U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Modeling Receiver Flux of Commercial Power Tower Concentrating Solar Power Plants Using Ray Tracing: A Round-Robin Comparison of SolTrace, Solstice, and TieSOL

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October 10-13, 2023 SolarPACES Sydney, NSW, Australia

conceptual design • components • integration • mass production • heliostat field

Ray Trace Collaboration Team

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SolTrace

- Developer: NREL
- Language: C++
- Software type: Open-source, CPU

Solstice

- Developer: CNRS-PROMES, Meso-Star
- Language: C
- Software type: Open-source, CPU

TieSOL

- Developer: Tietronix
- Language: CUDA, C++, C#
- Software type: Commercial, GPU

Why Conduct a Ray Trace Comparison Study?

- Previous study baselined ray trace tools for small case studies
  - Y. Wang et al., “Verification of optical modelling of sunshape and surface slope error for concentrating solar power systems,” Solar Energy, vol. 195, pp. 461–474, Jan. 2020, doi: 10.1016/j.solener.2019.11.035.No validation for simulation of a commercial-scale field with multi-facet heliostats
- Examination of blocking/shading
- Comparison of simulation of a commercial scale field with multi-facet heliostats with examination of canting and focusing
  - Are single facet heliostats sufficient for a simulation of a field with multi-facet heliostats?
- Accuracy of ray trace simulations can not be taken for granted and has implications for performance projections and techno economic analysis
- This effort to set the stage for a larger collaborative ray-trace comparison study

Ray Trace Comparison Methodology and Test Cases

Test Cases

- Single heliostat baseline cases, flat target
- Commercial field comparison cases, surround cylindrical target

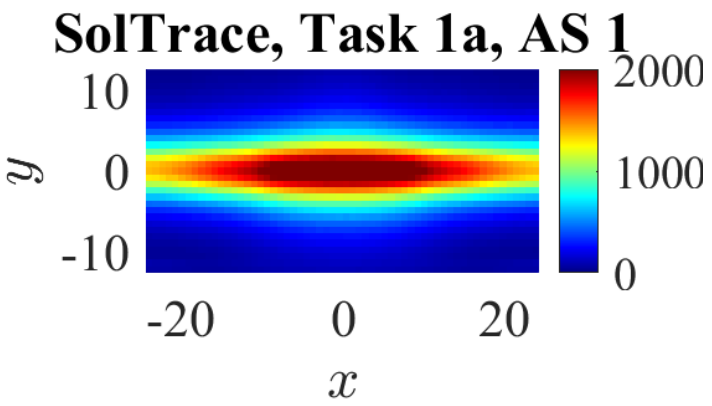
Comparison Metrics

- 2D plots of flux distribution
- 1D radial flux plots along flux distribution axes
- Peak flux (kW/m^2)
- Total power (kW)

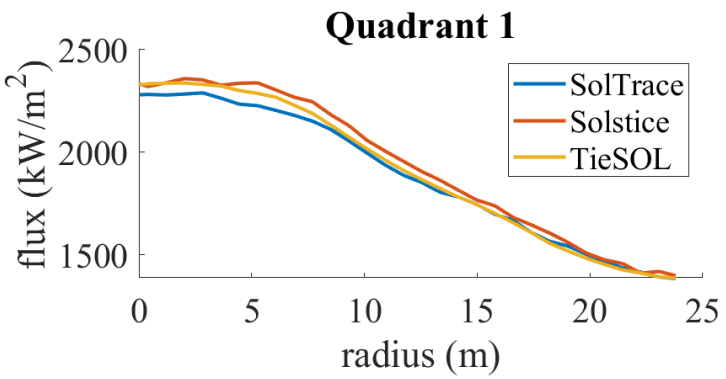
Model parameters

- Fixed parameters
  - No atmospheric attenuation
  - 90% reflectance
  - 2 mrad slope error
  - 4.56 mrad Pillbox sunshape
  - Day of the year
  - Target shape
- Varied parameters
  - Single facet and multi-facet heliostats
  - Canting and facet focusing
  - Heliostat location
  - Sun position
  - Aimpoint strategy (full-field)

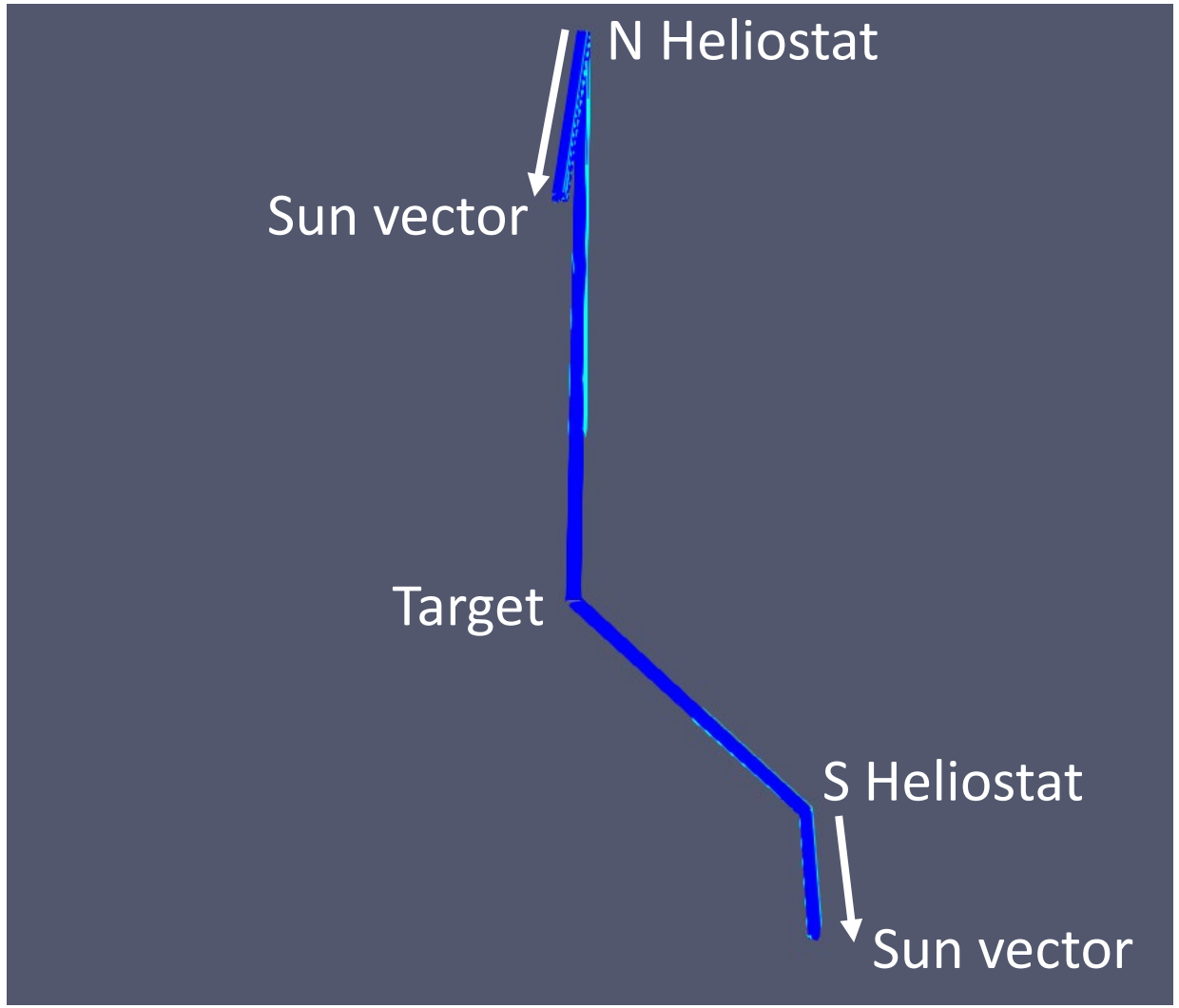
Example 2D flux plot



Example 1D radial flux plot



Single Heliostat Test Cases



Model Parameters

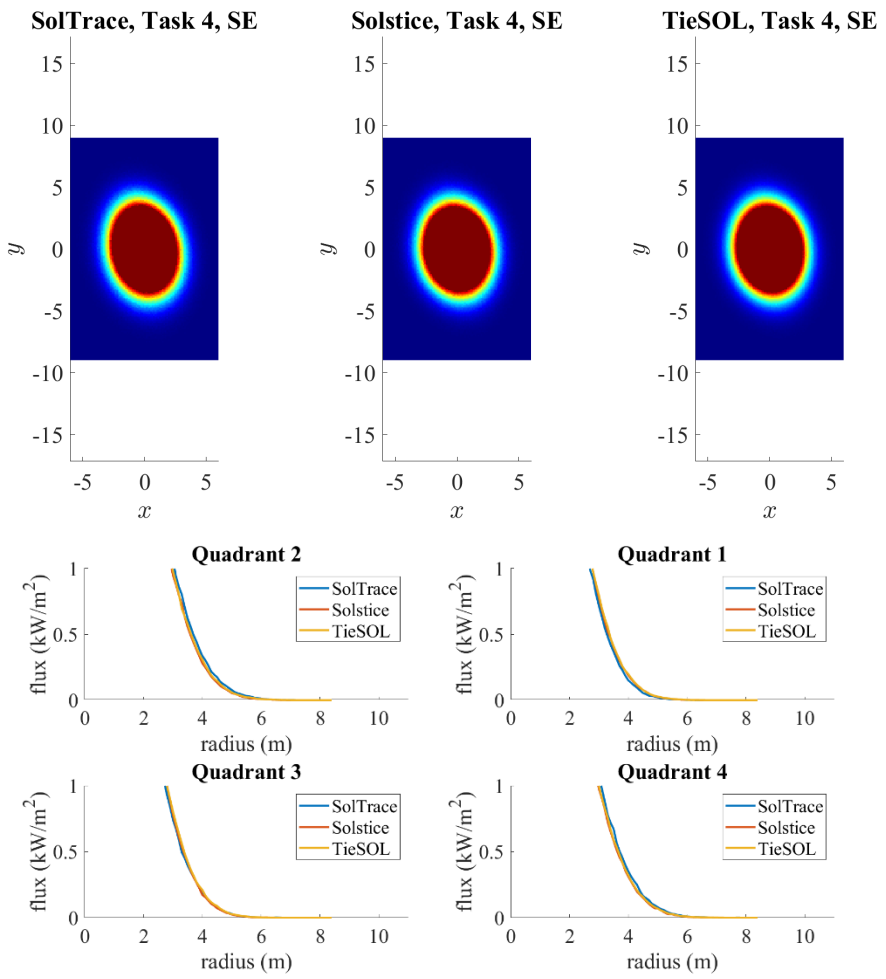
- Located in Nevada (Crescent Dunes location)
- Heliostats based on Crescent Dunes design (5 x 7)
- Solar noon on 8/31
- North (500 m) and Southeast (200 m E, 200 m S) heliostat locations
- Flat rectangular target

Test Cases

- Single facet
  - Flat
  - Curved to slant range
- Multi facet
  - No canting, flat facets
  - Canted to slant range, flat facets
  - Canted to slant range, facets curved to slant range

Single Heliostat Results and Lessons Learned

Good agreement (not perfect) across all test cases



Key Challenges and Learnings

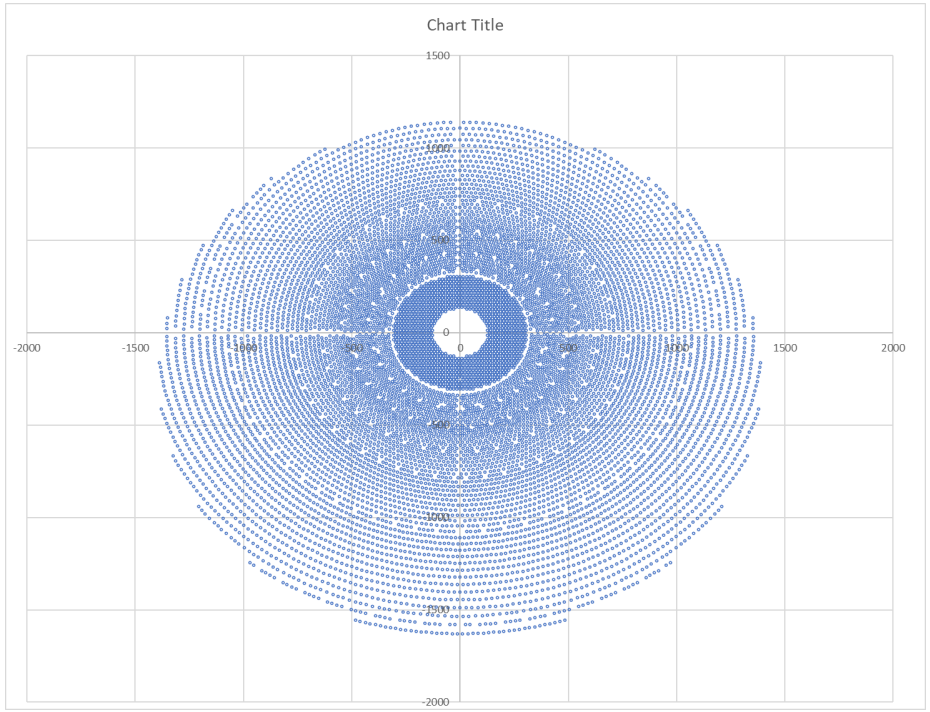
Expected this to go quickly and it did not…

SolTrace target was upside down

New capabilities created in Solstice for canted multi-facet heliostats

Thanks to Ye Wang's "solsticepy" wrappers

Full Field Test Cases



Canting Bands	Radius From	To	FocalLength
Band 1	120	502	516
Band 2	502.1	885	668
Band 3	885.1	1267	959
Band 4	1267.1	1650	1500

Facets Focal Length	Radius From	To	FocalLength
	127	502.5	353.8
	502.51	878	704.8
	878.1	1253.5	1072.5
	1253.51	1650	1444.3

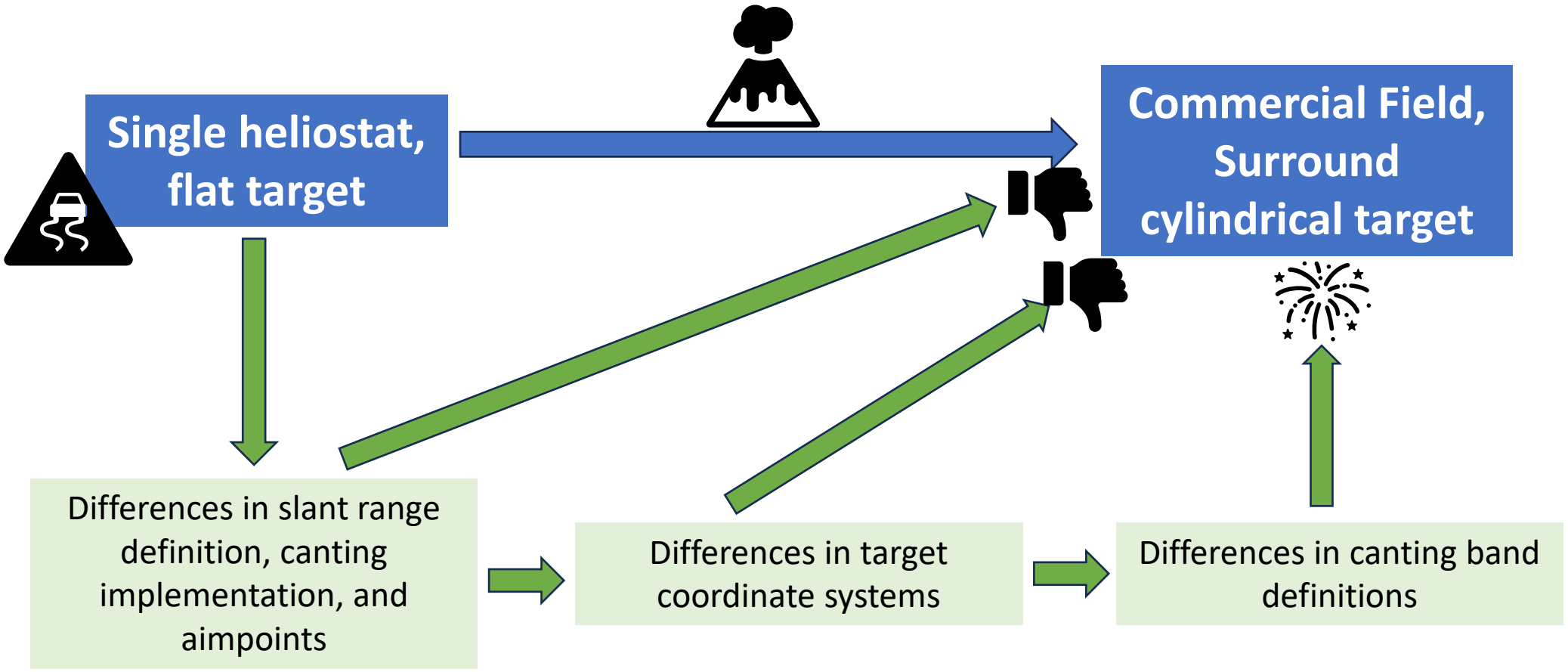
Model Parameters

- Located in Port Augusta, Australia based on planned plant
- Heliostats with 30 facet layout (6 x 5)
- Solar noon and 8 on the spring solstice (9/22)
- Cylindrical target
- Aimpoint strategy (none or scattered in elevation)

Test Cases

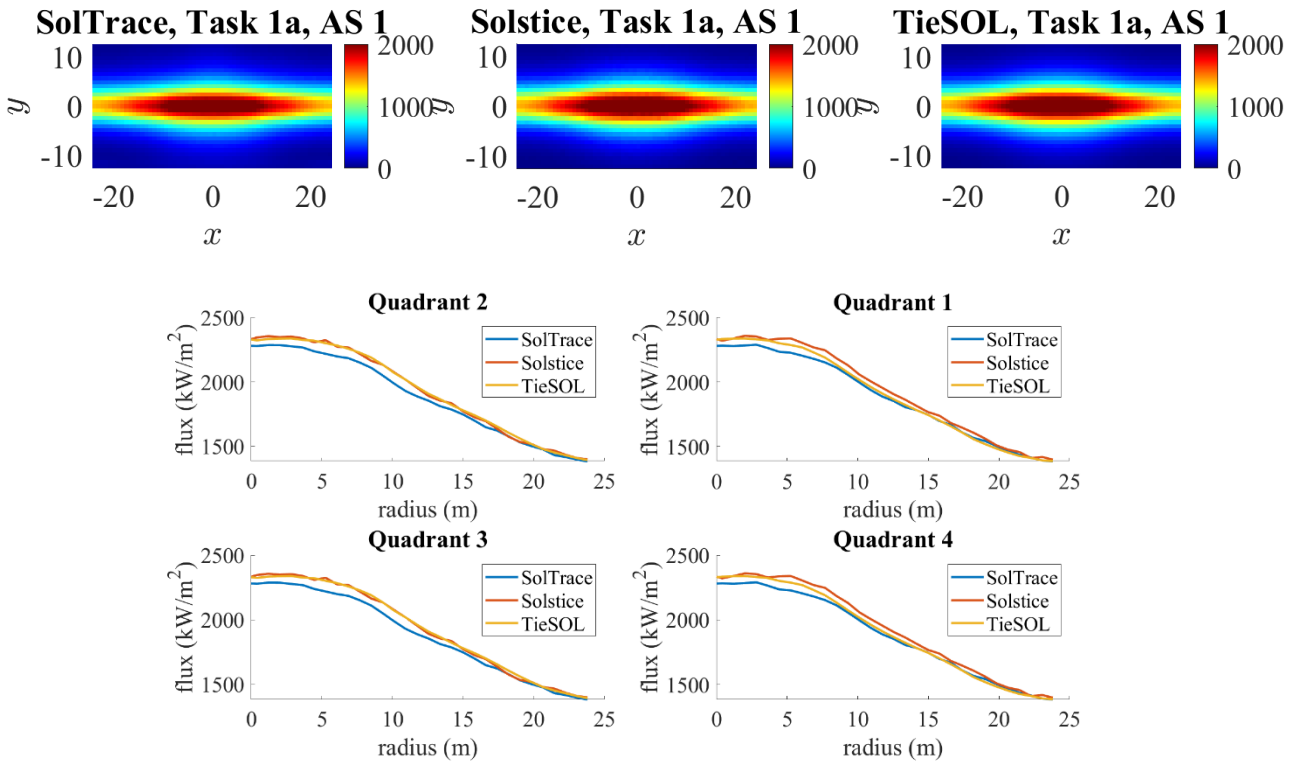
- Single facet
  - Curved to slant range
  - Curved according to 4 canting bands
- Multi facet, flat facets
  - Canted to slant range
  - Canting according to 4 canting bands
- Multi facet, curved facets
  - Canted to slant range, facets curved to slant range
  - Canting according to 4 canting band, facets curved according to 4 focusing bands

More Difficult Than We Expected



Full Field First Attempt

Nothing agreed at all



Key Challenges and Learnings

Radial flux plots and total flux metrics are key to identifying differences not visible in flux distribution plots

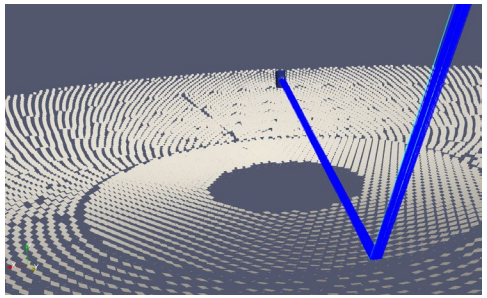
Too complex a leap, could not identify sources of discrepancy

Disagreement of all 3 tools, could not determine if anyone was correct

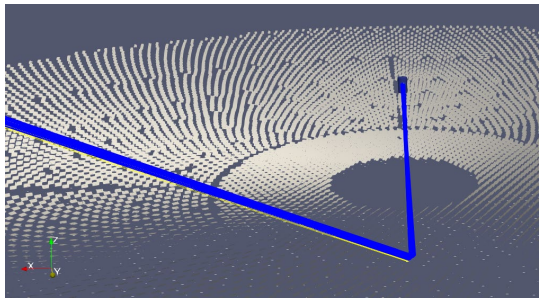
Designed a simpler test case: isolated heliostats with blocking neighbors

Isolated Heliostats With Blocking Neighbors

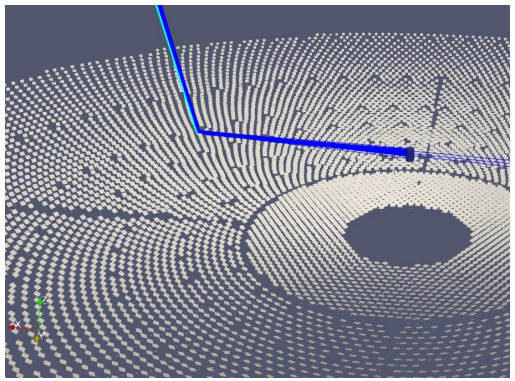
North heliostat, noon



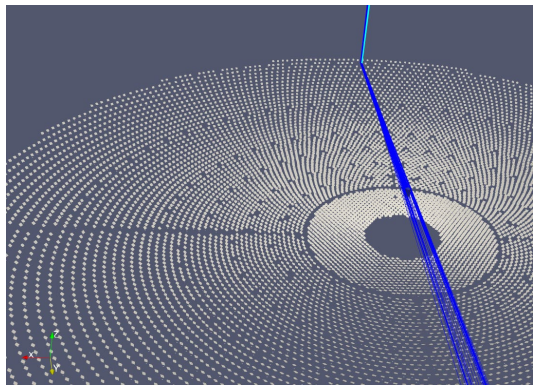
North heliostat, 8am

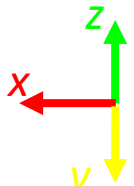


South-east heliostat, noon



South heliostat, noon





Model Parameters

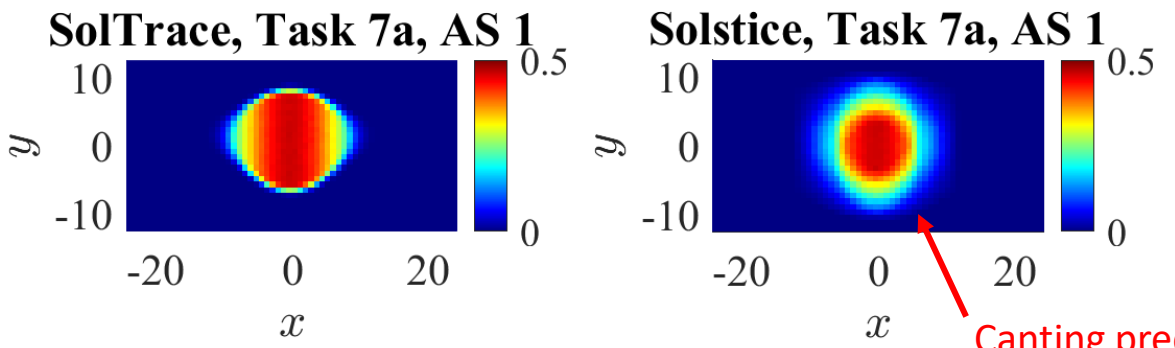
- Heliostats chosen at N, SE, and S locations in the field with selected neighbors that would create blocking
- Removed slope error in selected cases to troubleshoot

Test Cases

- Single facet, curved to slant range, no blocking or shading
- Canted to slant range, facets curved to slant range, no blocking or shading
- Canting bands, facets curved to slant range, blocking and shading from neighbors

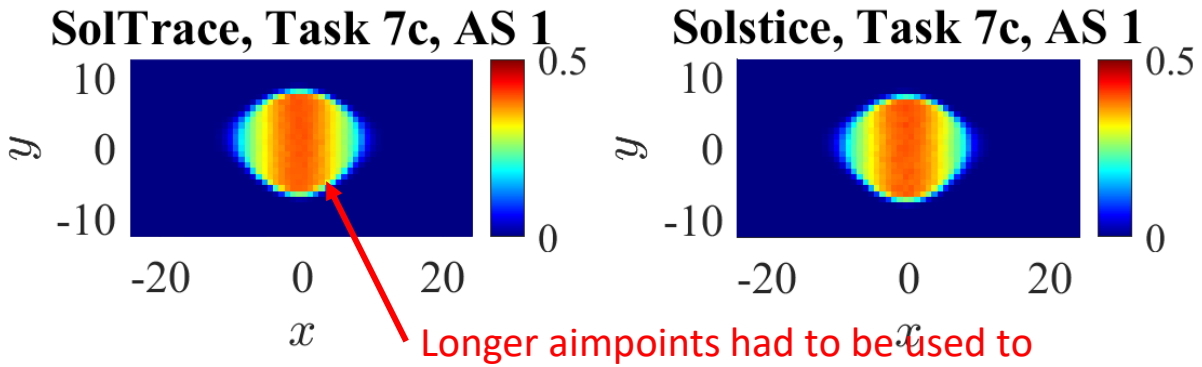
Isolated Heliostat Key Discoveries

Canting precision in Solstice



Canting precision had to be increased (from 10e-6 to 10e-12) for far field heliostats (1500 m)

Aimpoint precision in SolTrace



Longer aimpoints had to be used to avoid beam offset from precision loss from decimal truncation

Other Discrepancies Resolved

Target height and aperture

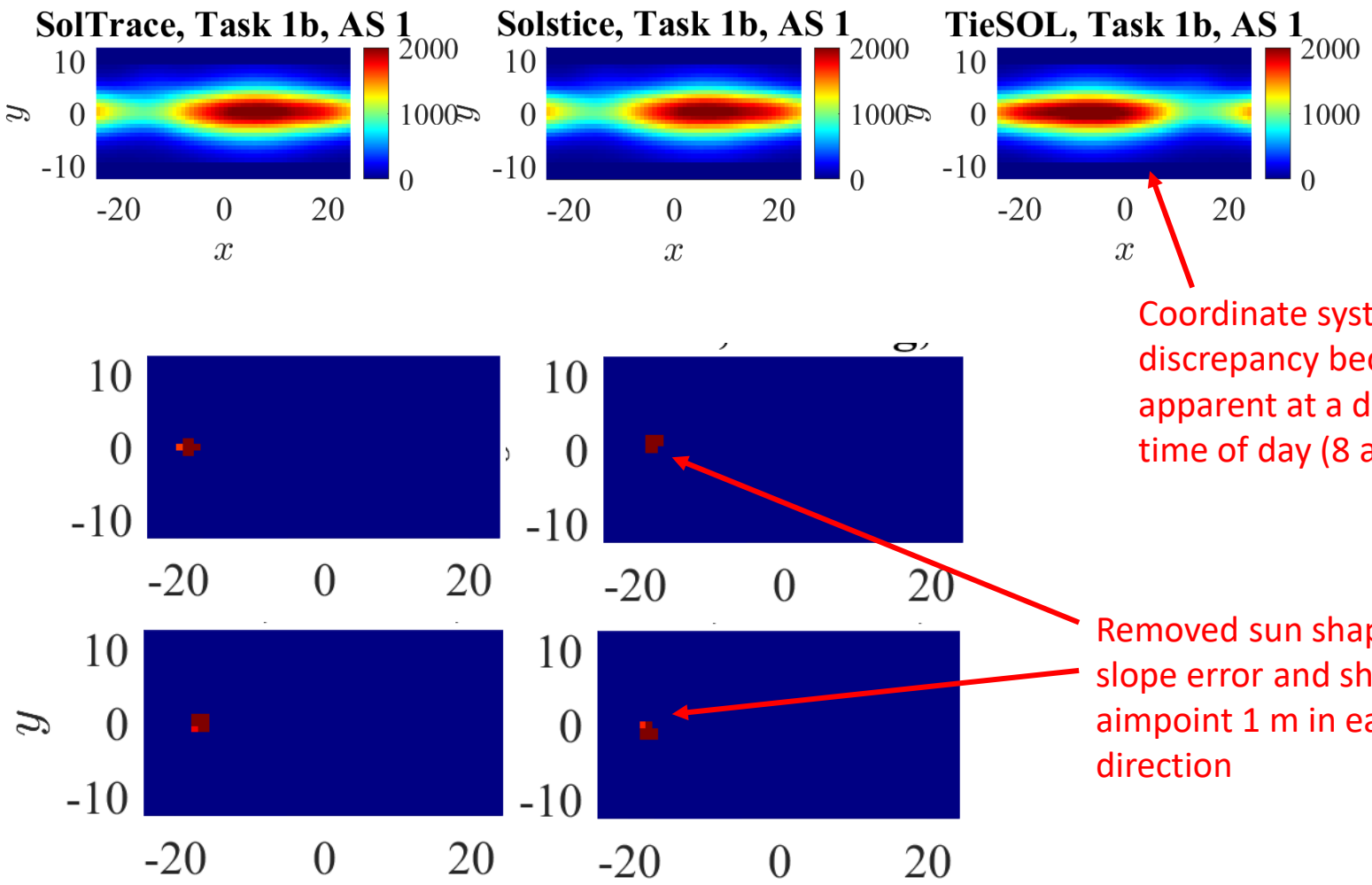
Atmospheric attenuation

Slant range definition

Distance to tower base?
Distance to receiver center-point?
Distance to receiver surface?

Shift Aimpoint to Align Coordinate Systems

Agreement of 2 out of 3 tools



Coordinate system discrepancy became apparent at a different time of day (8 am)

Removed sun shape and slope error and shifted aimpoint 1 m in each direction

Key Challenges and Learnings

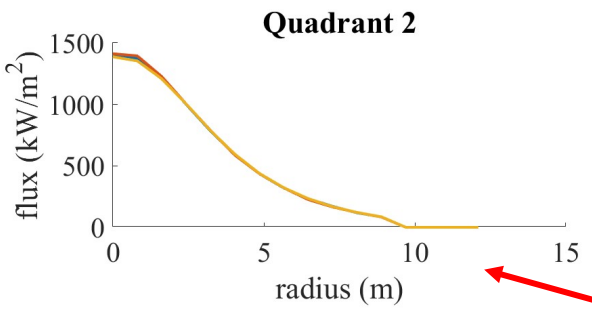
Beams from different parts of the field key to identifying coordinate system discrepancies

Had not verified agreement of new cylindrical target

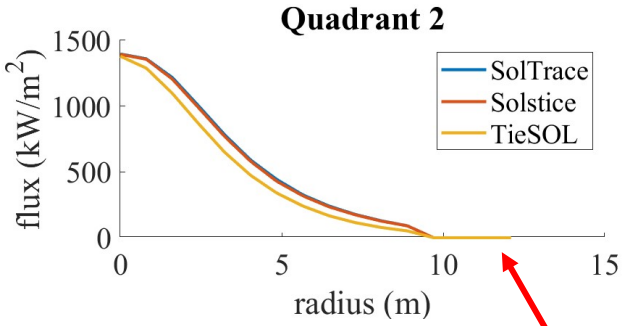
Coordinate systems reversed horizontally and vertically

Isolated Heliostats at Band Boundaries

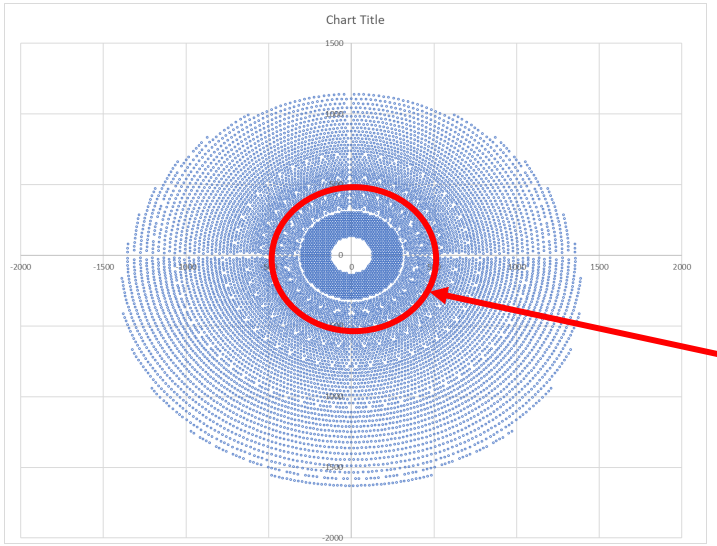
Focus defined by slant range



Focus defined by canting band



Agreement in definitions of slant range (distance from receiver surface), but not canting bands



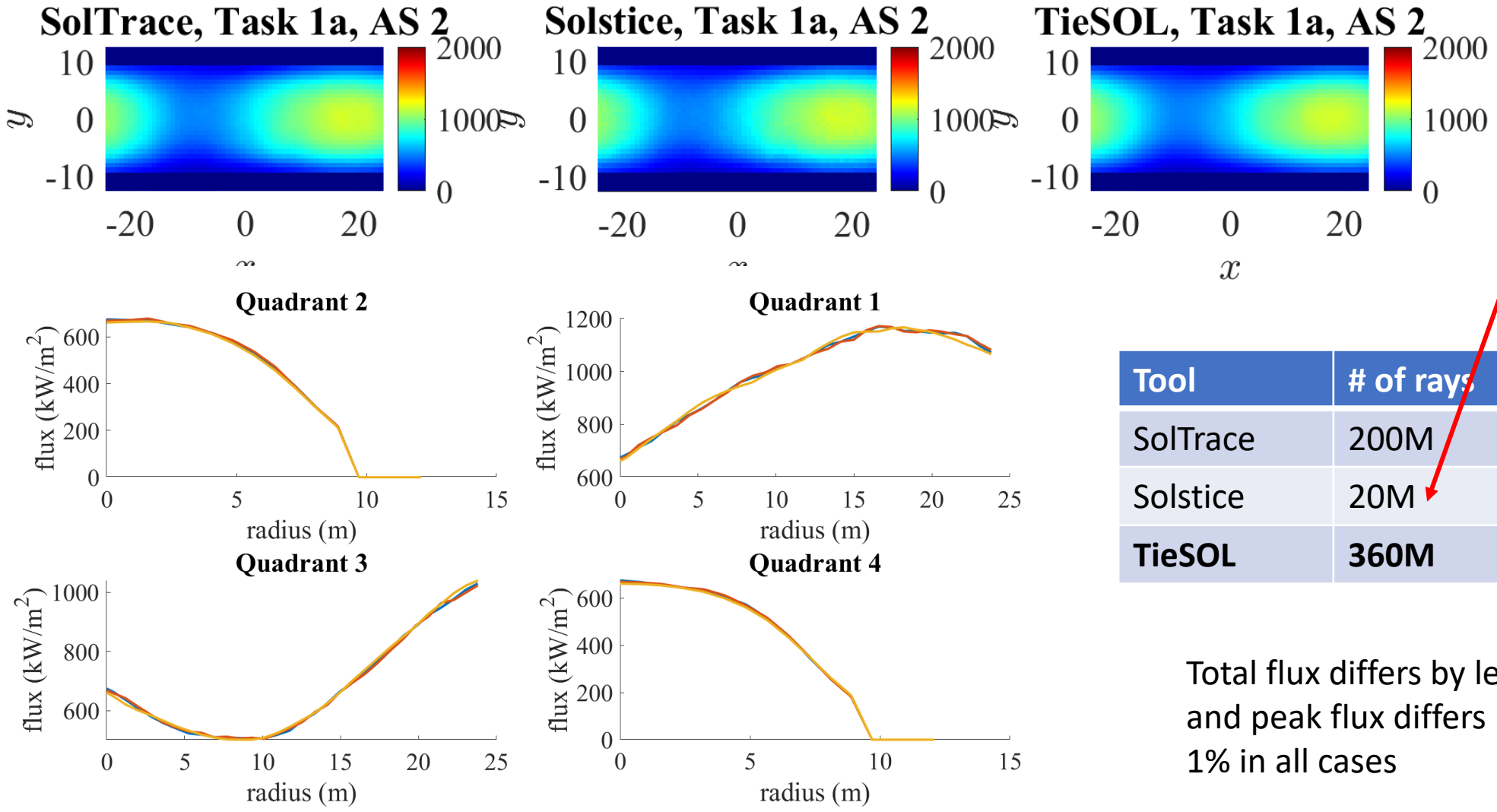
Chose two heliostats straddling the boundary between the first and second canting bands (502 m)

Key Challenges and Learnings

Able to identify discrepancy in band inputs

Band definitions must be clear (from the center of base of the tower)

Achieved Agreement of All Commercial Tests

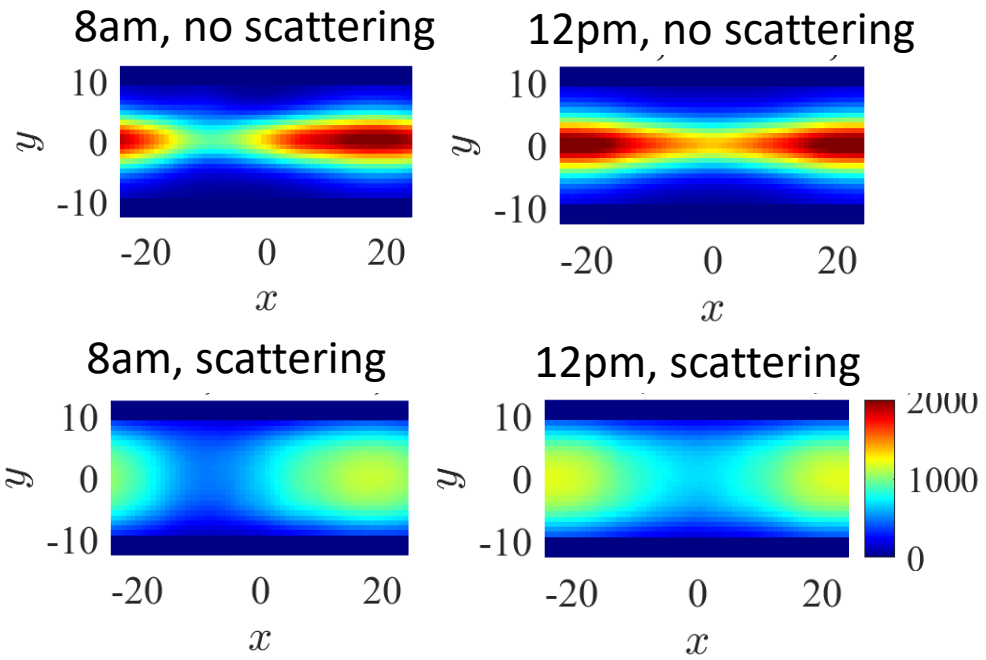


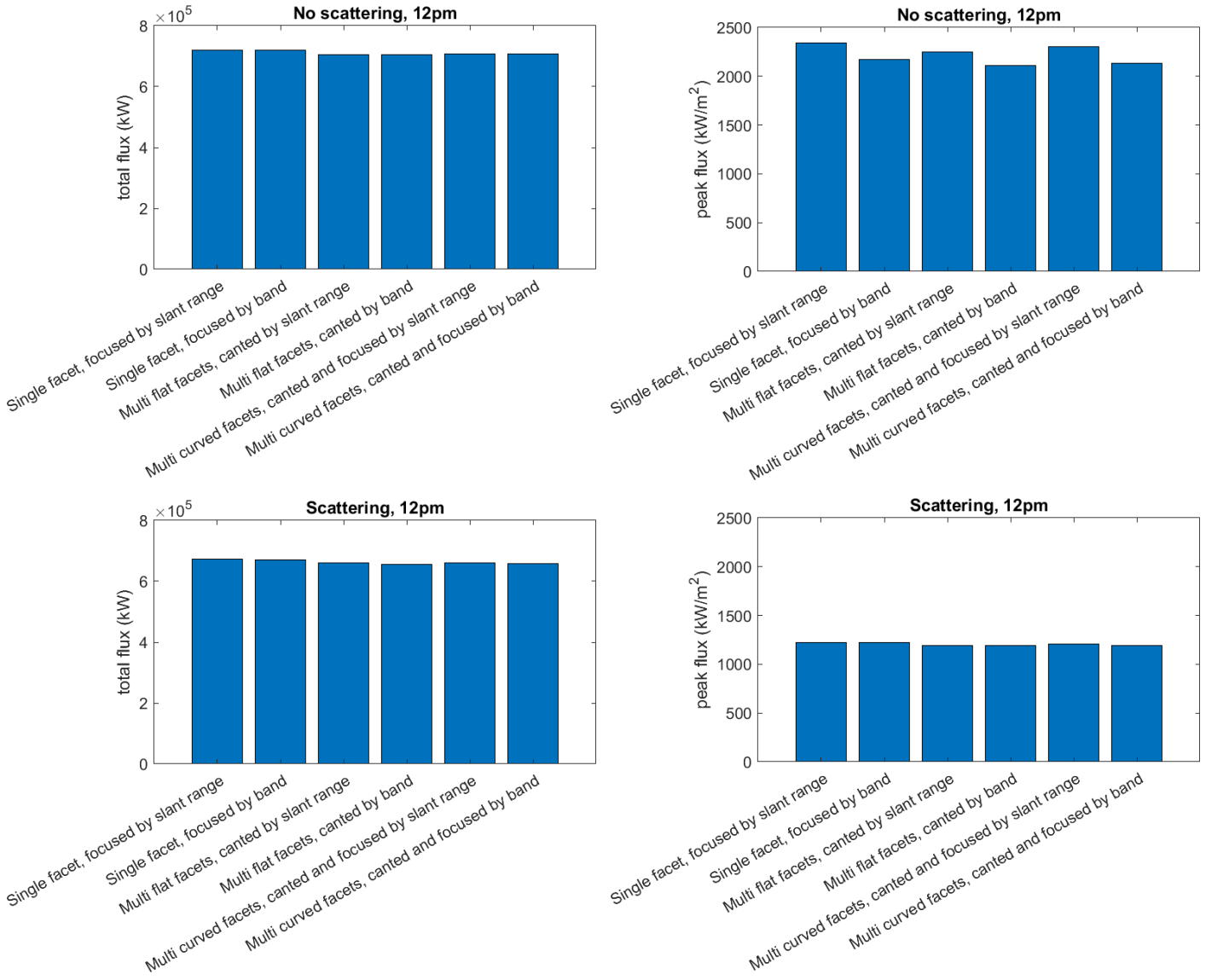
Solstice limits the number of elements, commercial field test cases completed by dividing the field into ~25 sections

Tool	# of rays	Run time
SolTrace	200M	~15 minutes
Solstice	20M	~10 minutes
TieSOL	**360M**	**4-7 seconds**

Total flux differs by less than 0.3% and peak flux differs by less than 1% in all cases

Commercial Field Test Results





Peak and total flux for a single facet approximation of multi facet heliostats canted/focused by band differs by ~2.3%

Top Learnings

- Best practices:
  - Accuracy of ray trace simulations cannot be assumed; standardized/benchmark tests are necessary for validation
  - Comparison of at least three tools with increasing complexity
  - Coordinate systems need to be defined clearly and verified
  - Isolate and verify each model parameter
  - Number of rays and elements required for commercial-scale ray trace simulation is difficult for SolTrace and Solstice

TieSOL is the clear winner

- Key discoveries:
  - Multi-facet canting capabilities introduced for Solstice (thank you Ye Wang)
  - Canting precision must be defined carefully for far-field heliostats in Solstice
  - Aimpoints should be specified at long distances (1000 m) to avoid precision truncation error in SolTrace

Next Steps

- Publish results and make test cases available in a public GitHub repository
- Develop standard validation guidelines for ray trace tools
- Expand ray-trace round robin to additional ray trace tools
  - Want to be involved in the next phase? Contact rebecca.Mitchell@nrel.gov

Thank You

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