Australia's National Science Agency

Simulation of the ASTRI demonstration particle receiver during on-sun testing

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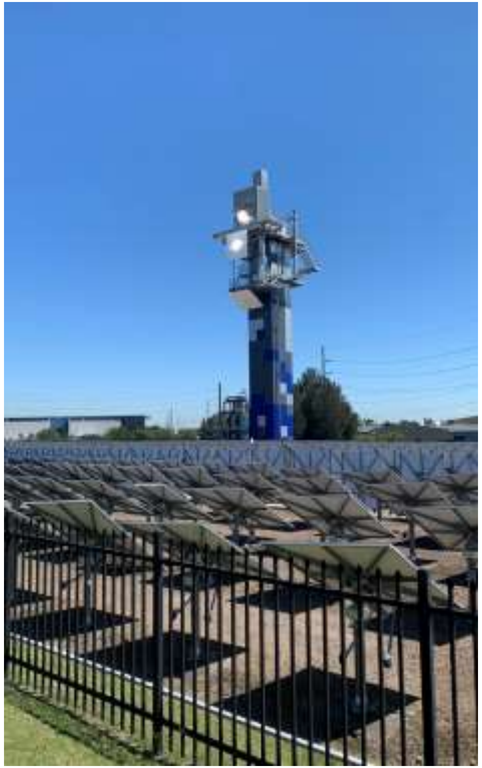
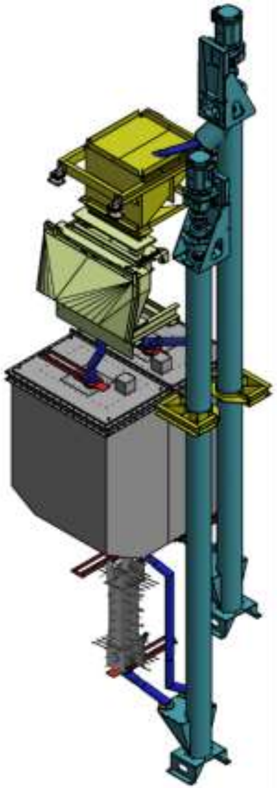
Wednesday 6th of December 2023
RMIT, Melbourne
Land of the Wurundjeri people of the Kulin Nations

ASTRI
Australian Solar Thermal Research Institute

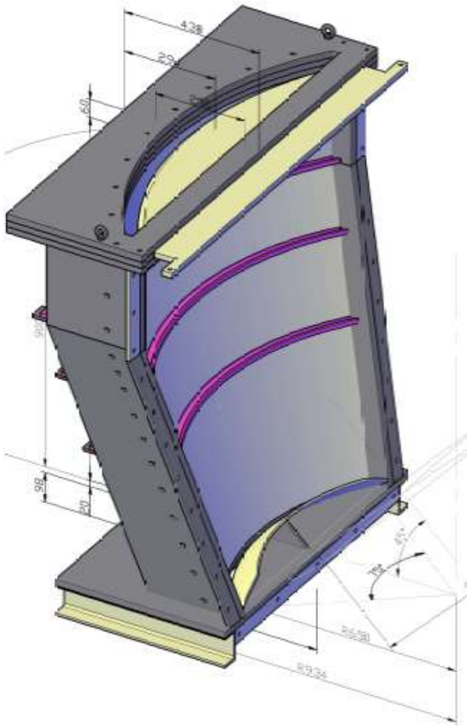
ASTRI demonstration particle receiver



(a) Solar Field 2 with particle system at CSIRO Newcastle



(b) CAD model of particle system with cooler



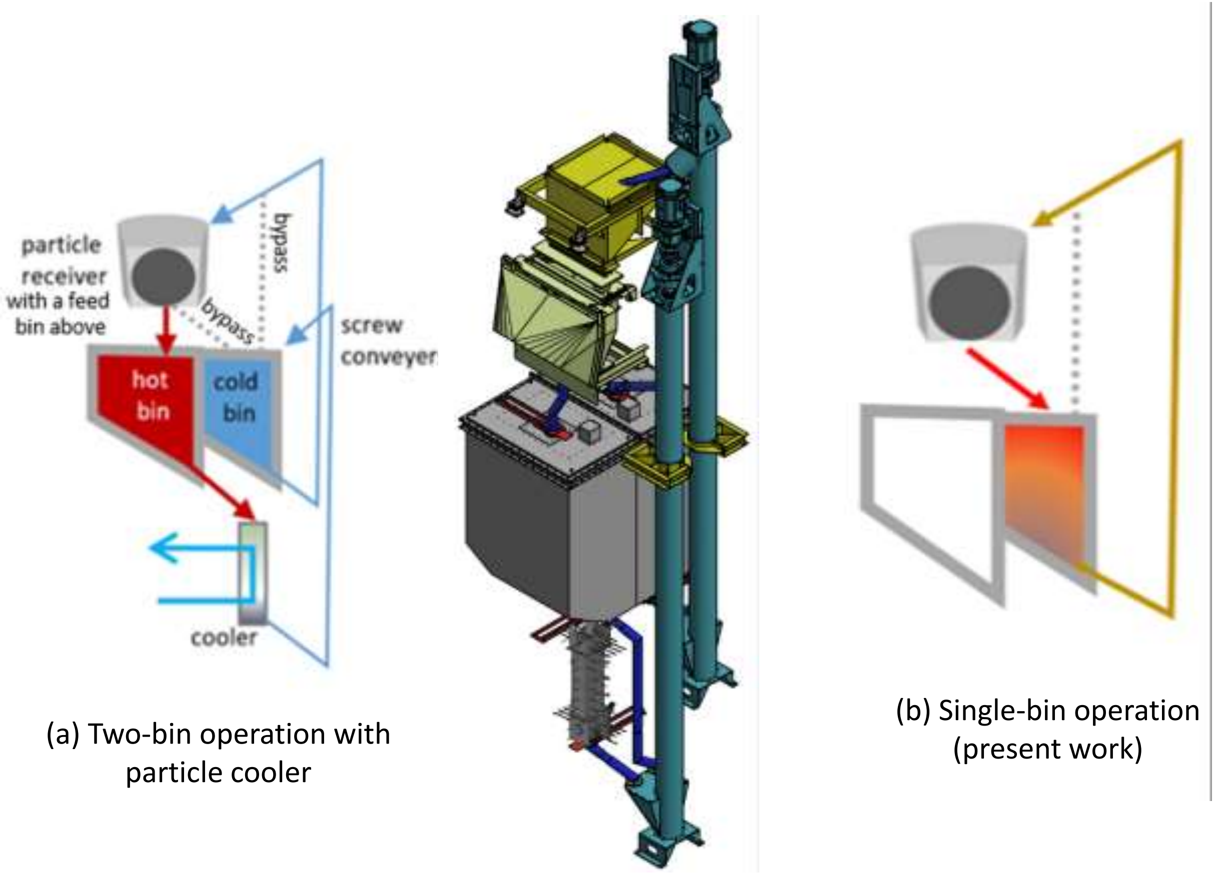
(c) CAD model of particle receiver (casing removed)

(d) Particle falling test

ASTRI demonstration particle receiver

- A 500kW packed-bed heat exchanger for cooling the particles for two-bin operation (left) has been installed

- Experiments considered in the present work (May 2022 to March 2023) used single-bin operation (right) where particles are recirculated without cooling

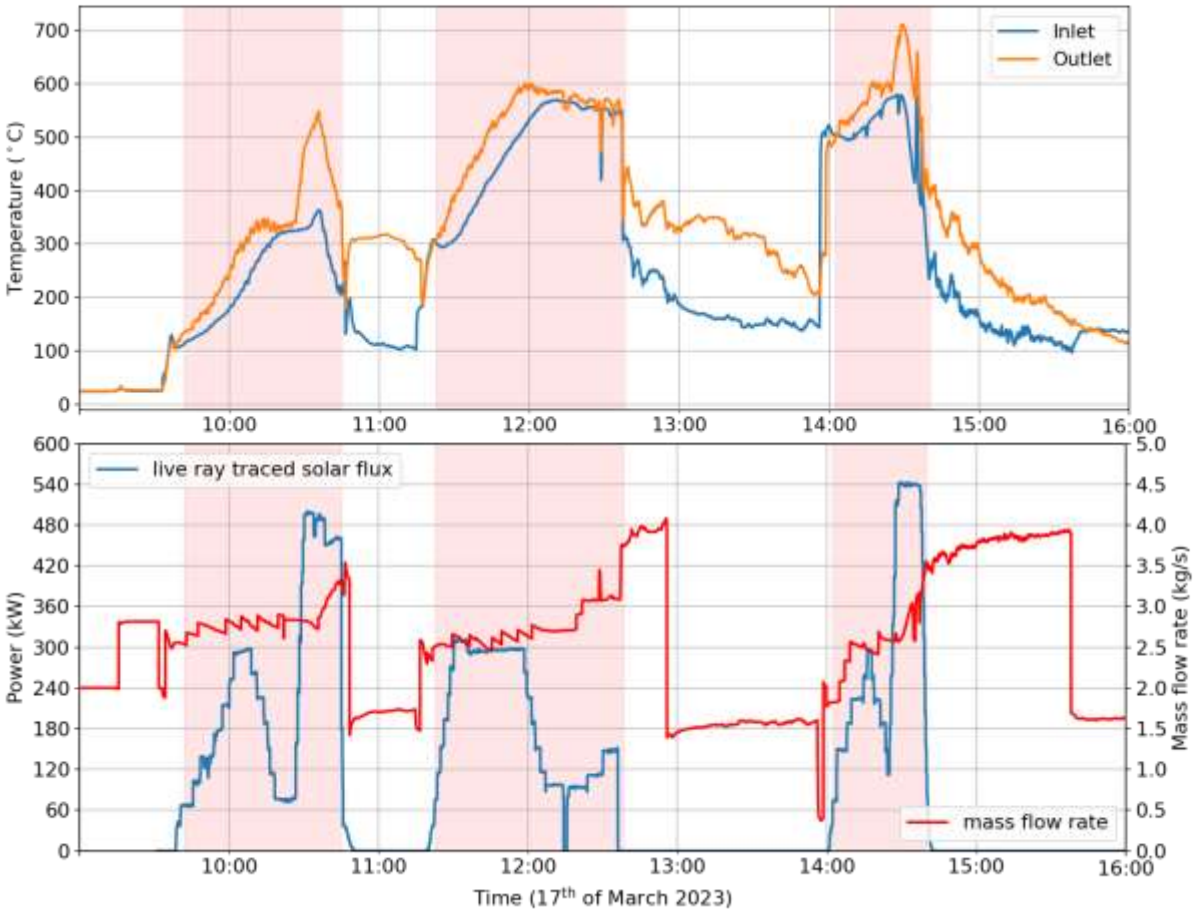


(a) Two-bin operation with particle cooler

(b) Single-bin operation (present work)

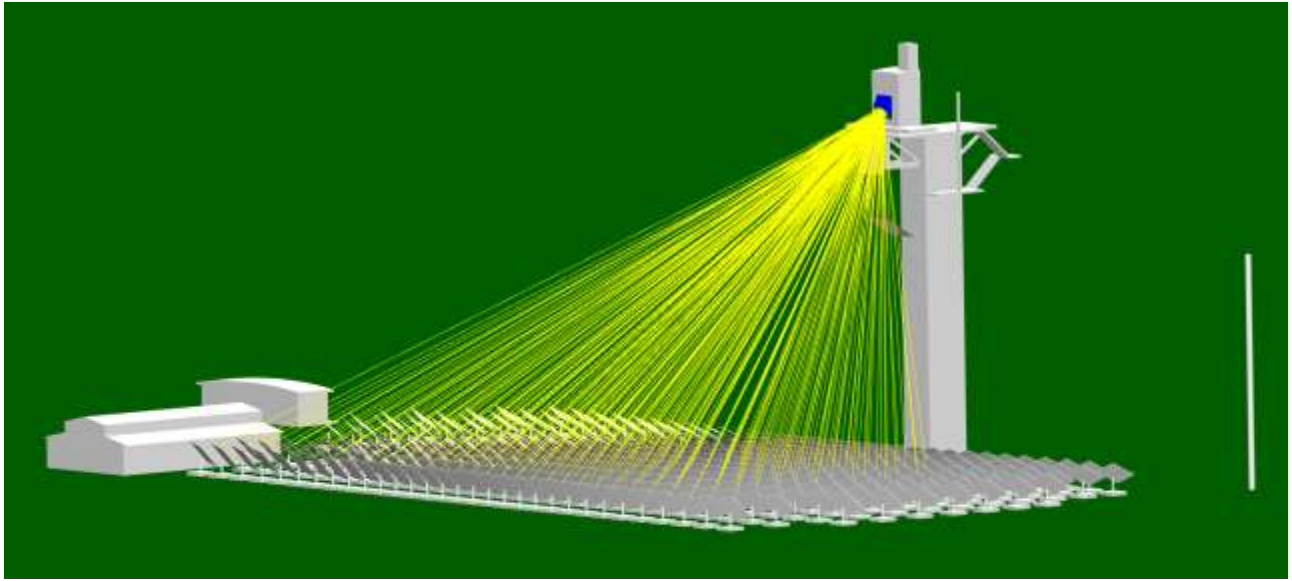
Experiment data

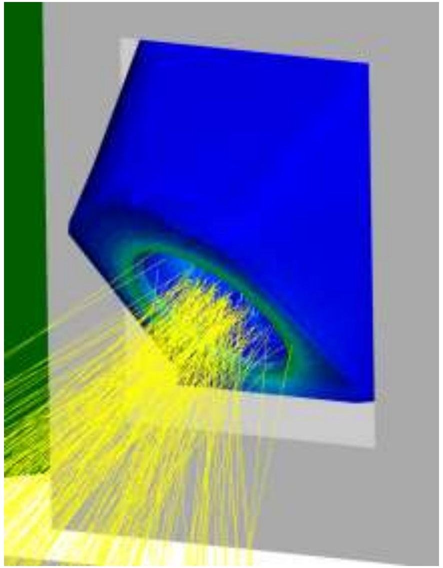
- Key parameters required for computational rebuilding are recorded during experiments:
  - Particle temperature at inlet and outlet
  - Particle mass flow rate
  - DNI
  - Heliostat field utilisation
- Typical day involves operating the receiver for multiple ~1hr runs with breaks in between
- Outlet temperatures reached up to 700°C with $\Delta T \approx 100$°C
- Goal of present work is to rebuild experiments with Heliosim and compare with the measured data



Physical modelling

- Heliostat field optics and receiver heat transfer model created using CSIRO's Heliosim software [1,2]



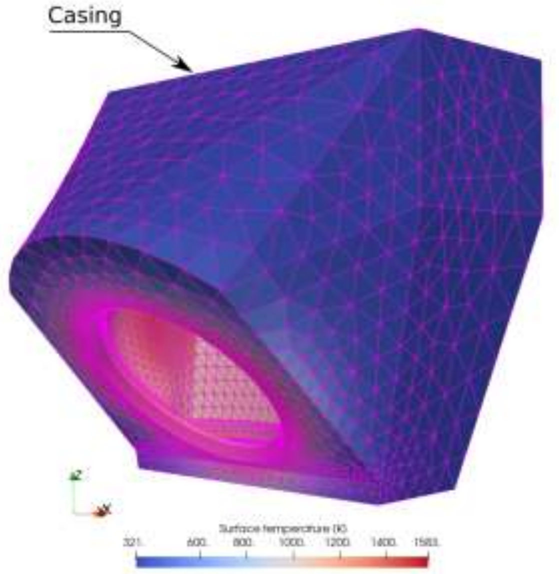


1. D. Potter et al., AIP Conference Proceedings, Nov. 2018, vol. 2033, no. 1, p. 210011, doi: 10.1063/1.5067213.

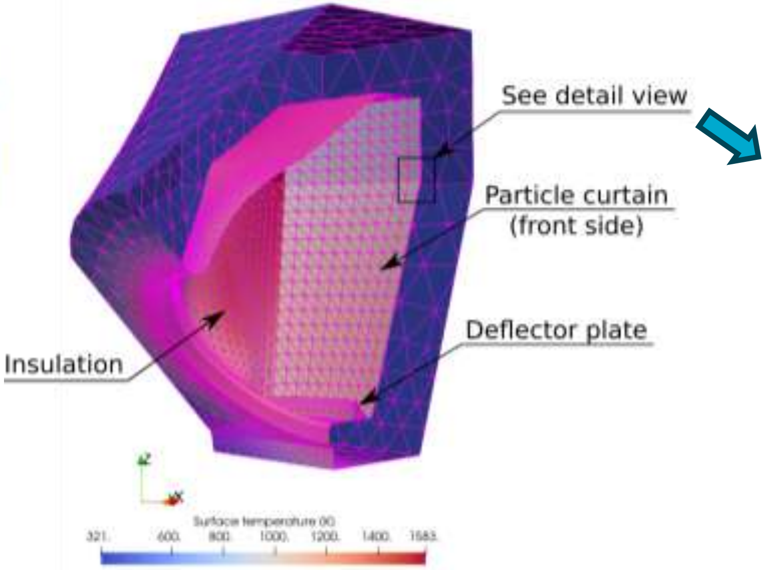
2. D. Potter, "The Heliosim software family: modelling, design, and control tools for CST systems," in Proceedings of the Asia Pacific Solar Research Conference, 2022.

Receiver modelling

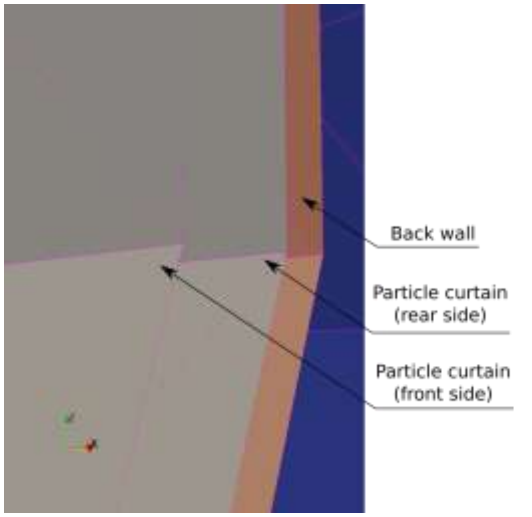
- Surface mesh -based model of receiver with front and rear sides of particle curtain
- Steady state energy balance applied to each mesh facet to solve for temperature



(a) Receiver surface mesh (12 x 10^3 facets)



(b) Receiver surface mesh clipped in symmetry plane

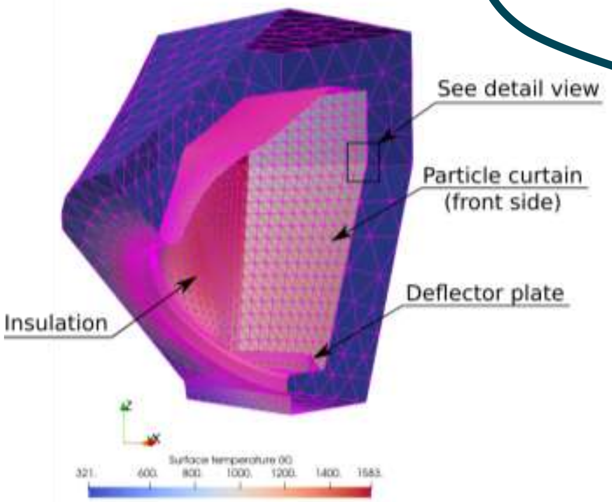


(c) Particle curtain and back wall detail

Receiver modelling

<u>Receiver heat transfer mechanisms</u>

- Solar and thermal radiation heat transfer
- Convective heat loss due to ambient air flow
- Conduction through walls
- Transport of thermal energy by particle advection

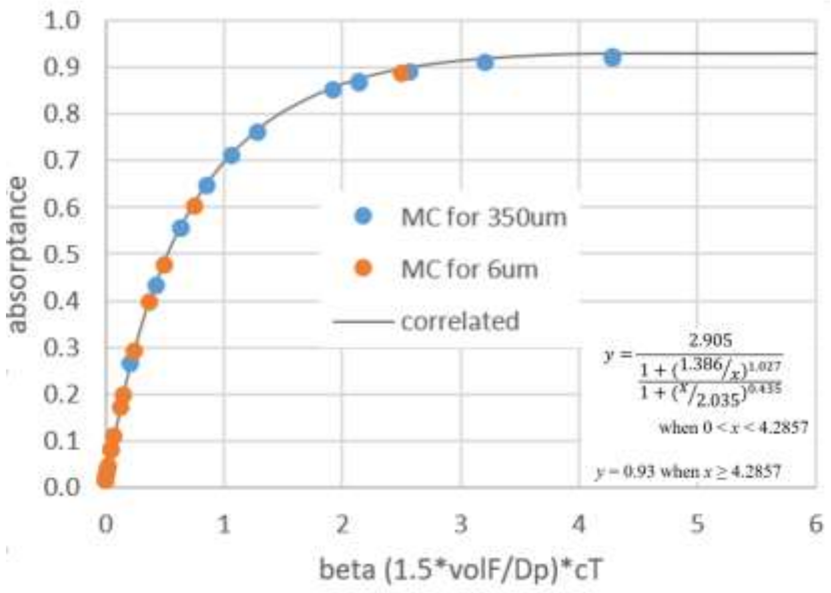


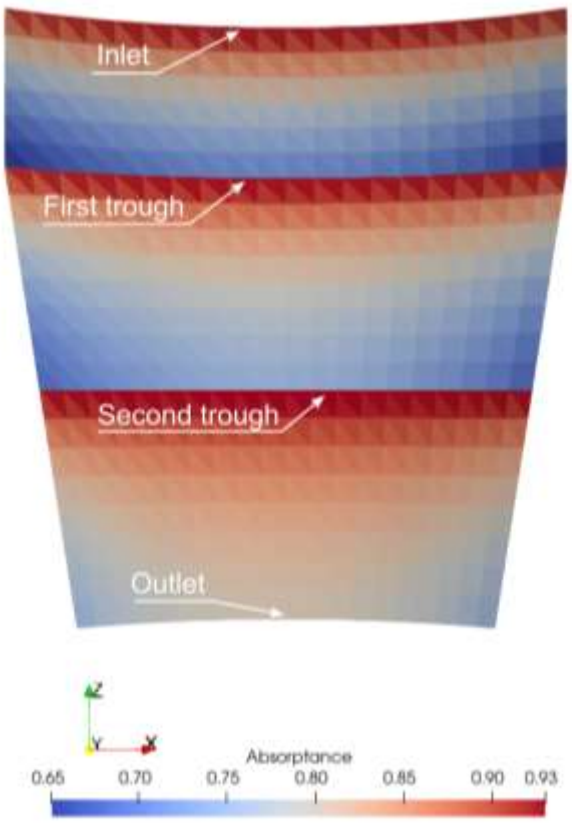
<u>Particle curtain model</u>

- Divided into multiple vertical "channels" with equal mass flow rate
  - ➢ Mixing between adjacent channels is assumed to be negligible
  - ➢ Drag not considered
- Constant temperature assumed through the curtain thickness
- Optical properties are calculated using correlations

Curtain optical properties

- Correlations fitted to detailed Monte Carlo ray tracing simulations [1] for various curtain thicknesses, particle diameters and particle volume fractions



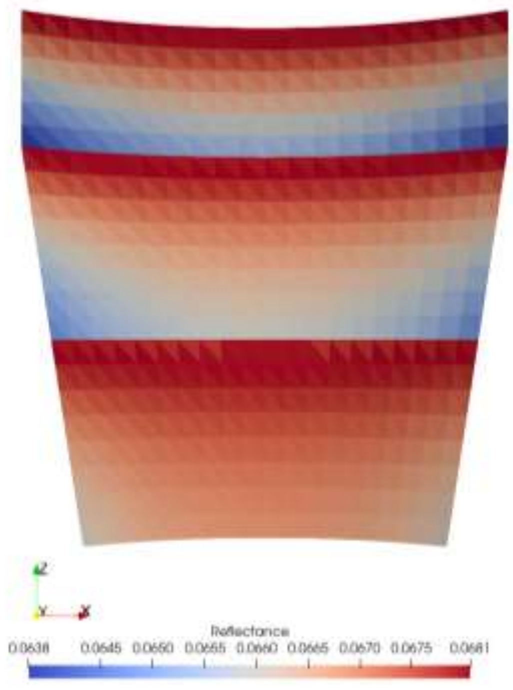


One-way solar absorptance at design point (2.73kg/s)

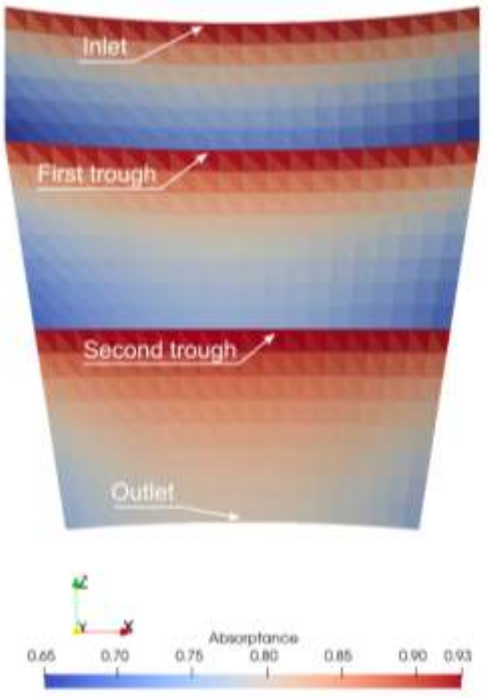
[1] A. Kumar et al., *J. Sol. Energy Eng. Trans. ASME*, vol. 140, no. 6, 2018, doi: 10.1115/1.4040290.

Curtain optical properties

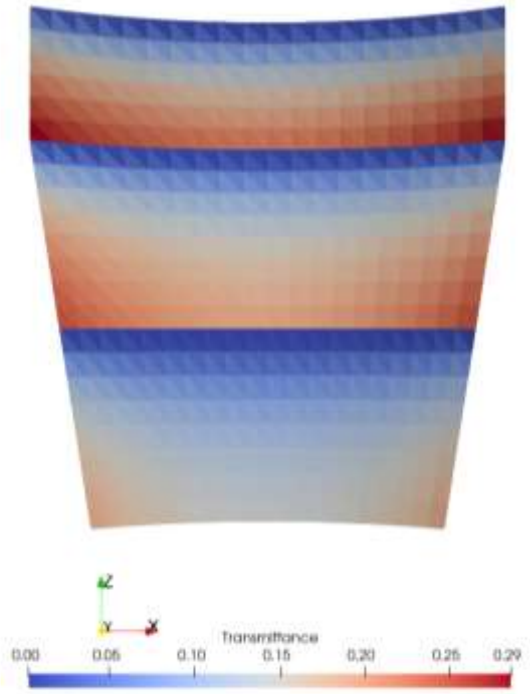
- One-way optical properties at design point (2.73kg/s):



(a) Diffuse reflectance
(average of 0.0668)



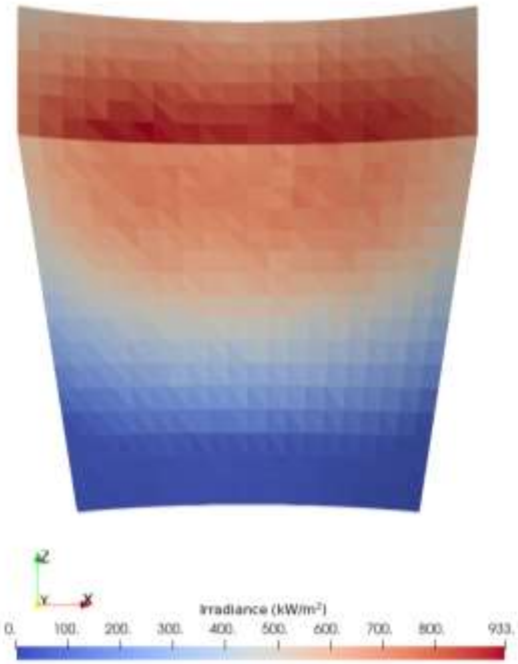
(b) Absorptance
(average of 0.8039)



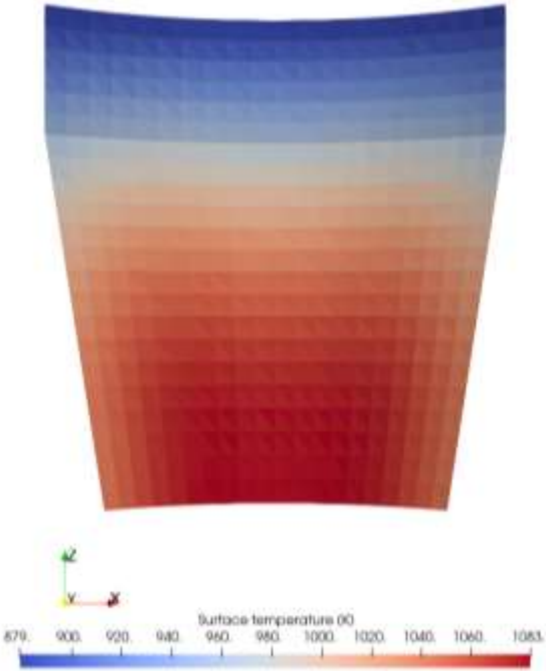
(c) Transmittance
(average of 0.1292)

Curtain optical properties

- Particle curtain and back wall temperature distributions at design point conditions:



(a) Particle curtain incident solar irradiance

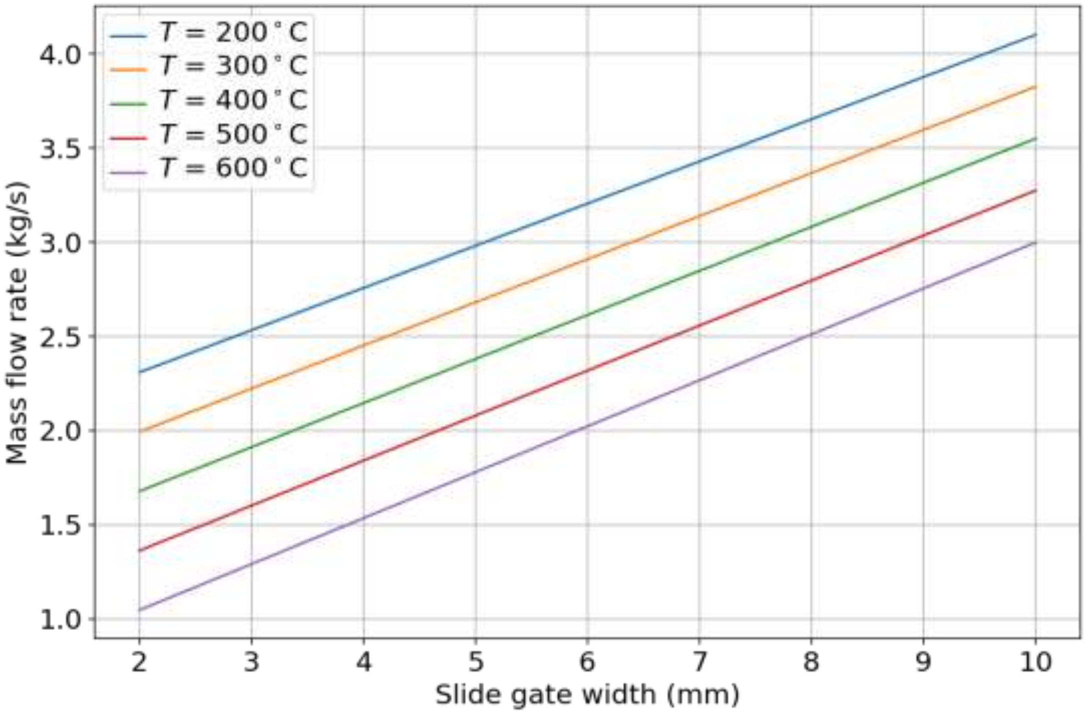


(b) Particle curtain temperature

(c) Back wall temperature

Mass flow rate correlation

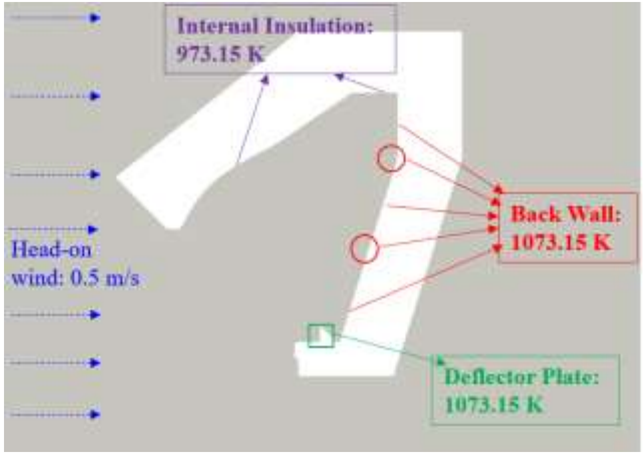
- Designed method for mass flow rate determination was measuring change in feed hopper mass over a fixed time interval using a load cell
- Thermal expansion issues made this method unreliable at high temperatures (≥ 400°C)
- After this issue was fixed in 2023, a correlation was made to calculate mass flow rate as a function of slide gate width and particle inlet temperature [1]

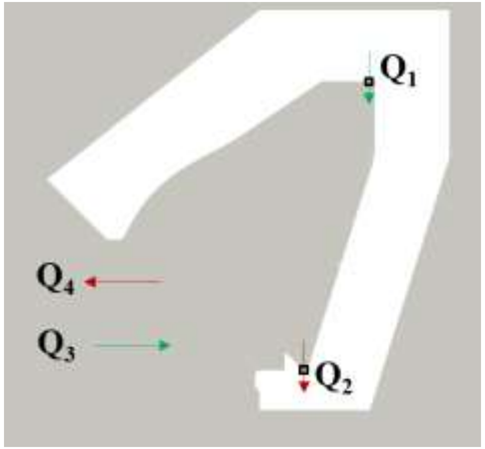


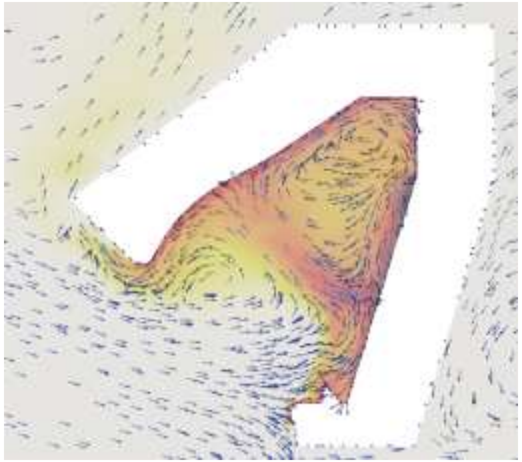
[1] G. R. Drewer, J. Kim, and D. Potter, "The Importance of Managing the Performance of Particle Lift and Flow Control Systems in Research CST Plants to Facilitate Commercialization," presented at SolarPACES 2023.

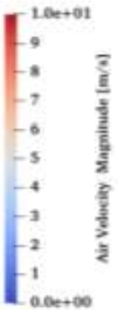
Convective heat loss

- ‘Coarse-grained’ CFD-DPM simulations performed using OpenFOAM [1]
- Fixed wall and particle temperatures
- Particle flow rate was varied from 5 million particles/s (0.4 kg/s) to 30 million particles/s (2.4 kg/s)
- Net convective heat loss computed as $Q_4 + Q_2 - Q_1 - Q_3$

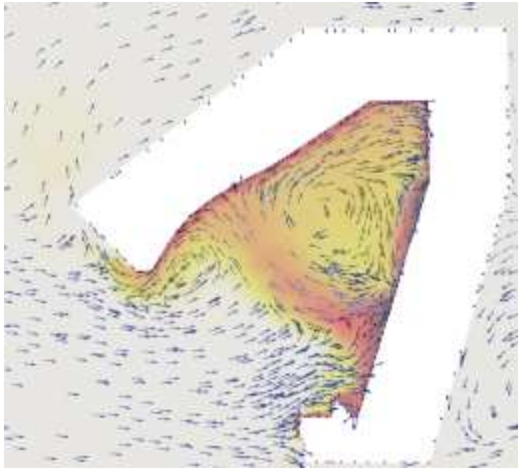


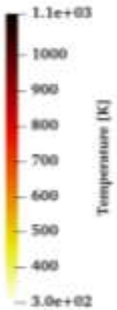






(a) 10 million particles/s (0.81 kg/s)





(b) 20 million particles/s (1.62 kg/s)

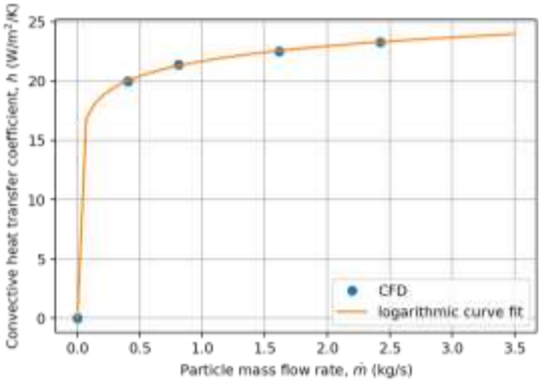
1. Kuruneru et al. (2022). *Energy Reports*, *8*, 3902–3918. https://doi.org/10.1016/j.egyr.2022.03.034

Convective heat loss coefficients

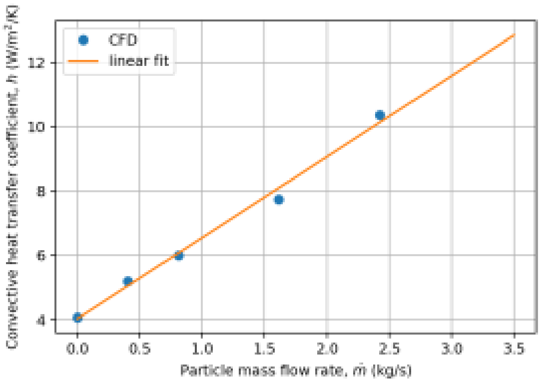
- Convective heat loss coefficients for each receiver surface computed from CFD-DPM heat flux results:

$$h = \frac{q}{A(T - T_a)}$$

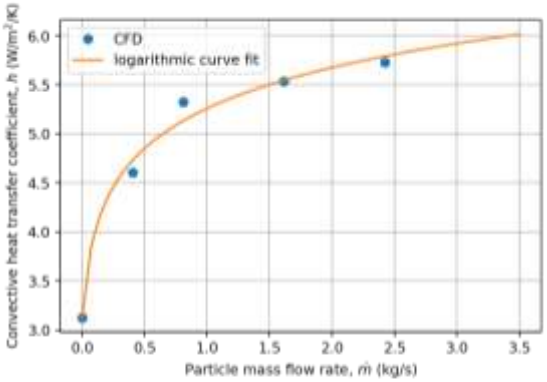
- Correlations for convective heat loss coefficients as a function of mass flow rate determined by fitting to CFD-DPM results using logarithmic expressions



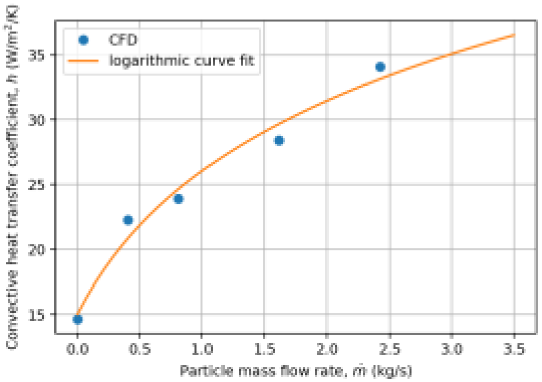
(a) Particle curtain (single-sided area)



(b) Back wall

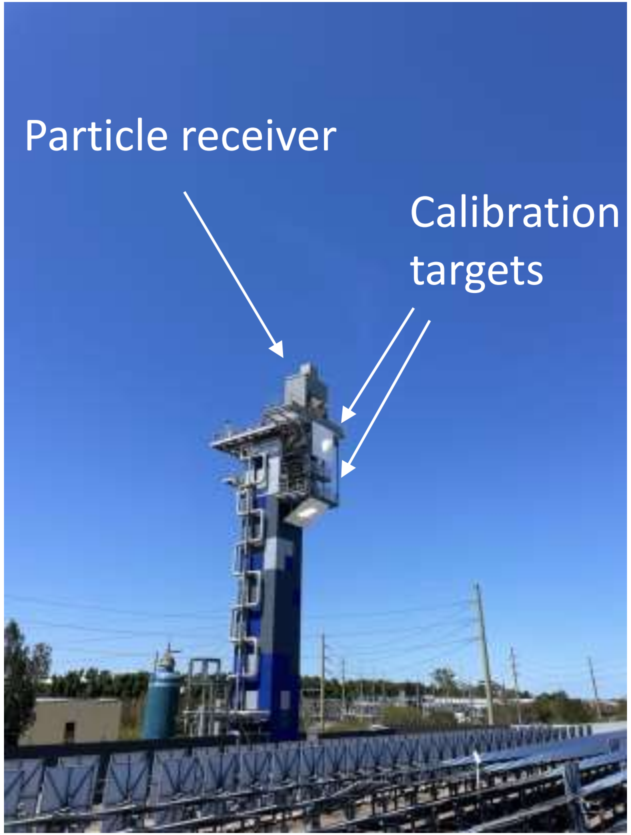


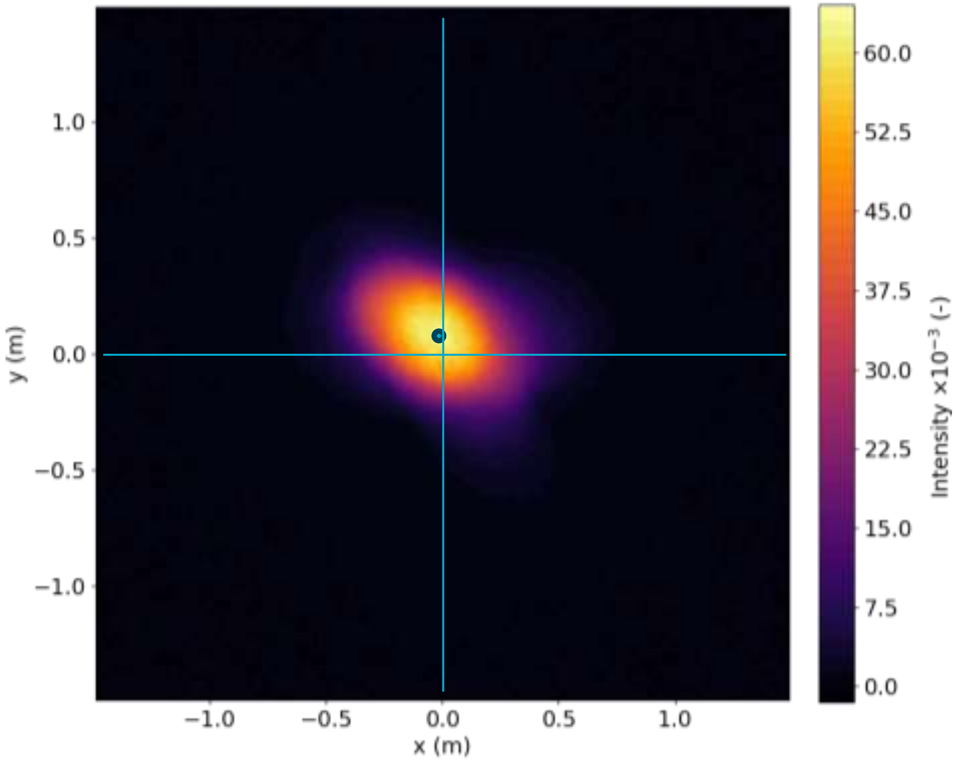
(c) Insulation



(d) Deflector plate

Tracking error measurements

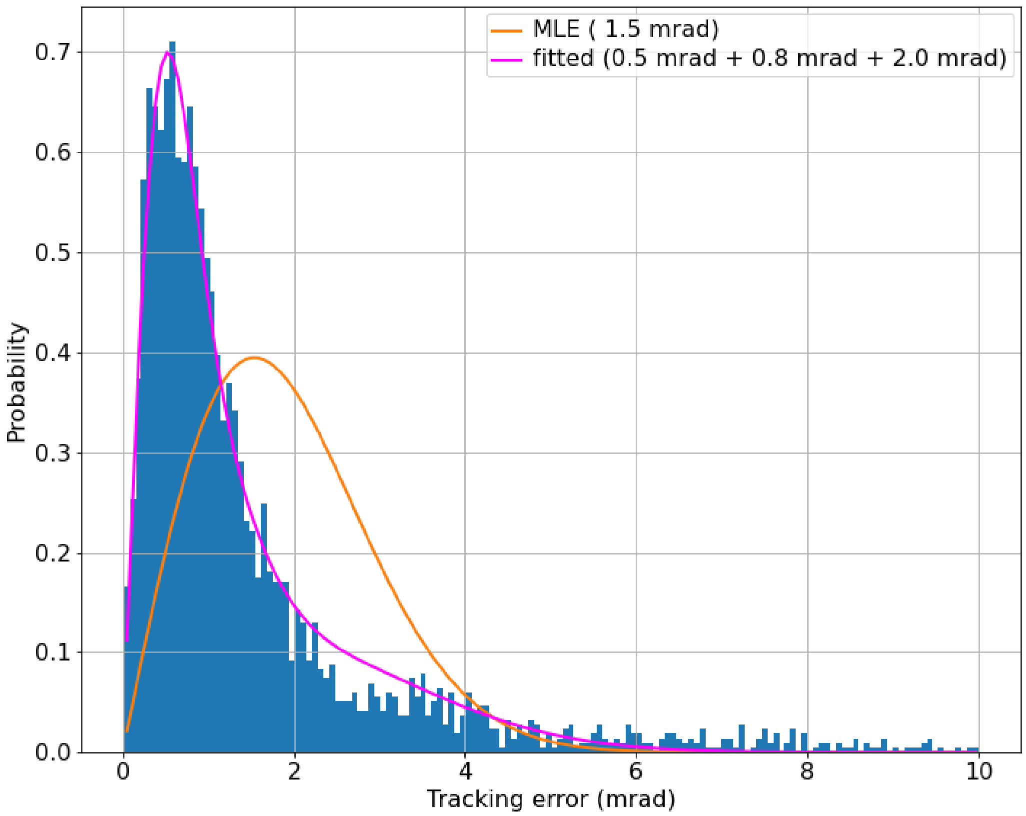




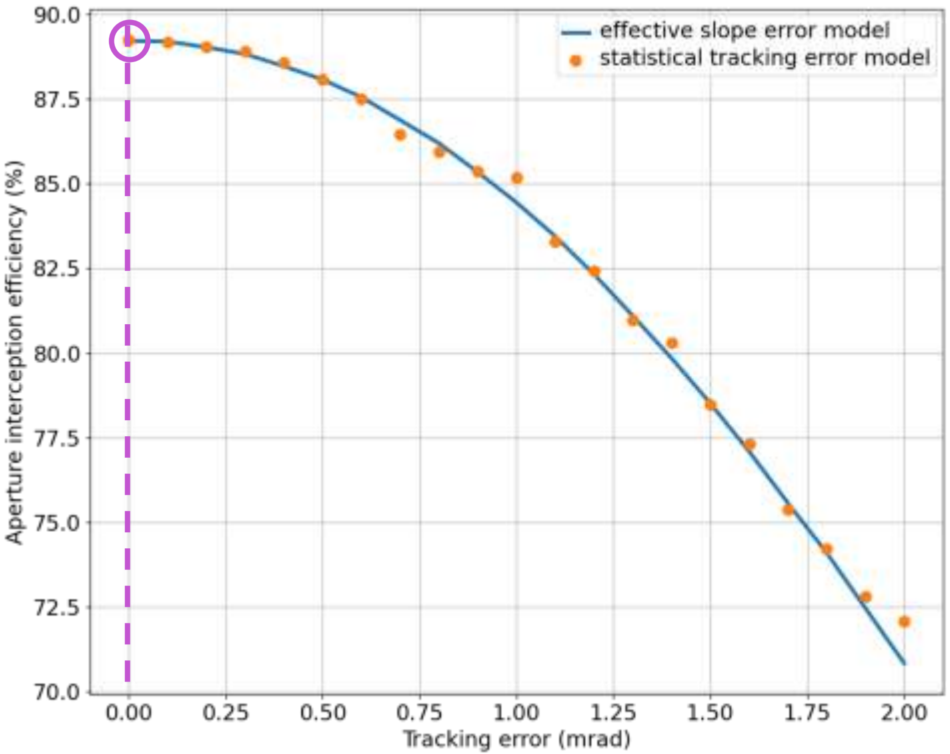
Typical heliostat image on target just prior to calibration procedure

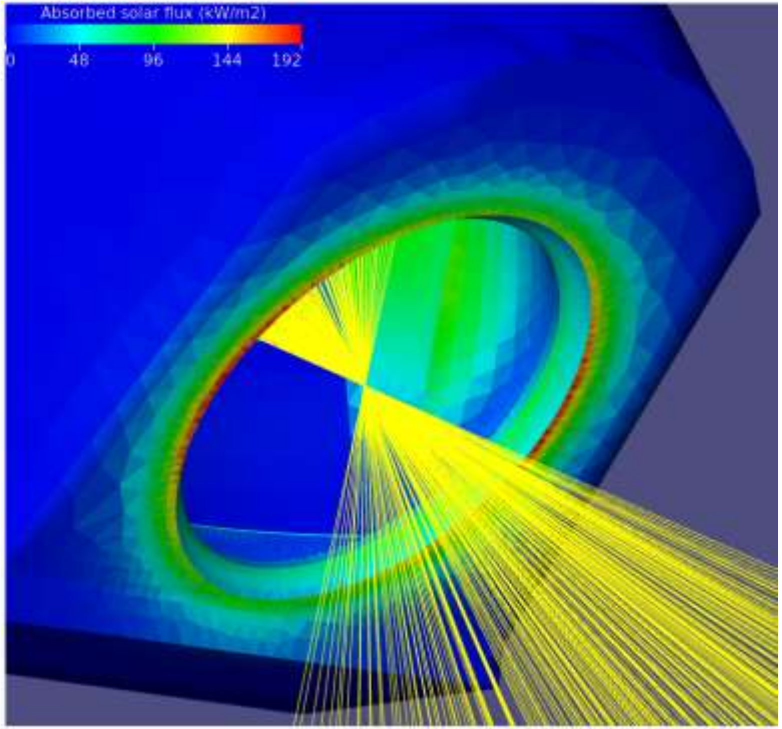
Tracking error measurements

- 3314 calibration images acquired between November 2021 and May 2023
- Tracking errors greater than 10mrad discarded (56 cases)
- Probability histogram is well described by a combination of multiple (3) evenly weighted Rayleigh distributions
- Multiple Rayleigh distribution model has yet to implemented in Heliosim, therefore tracking error is varied between 0.5 and 1.5mrad to gauge sensitivity



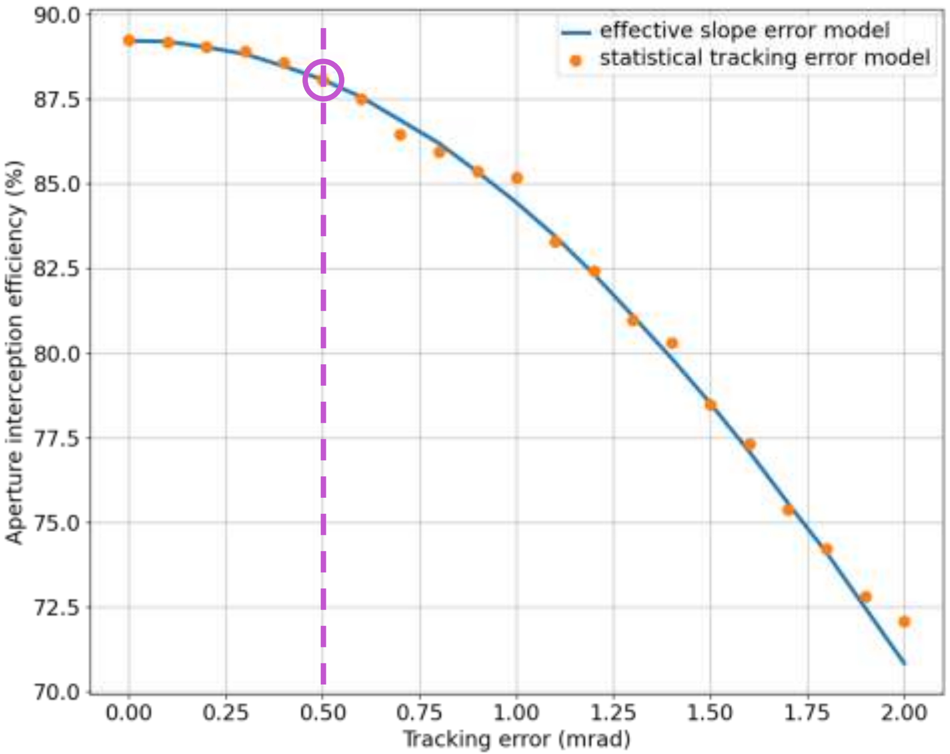
Tracking error modelling

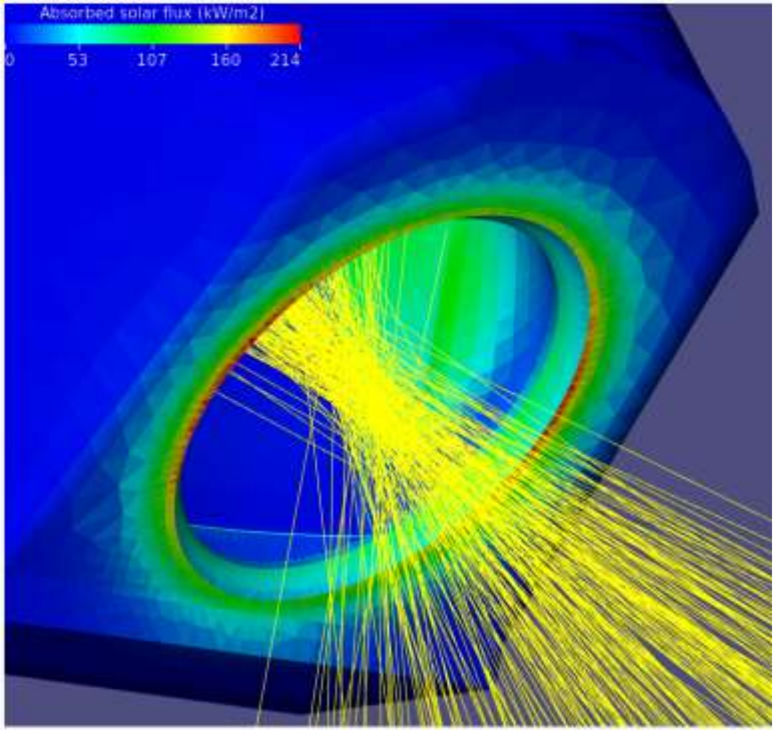




0 mrad

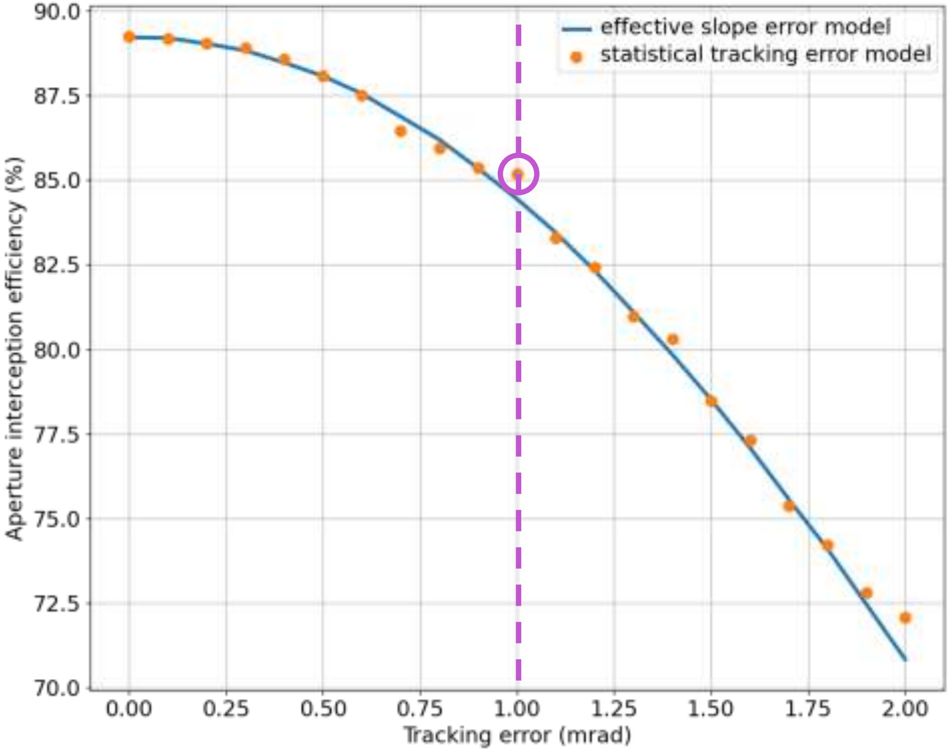
Tracking error modelling

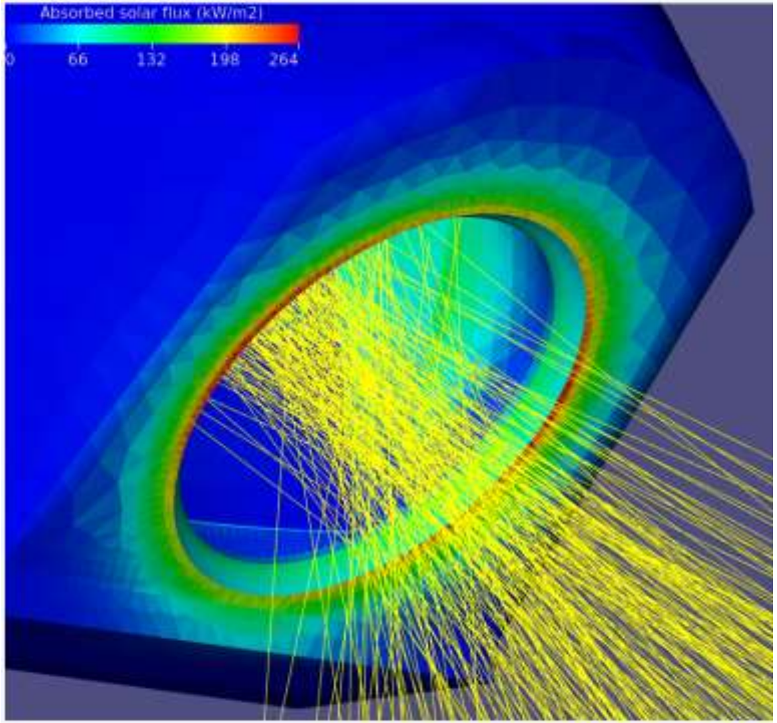




0.5 mrad

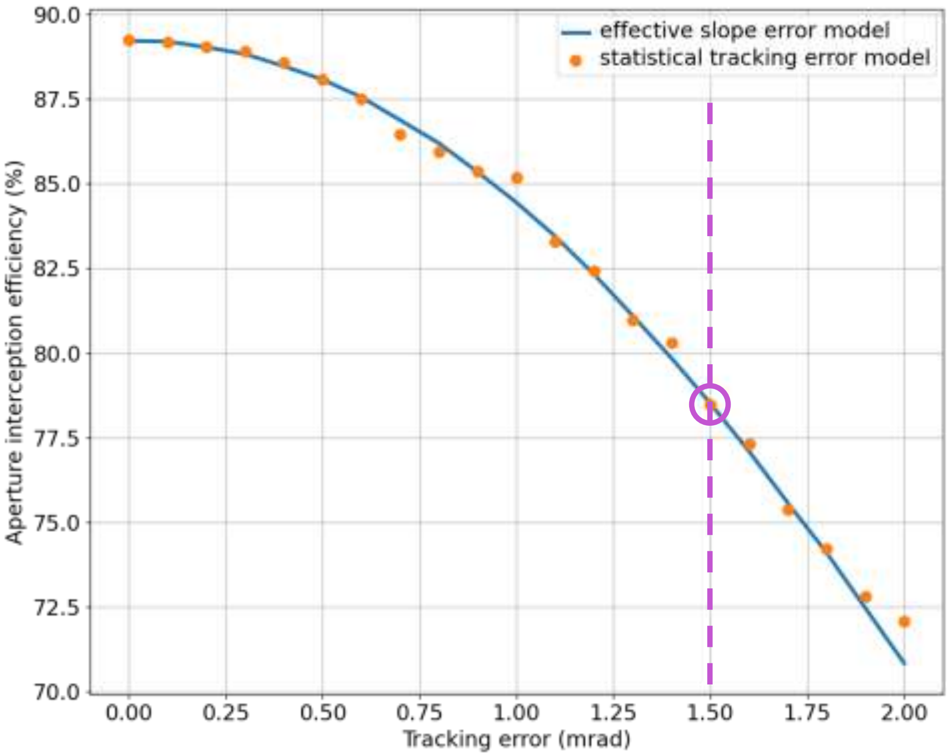
Tracking error modelling

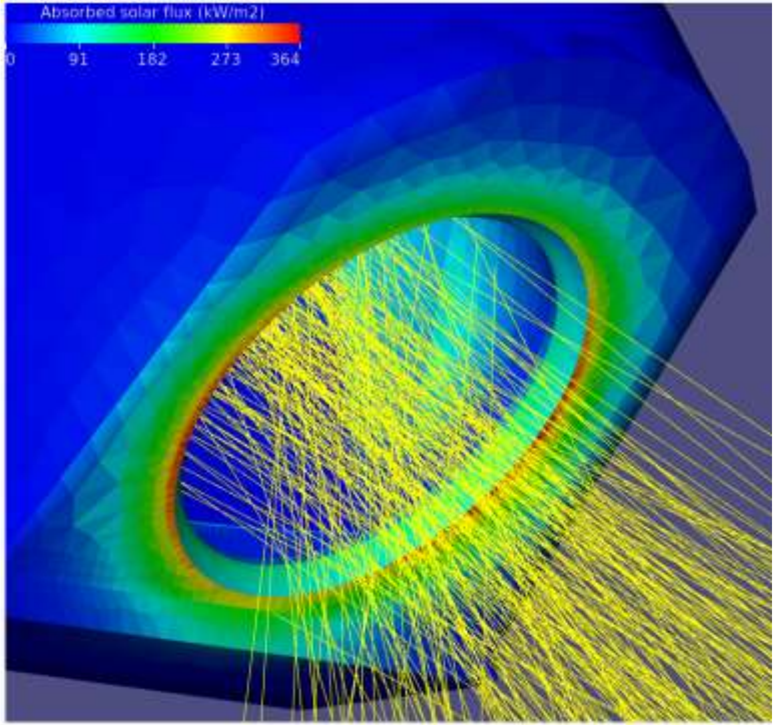




1.0 mrad

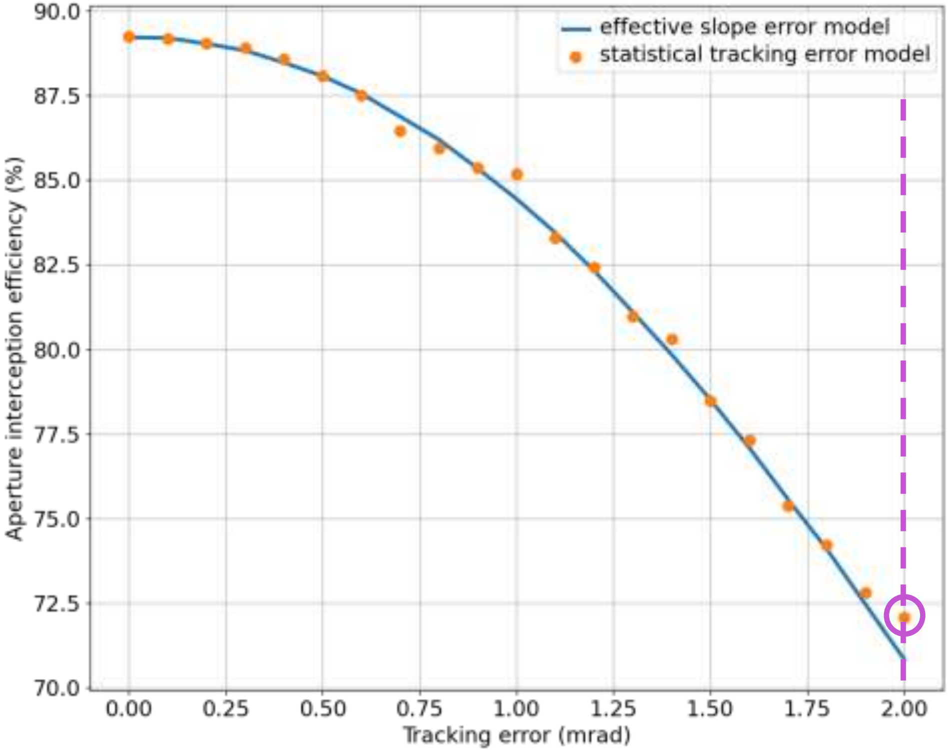
Tracking error modelling

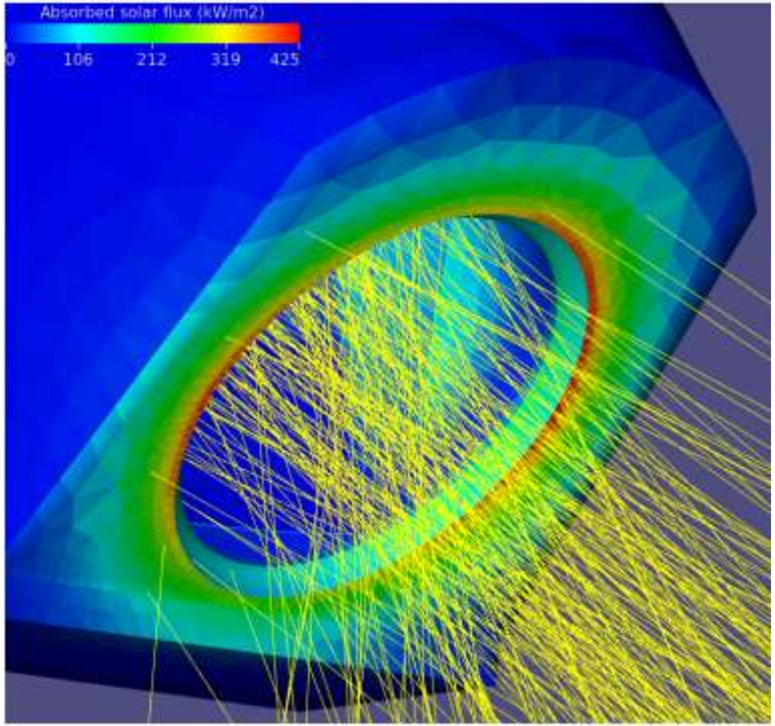




1.5 mrad

Tracking error modelling

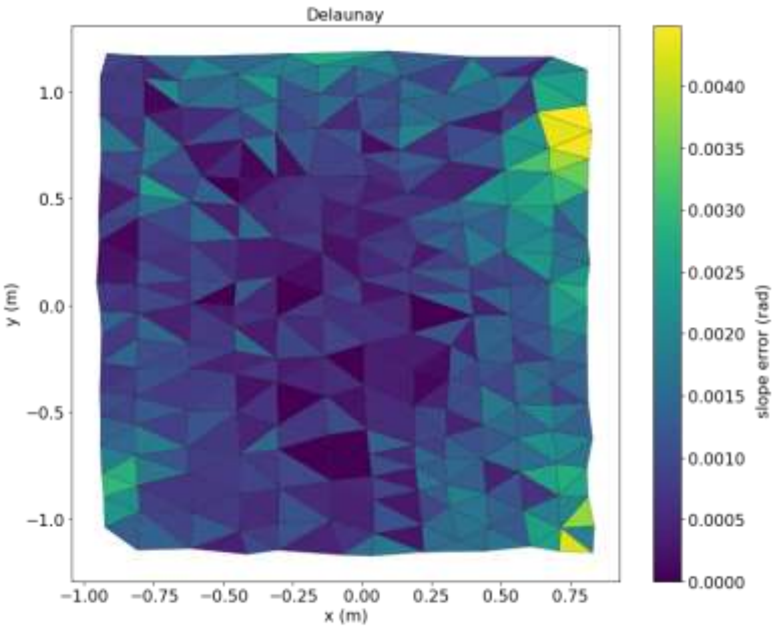




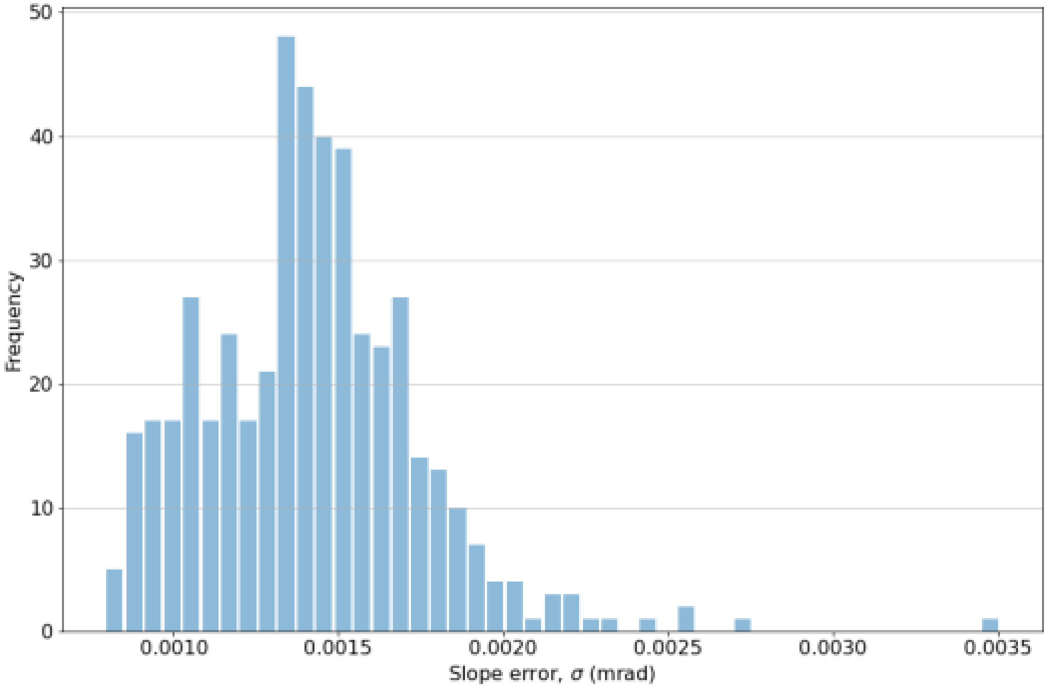
2.0 mrad

Heliostat facet modelling

- 90% specular reflectance assumed
- Slope error of 1.4mrad used based on analysis of surface metrology data for Solar Field 2 heliostats

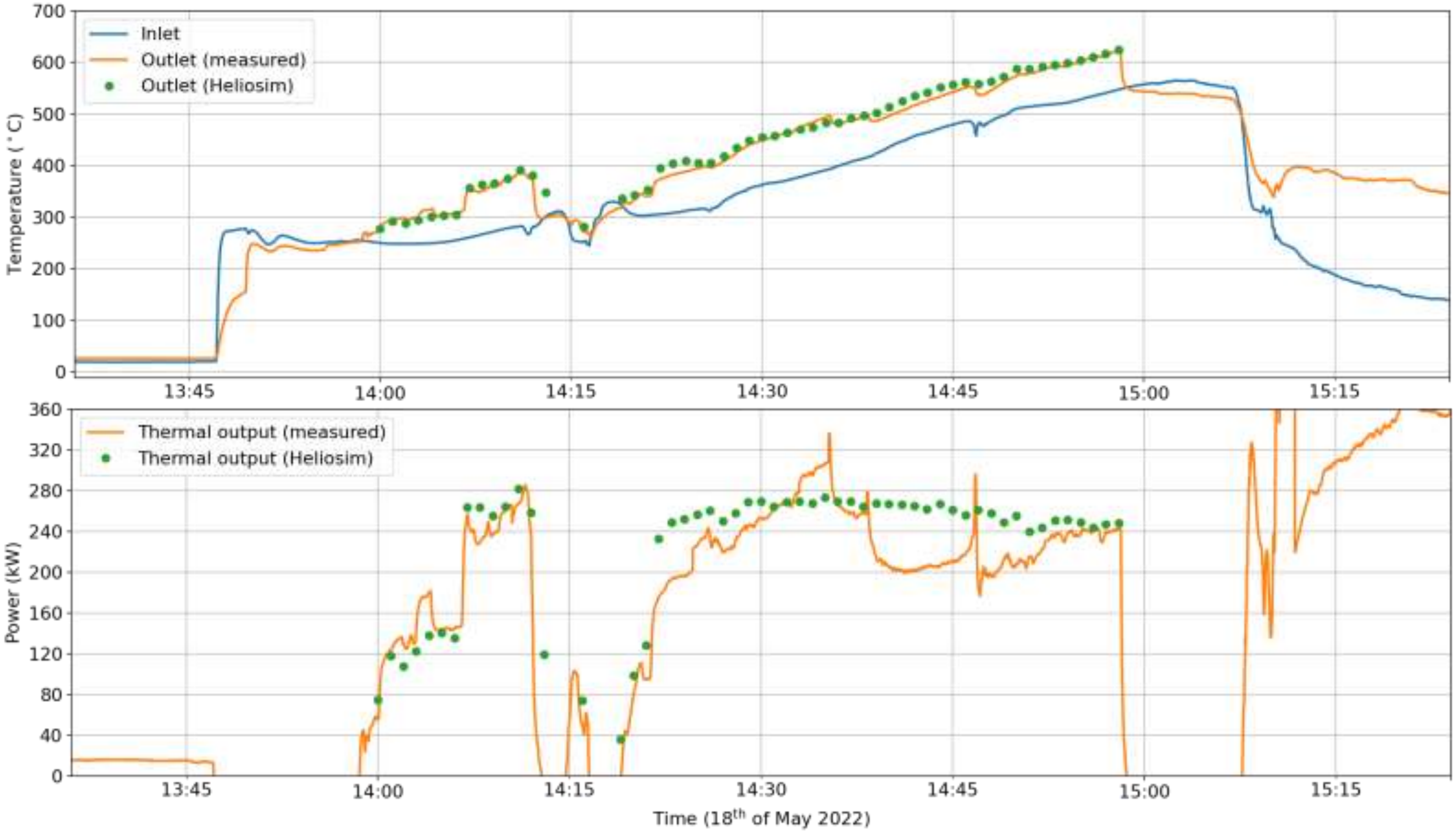


(a) Example of surface mesh constructed from measured facet coordinates

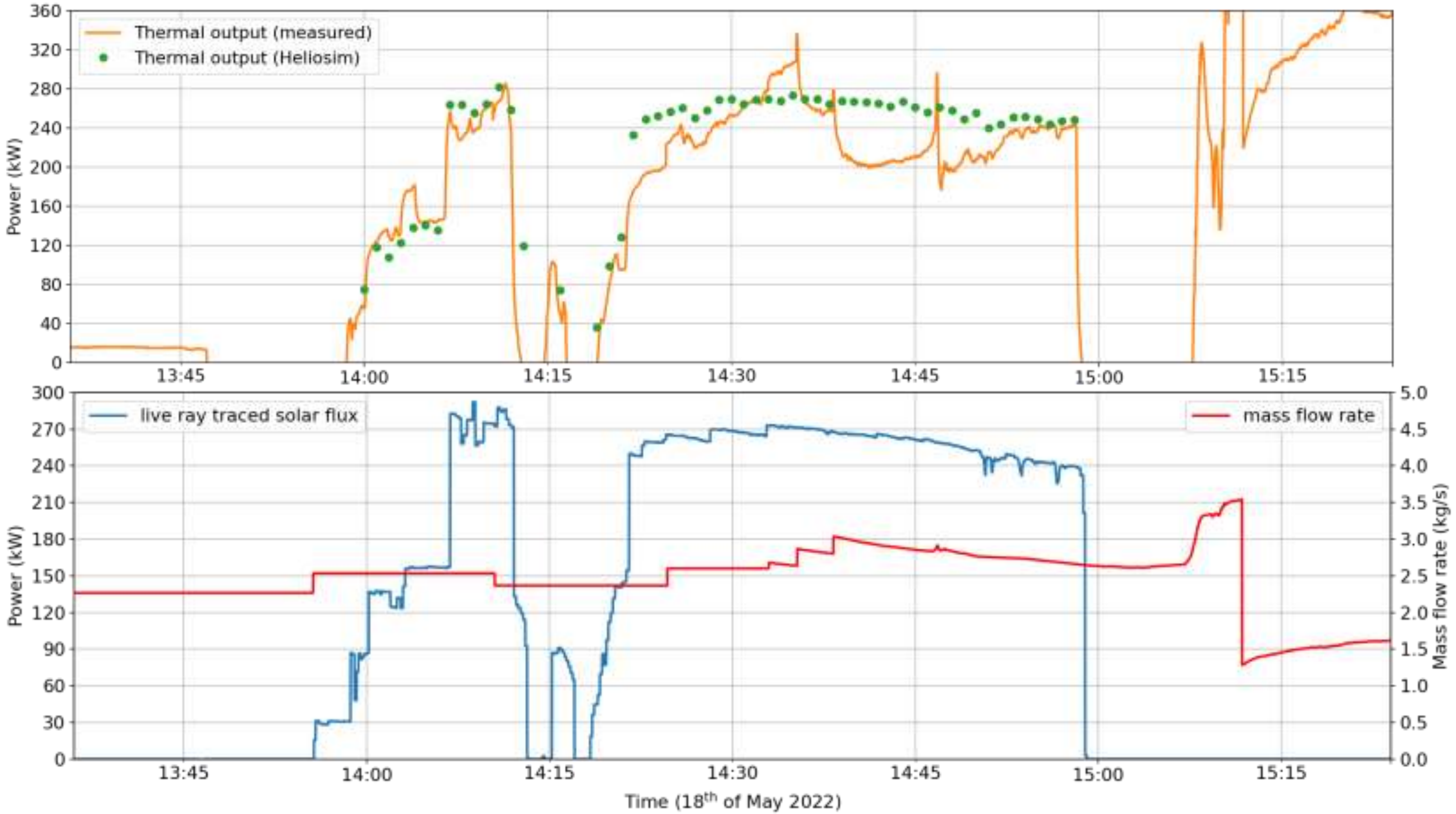


(b) Histogram of average facet slope error for Solar Field 2 heliostats

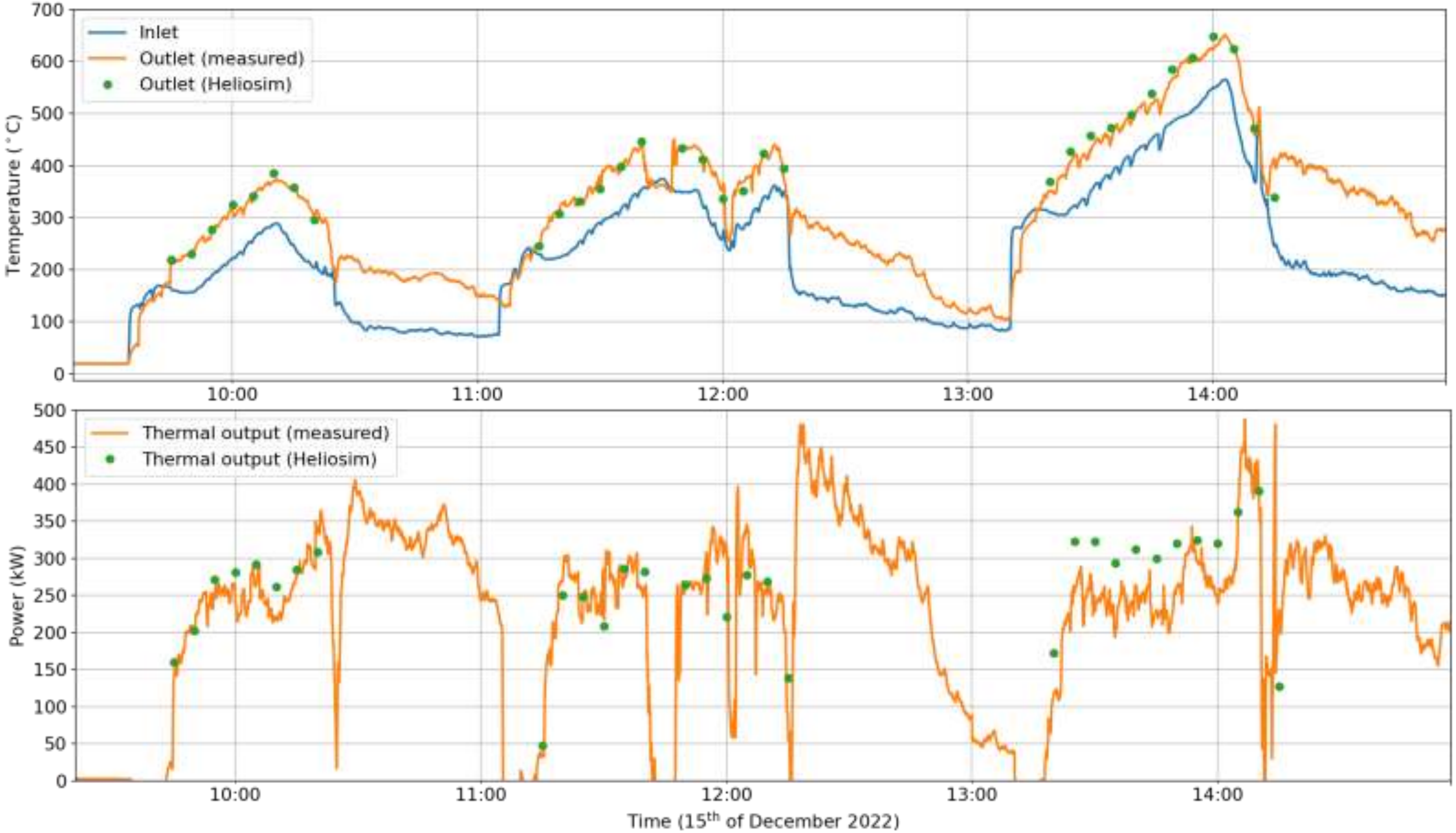
Results – 18th of May 2022



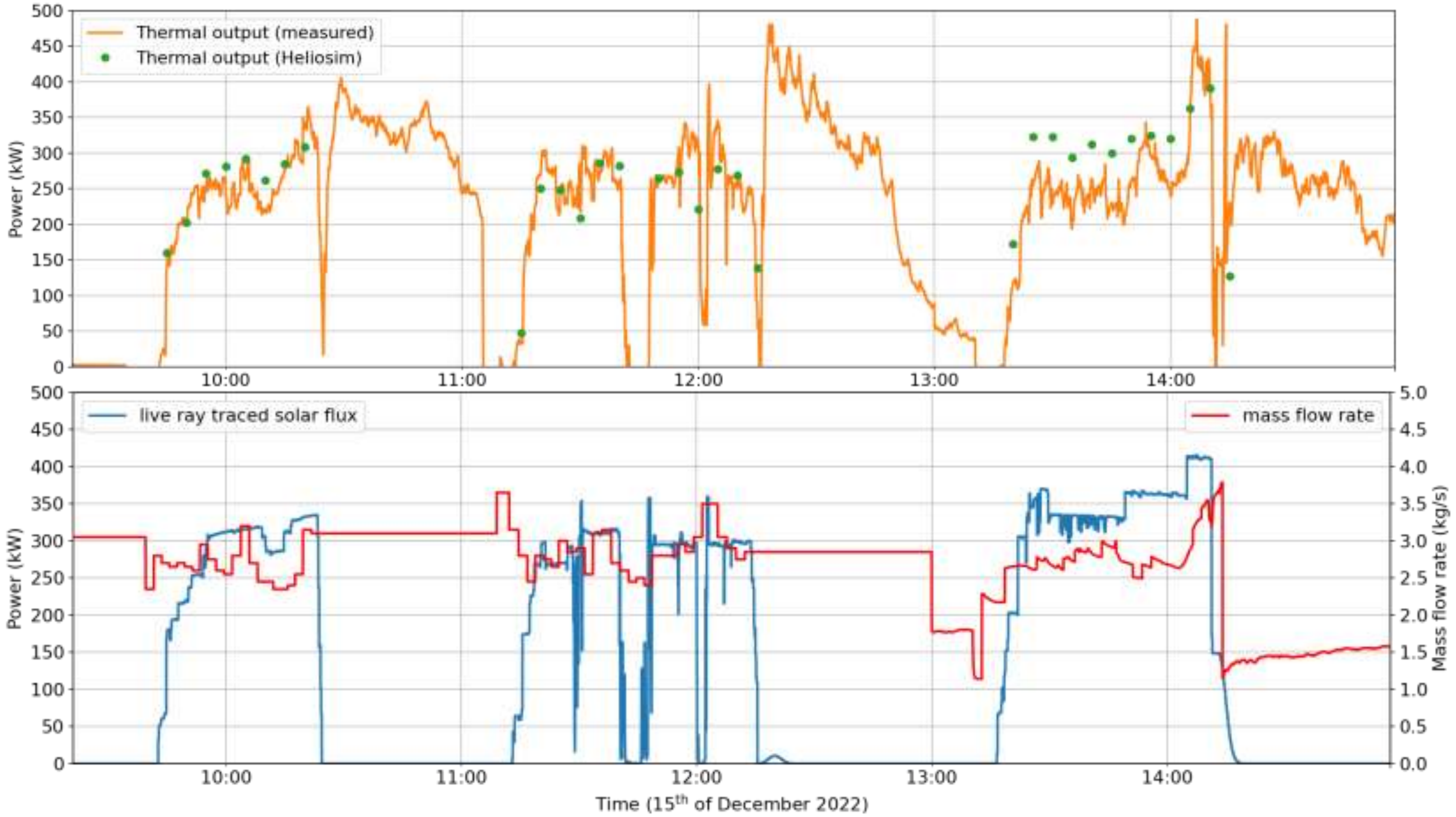
Results – 18th of May 2022



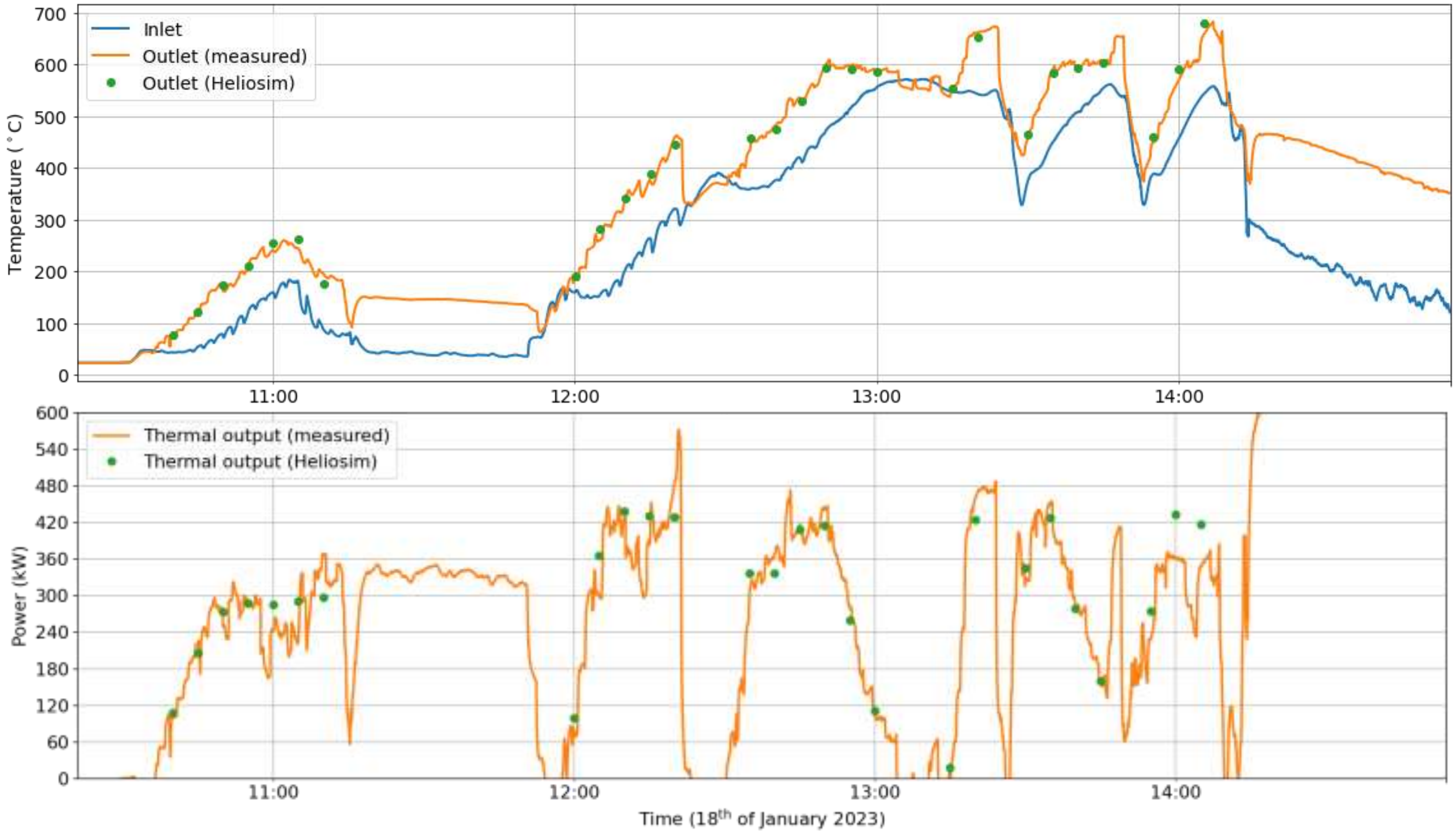
Results – 15th of December 2022



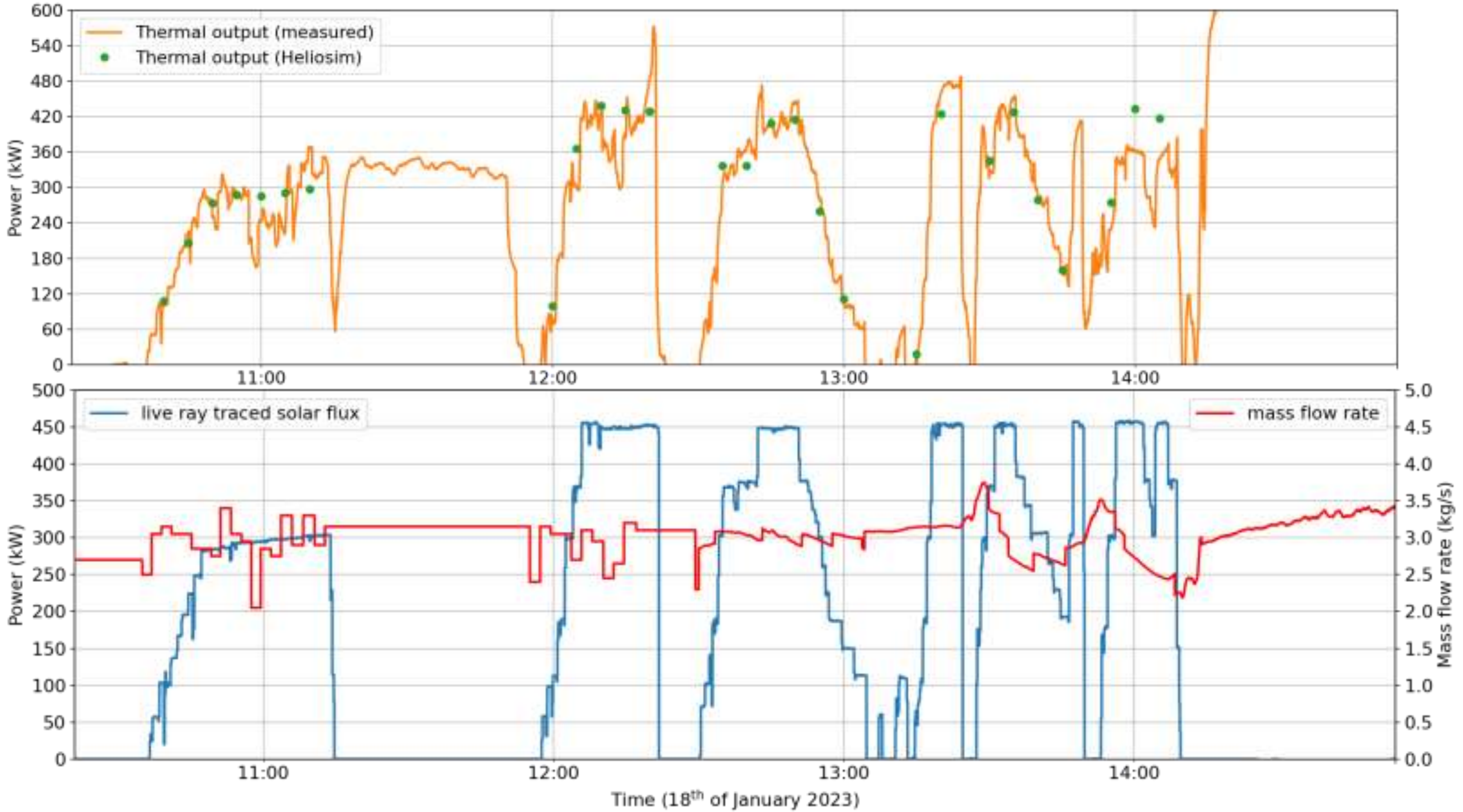
Results – 15th of December 2022



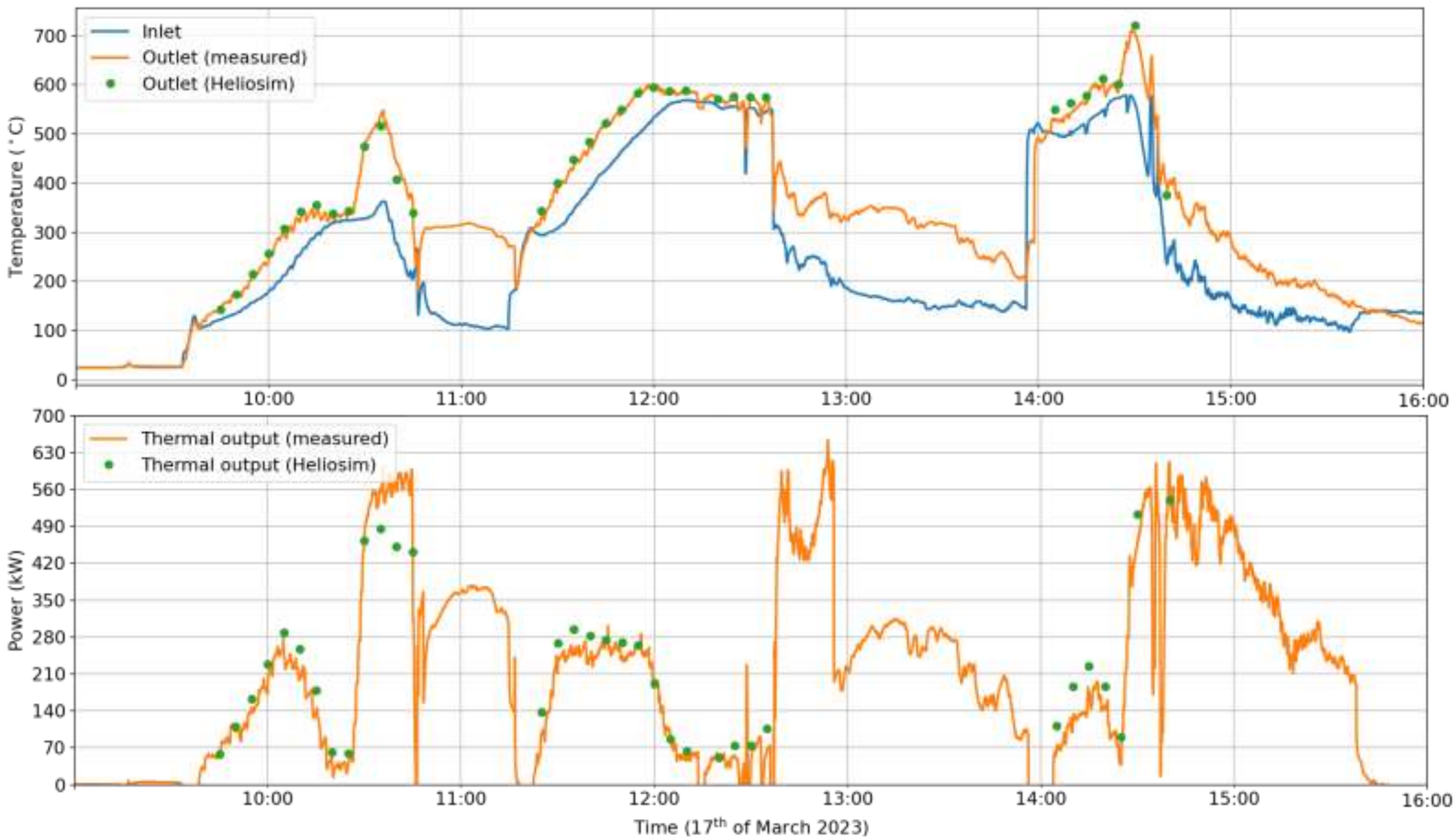
Results – 18th of January 2023



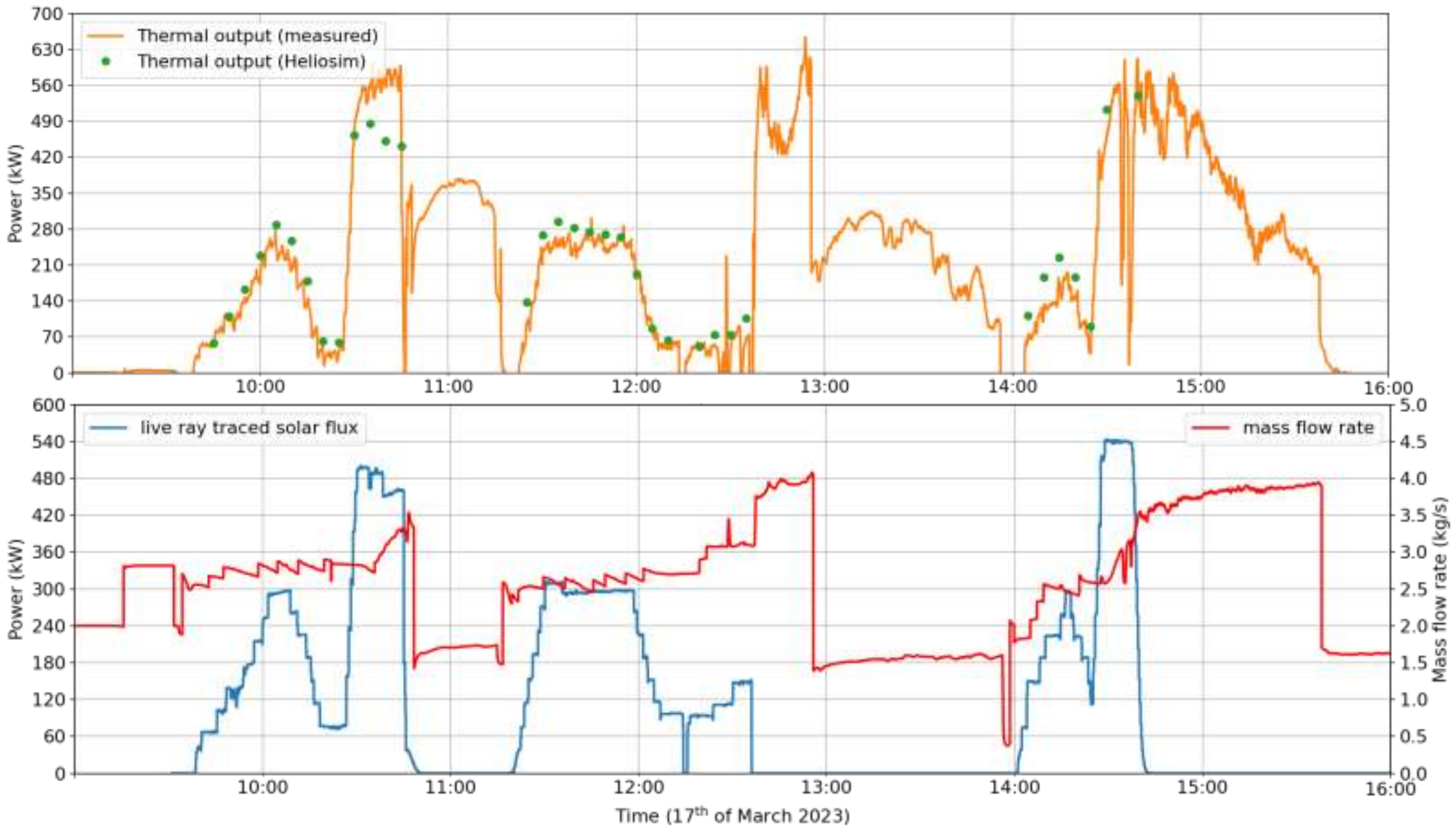
Results – 18th of January 2023



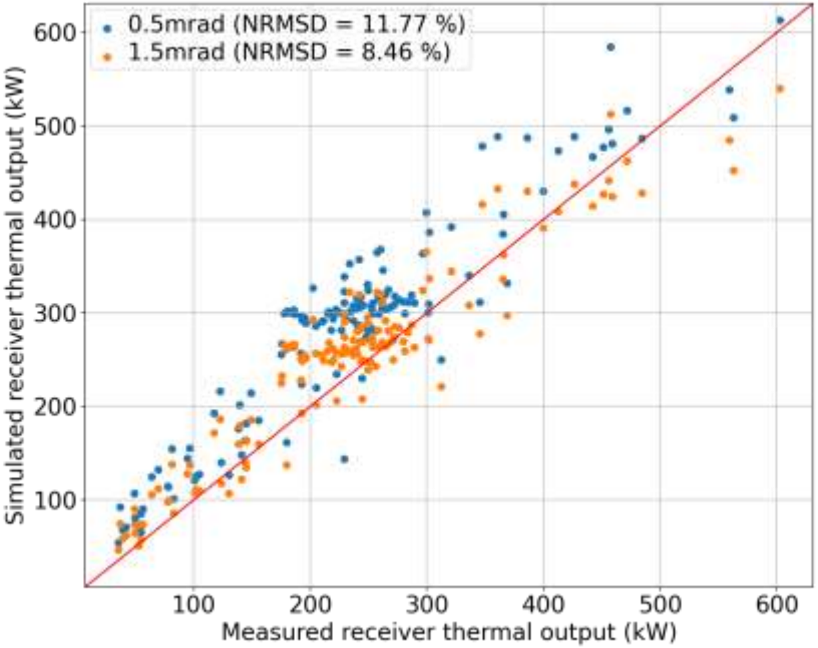
Results – 17th of March 2023



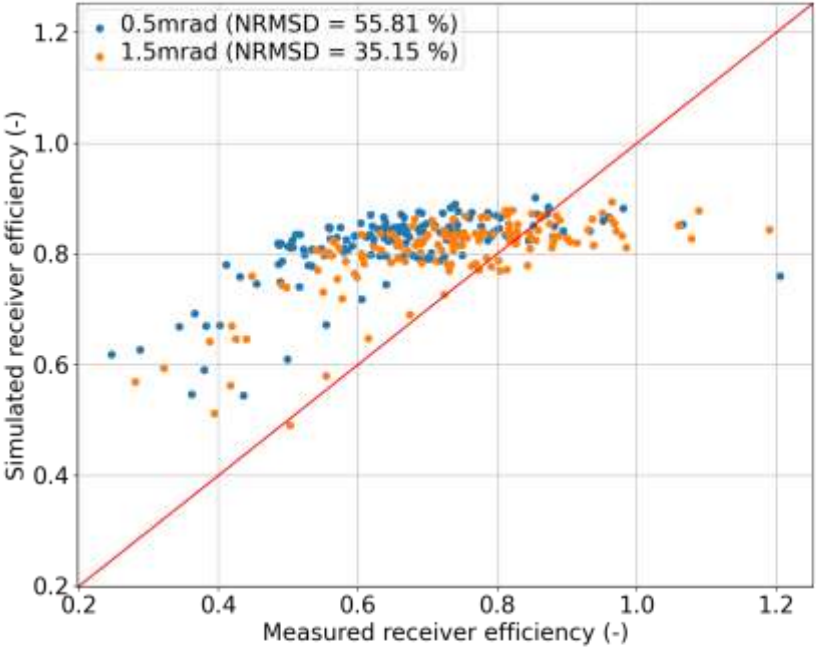
Results – 17th of March 2023



Aggregated results



(a) Thermal output

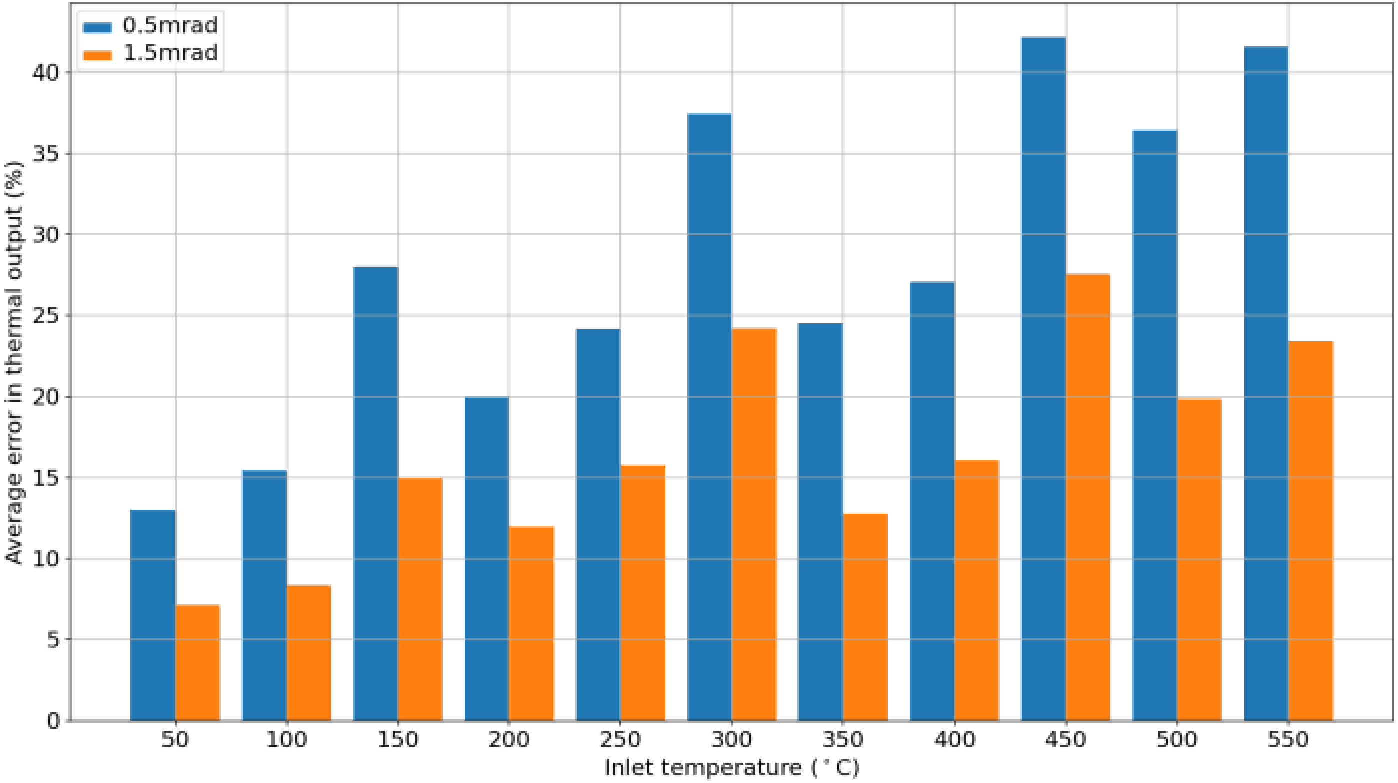


(b) Efficiency

* “Measured” receiver efficiency is calculated as:

measured thermal output / simulated aperture solar flux

Aggregated results



Conclusion

- A computational model for the ASTRI demonstration particle receiver has been developed using the Heliosim software
- The model has been applied to rebuild single-bin experiments conducted between May 2022 and March 2023
- Reasonable agreement is observed between measurement and simulation for the timeseries trend of receiver outlet temperature
- Significant discrepancy is found for receiver thermal output and receiver efficiency, especially at elevated inlet temperatures (above 400°C)
- Both the measured particle mass flow rate and aperture solar flux need to be more accurately determined to characterise the receiver performance with more confidence

Thank you

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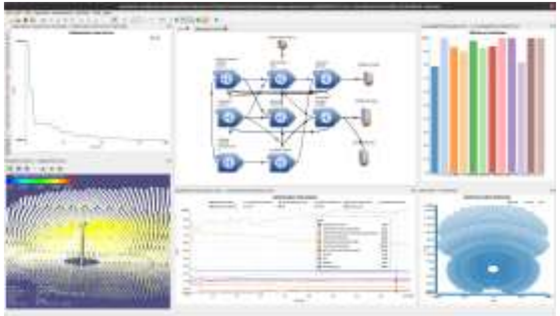
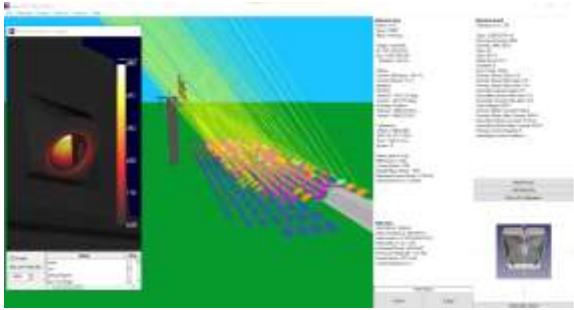
The Heliosim software family

A collection of libraries, plugins and applications that has been developed by the CSIRO for modelling, design, and control of heliostat-based concentrating solar thermal (CST) systems [1, 2]





Defining features

- Object-orientated implementation of core functionality in C++
- GPU-accelerated Monte Carlo ray tracing with mesh-based models of heliostats, receivers, etc.
- Standalone applications with graphical and command line interfaces

Usage

- Provides critical tools for the design and operation of receiver experiments at CSIRO Newcastle
- Modelling capability is used in numerous research and commercial projects
  - Detailed performance modelling of heliostat fields & receivers
  - LCOE & LCOH based system-level optimisation

1. D. Potter, et al., AIP Conf. Proc., vol. 2033, 2018, doi: 10.1063/1.5067213
2. D. Potter, “The Heliosim software family: modelling, design, and control tools for CST systems,” in Proceedings of the Asia Pacific Solar Research Conference, 2022.