flux distribution on the test case solar receiver.

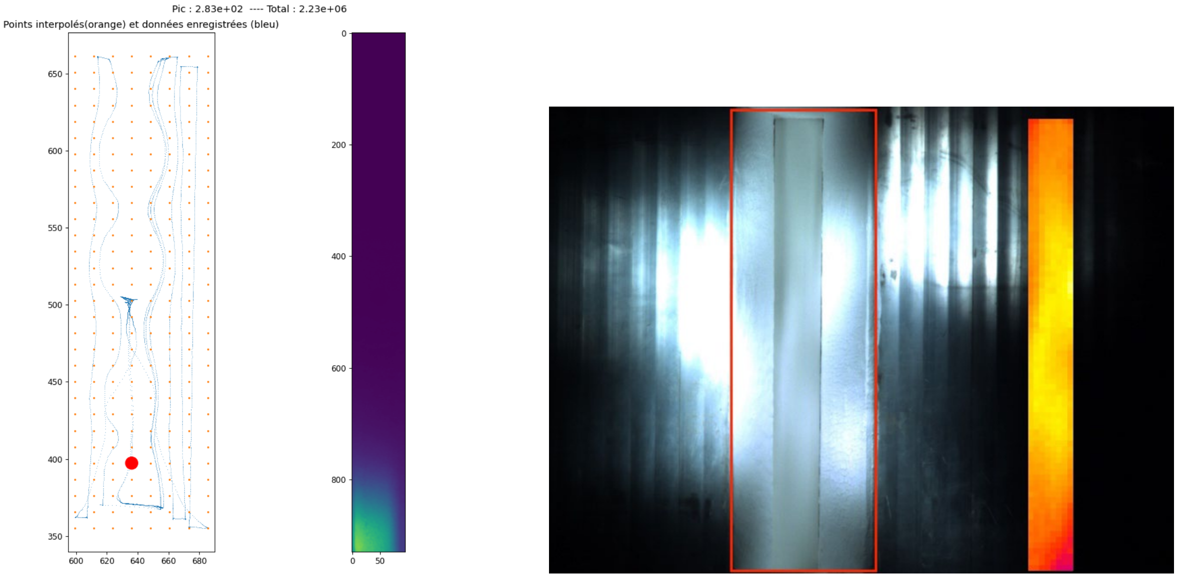

Figure 5. (left) Plots of the 5D database: on left the 2D aiming of this heliostat, with in blue the measured locations and in red the interpolated locations. The large red dot is the location at which the interpolated flux on the 10x100cm target is displayed.
(right) Raw camera flux image in gray level, with a high power white water-cooled target in center to validate the method. The red rectangle highlights the cavity. The false image in orange hue displays the expected flux distribution simulated using the 5D database

5. Results and Discussion

From the best quality experimental data (recorded on December 20th, 2021), a 5D database has been built. It has been used as basis for the heliostats aiming strategy using genetic algorithm (GA) by the same authors presented at the same conference [4]. The early qualification tests of this two-step work has been visually validated on initial scenarios in January 2022. Instead of the low power passive white target, a water-cooled target was used with plasma deposited magnesium oxide, without an integrated radiometer [Figure 5 right].

However, further in-depth testing of the produced aiming strategies for different scenarios (April-May 2022) showed a mismatch between predicted flux distribution — using the 5D database and genetic algorithms — and the actual measured flux distribution on the big solar furnace.

No issue could be found on the GA step; however, 3 issues have been identified and discussed for the 5D database building:

- Radiometer damaged. After further evaluation, the radiometer reference sensor used for the experimental campaign in 2021 has been found to be damaged. Experimental measures have been conducted in spring 2022 to compare these radiometer measurements with one of the water calorimeters available at the big solar furnace [5],[6]: the radiometer measurements were about twice the level expected, and moreover, the correction factor would have been nonlinear over the required flux range. Given the physical principle of the radiometer used [3], it has been evaluated that this non-linearity was related to a significant problem with the radiometer, not just a bias that could be corrected such as a change of absorber properties. Due to this issue, all the 2021 experimental lack therefore a reference data to accurately calibrate gray levels, hence obtain flux distribution in kW/m^2.
- Interpolation quality. In addition, after a careful lengthy observation of the interpolated data, it has been observed a large disparity of data density over the 2D focal plan

scans, depending on the heliostat, and possibly depending on the wind gusts during the recording. Some areas exhibited a large number of points, sometimes incoherent (probably due to wind gusts). On the contrary, some areas for some heliostats lacked recorded data, probably due to bad combination of mechanical play and improper trajectory tuning parameters.

- Position of the sun. The experimental dataset was recorded in late December (low position of the sun in the sky), but in-depth used as 5D database in late spring: the shadowing between heliostats is different, hence power distribution on the focal plane. This last step has been considered secondary if not neglectable compared to the two other issues identified above.

6. Conclusion and further work

A 5D database has been built based on experimental data. The method is usable to develop an accurate knowledge of the localized concentrated flux of a solar furnace with multiple heliostats. An automatic recording and heliostats control system has been developed and used, adapted to Odeillo’s big solar furnace. Experimental datasets have been collected. Synchronisation of the datasets, supersampling and interpolation have been achieved with custom developed python code. However, even if the first validations of the 5D database were successful, in-depth analysis showed flawed data due to a damaged sensor, and a probable higher sensitivity than expected to wind that would require either longer measurements at slower heliostat moving speed, and/or improved interpolation algorithm.

Data availability statement

Experimental flux measurement data recorded at the big solar furnace in 2021 is available on CLE-DE-SOL project page on Zenodo data repository. The data includes raw images and heliostats position recorded at full rate, and high resolution sketches. Code snippets are available on a github repository.

https://zenodo.org/communities/feder_cle-de-sol_2020
https://github.com/eguillotcnrs/cledesol-exploiteurscans1000

Author contributions (CRediT)

Emmanuel Guillot: Conceptualization, Data curation, Format Analysis, Funding acquisition, Investigation, Methodology, Project Administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft.

Michaël Tessoneaud: Investigation, Resources.

Jean-Louis Sans: Investigation, Methodology, Resources, Supervision, Validation.

Competing interests

The authors declare no competing interests.

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