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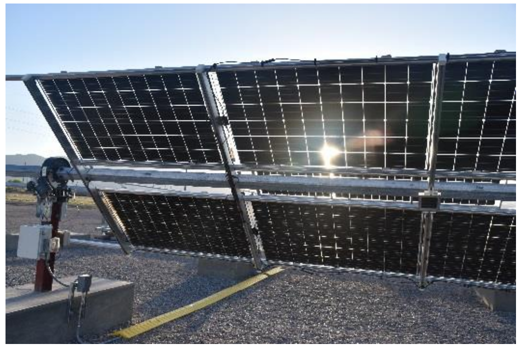
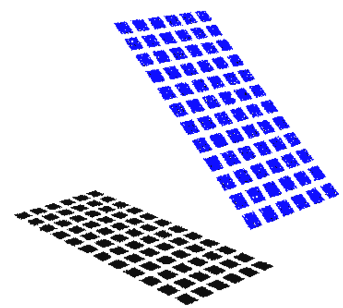
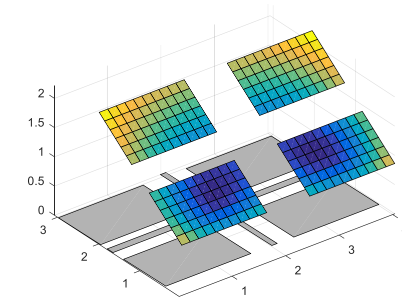

A Detailed Model of Rear-Side Irradiance for Bifacial PV Modules

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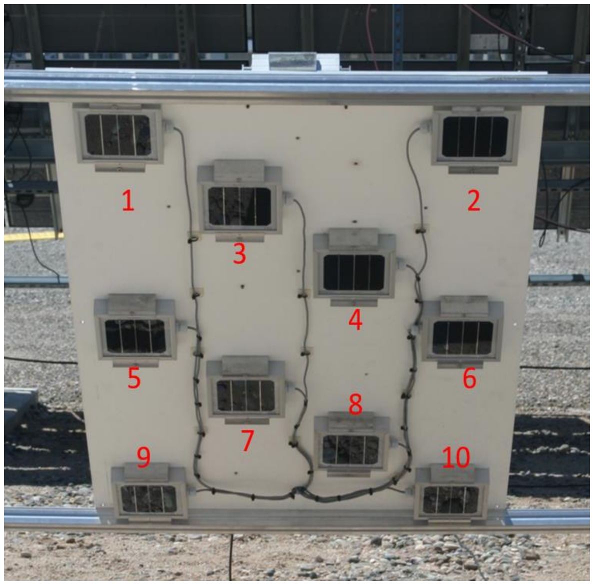
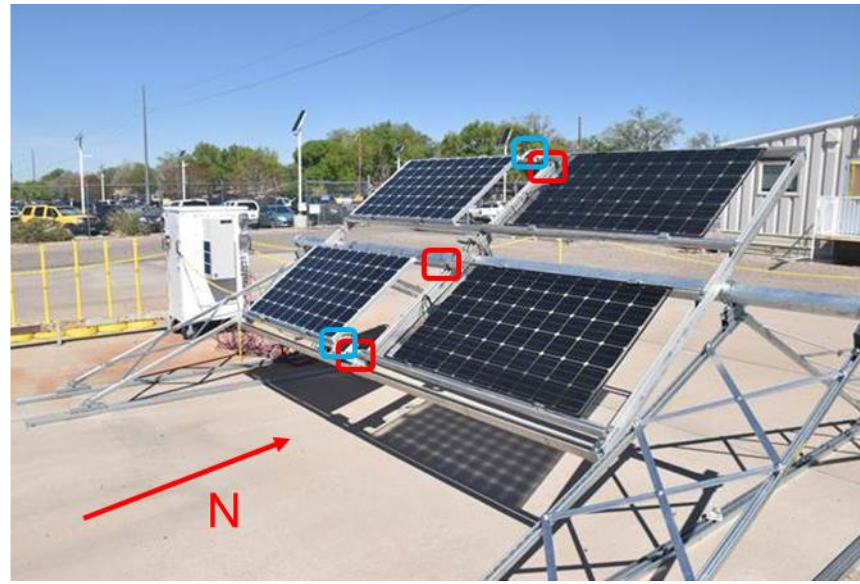
Validation data





10 rear-facing reference cells on plate with module form factor

Calibrated to ±4W/m^2 @1000 W/m^2

Reference Cells

- 3 rear-facing
- 2 front facing

Modules

- 2 bifacial (east)
- 2 monofacial (west)

Adjustable height, tilt, albedo

Rear surface irradiance model

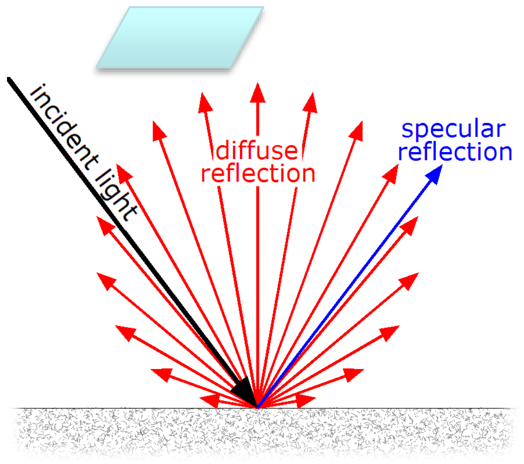
- View factor (configuration, shape factor) $F_{A1 \rightarrow A2}$: fraction of radiation from A1 that strikes A2
  - Assumes **diffuse reflection** of irradiance from A1
- Irradiance (W) on surface A2 from source A1:

$$G_{A1,A2} = G_{A1} \times F_{A1 \rightarrow A2}$$

- Total irradiance on A2:

$$G_{A2} = \sum_i G_{A_i,A2} \times F_{A_i \rightarrow A2}$$

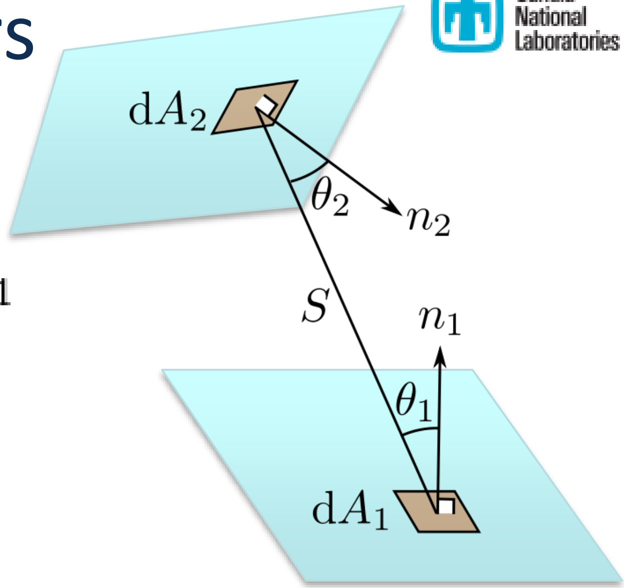
- Irradiance on a rear-surface cell from:
  - Reflections from shaded ground
  - Reflections from unshaded ground
  - Sky diffuse
  - Direct beam
  - *Specular reflections*



Efficiently calculating view factors

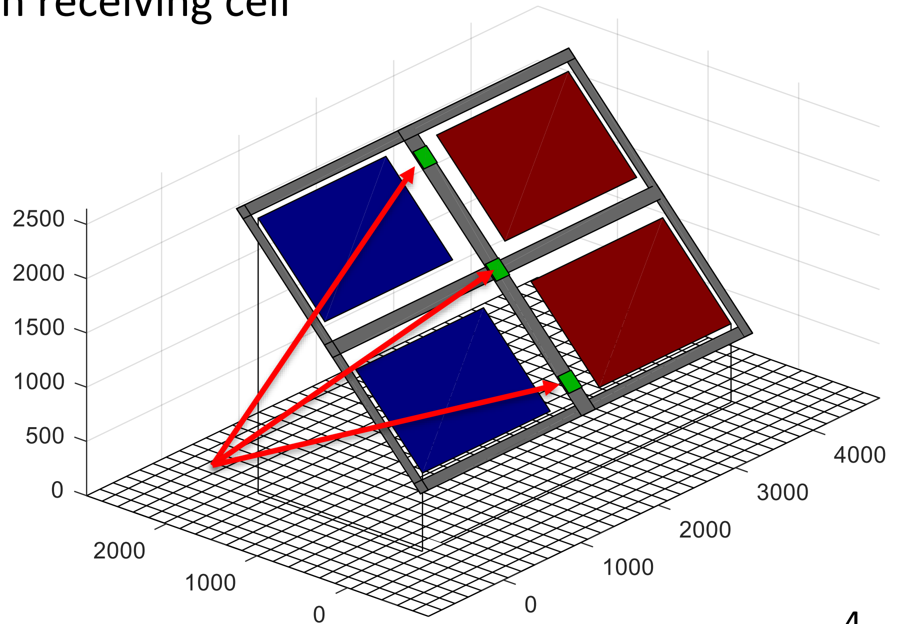
- Formal approach

$$F_{1\to 2} = \frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos\theta_1\cos\theta_2}{\pi s^2}\,\mathrm{d}A_2\,\mathrm{d}A_1$$



- Implemented as massively parallel algebraic computation
  - Grid the ground (emitting) surface
  - For each grid cell, compute VF to each receiving cell

> - Approximate integrand with value at centroids of each cell
> - `cos` computed by matrix product
> - Fast enough on CPU, x10 faster on GPU

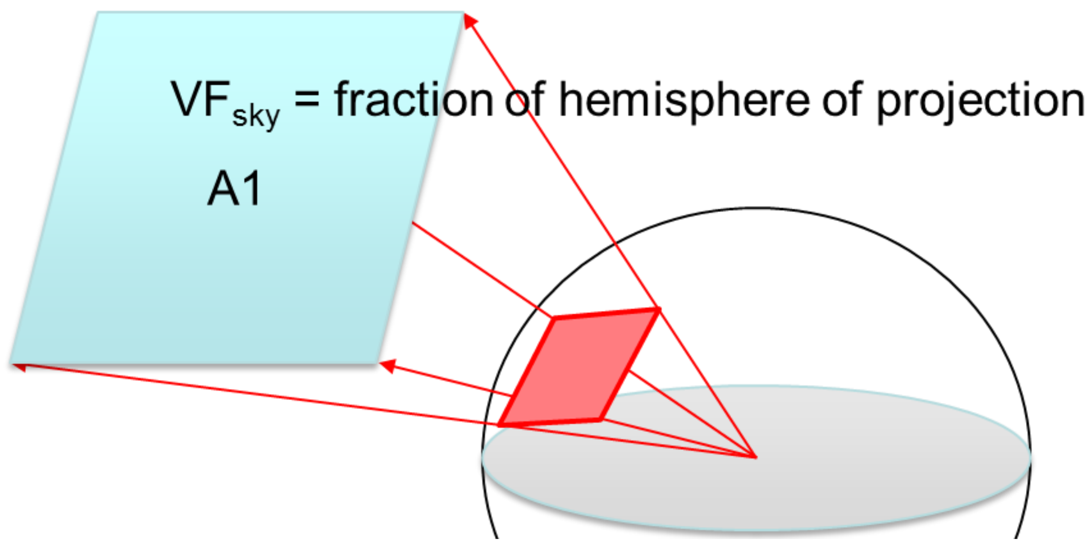


- VFs depend on geometry NOT sun position
- Compute once before irradiance modeling

Irradiance modeling

- Irradiance reflected from a ground grid cell:
  - Shaded cell: $G_{A1} = \alpha \times DiffuseSky \times F_{A1 \to sky}$
  - Unshaded cell: $G_{A1} = \alpha \times \left(DNI \cos Z + DiffuseSky \times F_{A1 \to sky}\right)$
- Part of diffuse sky irradiance is blocked by array objects (e.g., modules)

- $F_{A1 \to sky}$ calculated as solid angle of projection of A1
- $DiffuseSky =$ DHI – circumsolar
- Circumsolar estimated using Hay-Davies



Validation: cell by cell

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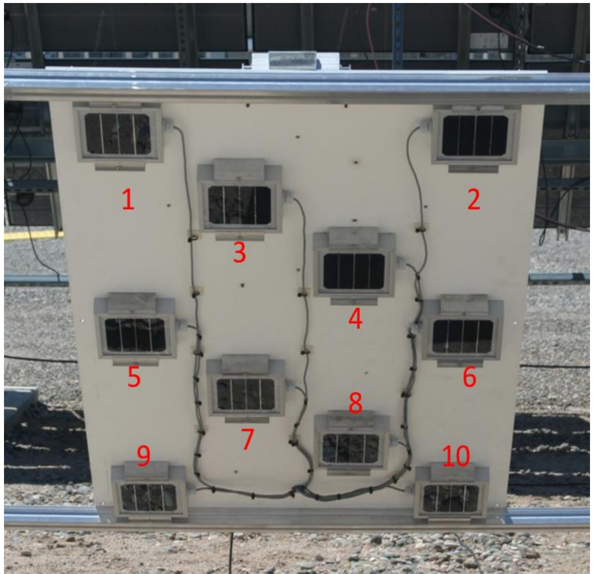
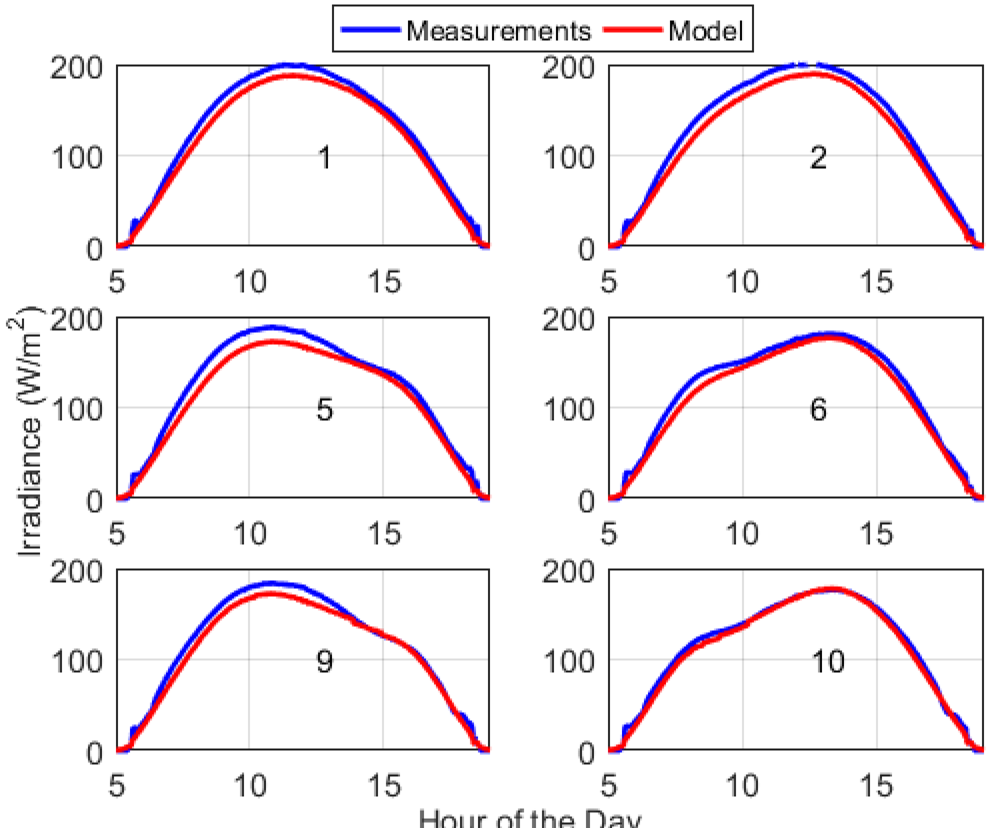
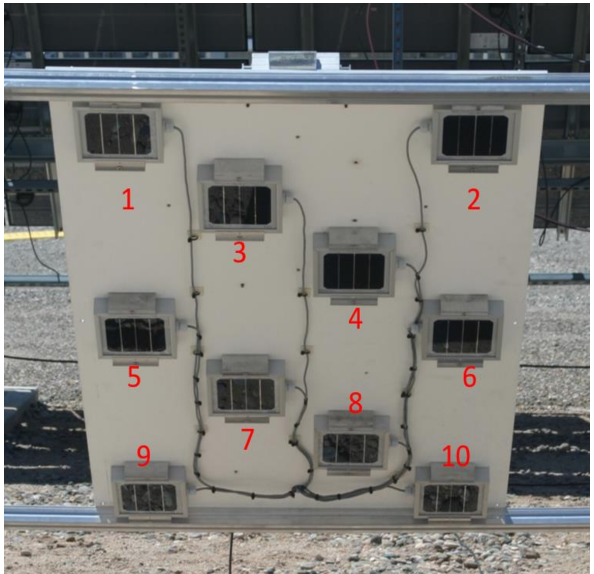


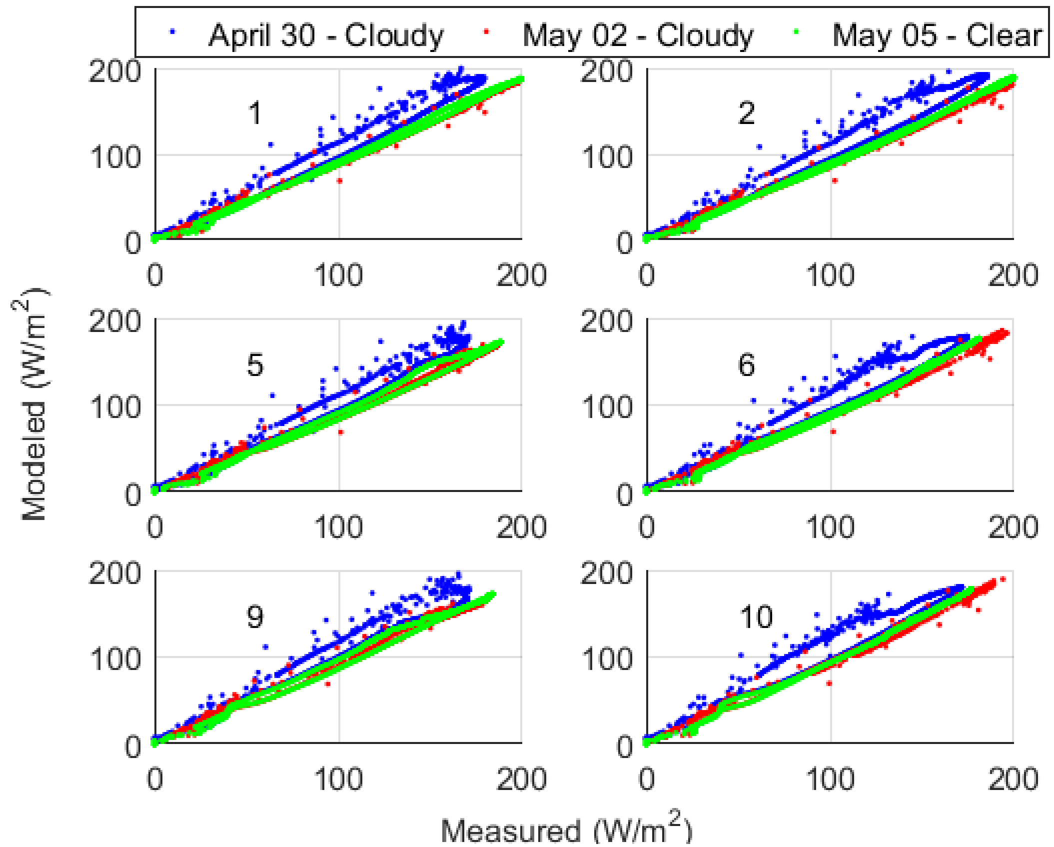
- May 5, 2017: clear skies all day
- Isolated open rack, 30° tilt, clear view to north
- ~15 W/m^2 negative bias



Validation: cell by cell



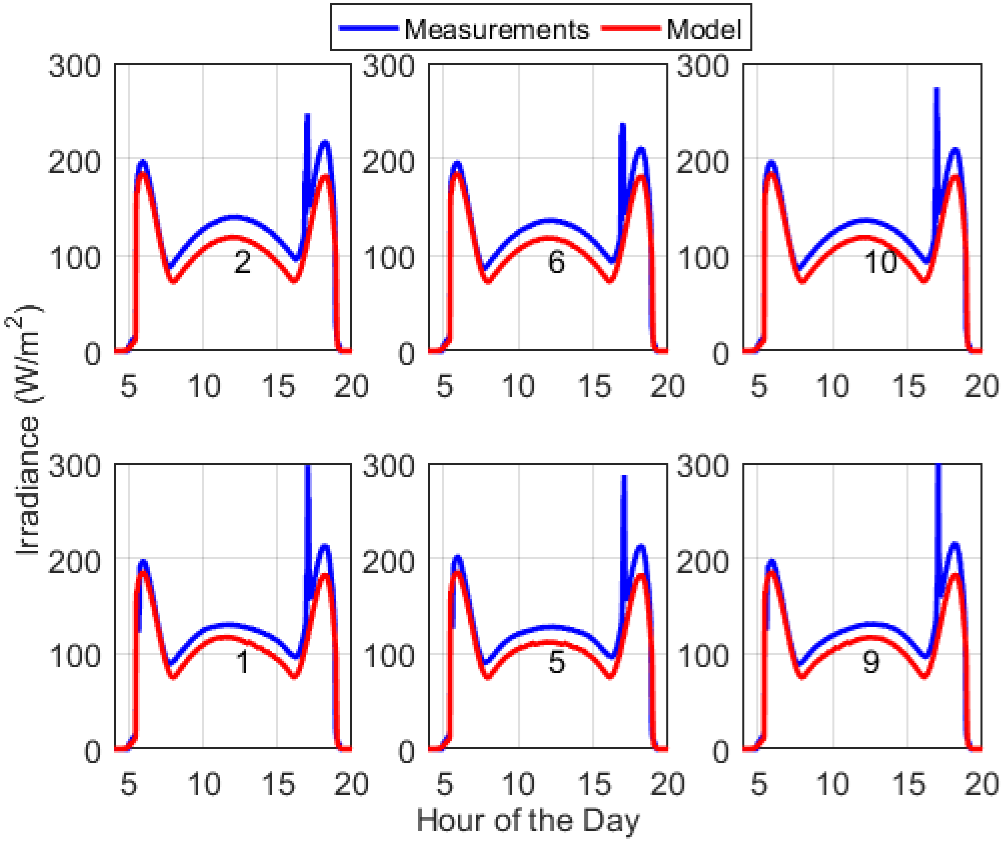
- All-sky conditions
- Isolated open rack, 30° tilt, clear view to north
- Error envelope ±10%



Validation: cell by cell

- All-sky conditions
- Isolated on block, vertical, clear view to north

- 20 W/m² negative bias
- 'Ears': direct irradiance on rear surface
- Preceding spike: near-field reflection



Observations

In general:

- Rear-surface irradiance is mostly from ground reflection
- Ground reflected irradiance is primarily from sunlit areas

Consequently:

- Rear-surface irradiance ~proportional to albedo
- Rear-surface irradiance increases as sunlit proportion of back-field increases
  - Increase array height, spacing
  - Gaps between cells
- Infrequent sources (direct, near-field reflections) can have significant magnitude

Rear surface irradiance model - results

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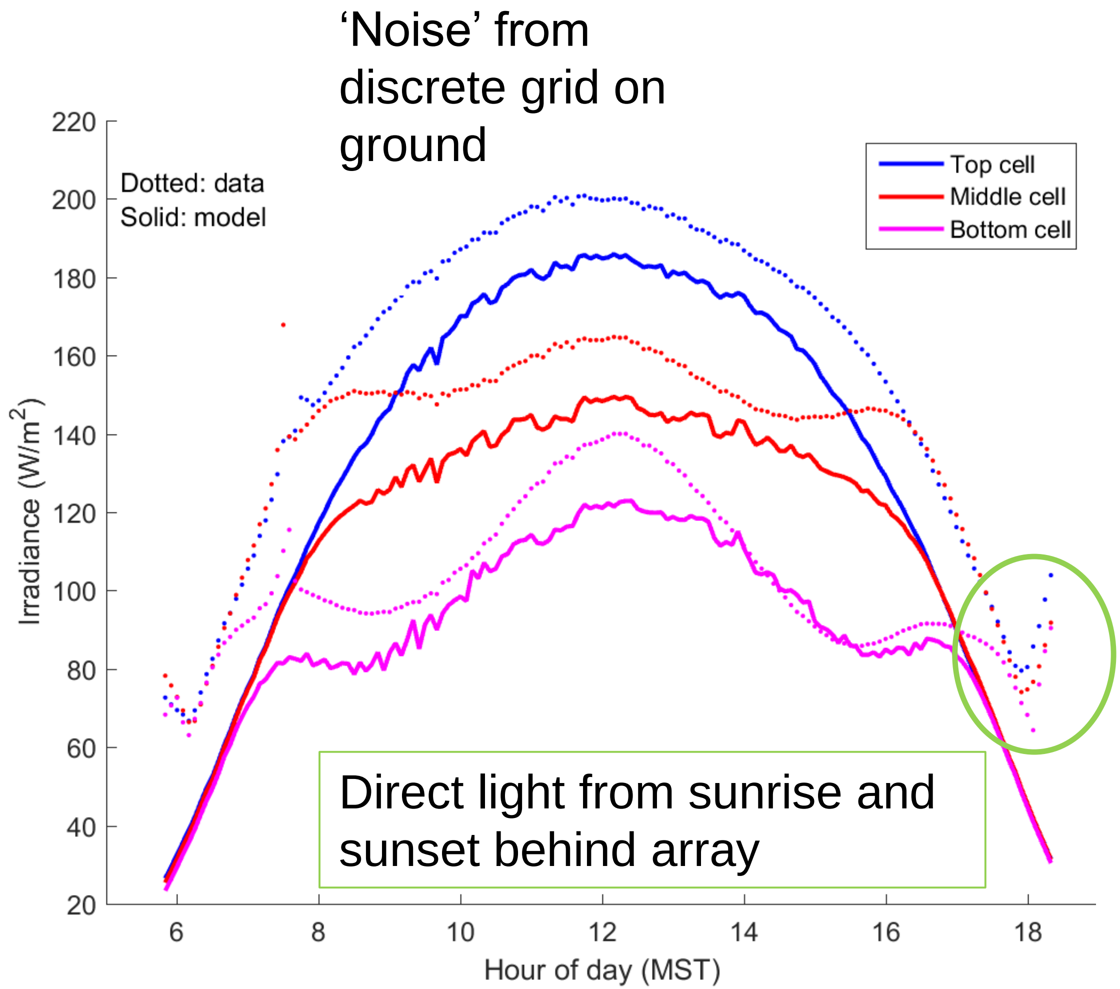
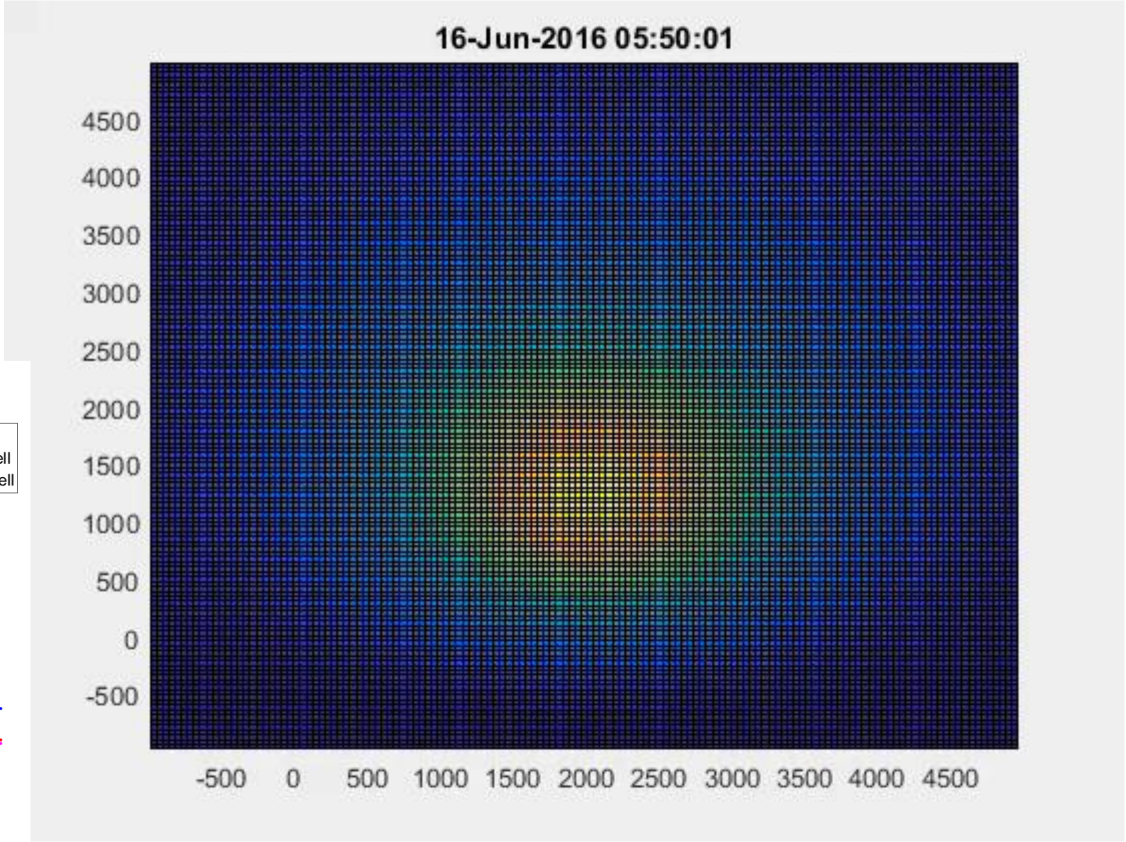
- Negative bias ~15 W/m2
- Model generally follows patterns in data

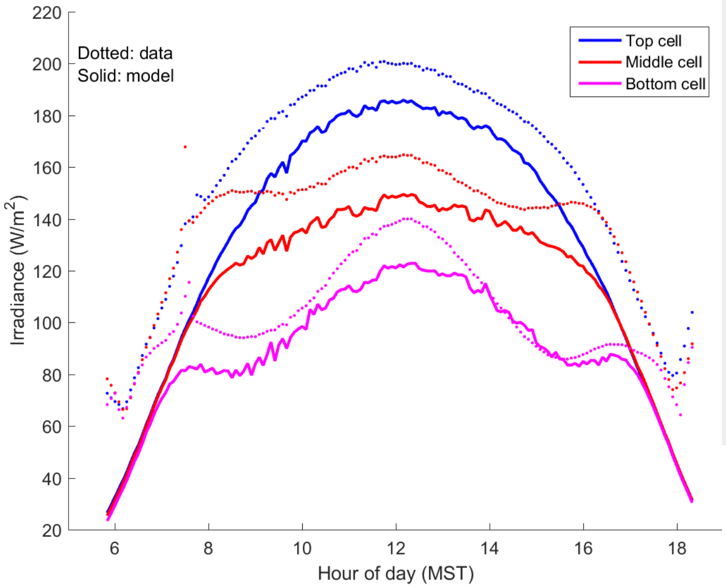
- Clear-sky conditions
- 45° tilt, center at 1.63m



Rear surface irradiance model - results

Grid cell color corresponds to irradiance contributed to middle cell

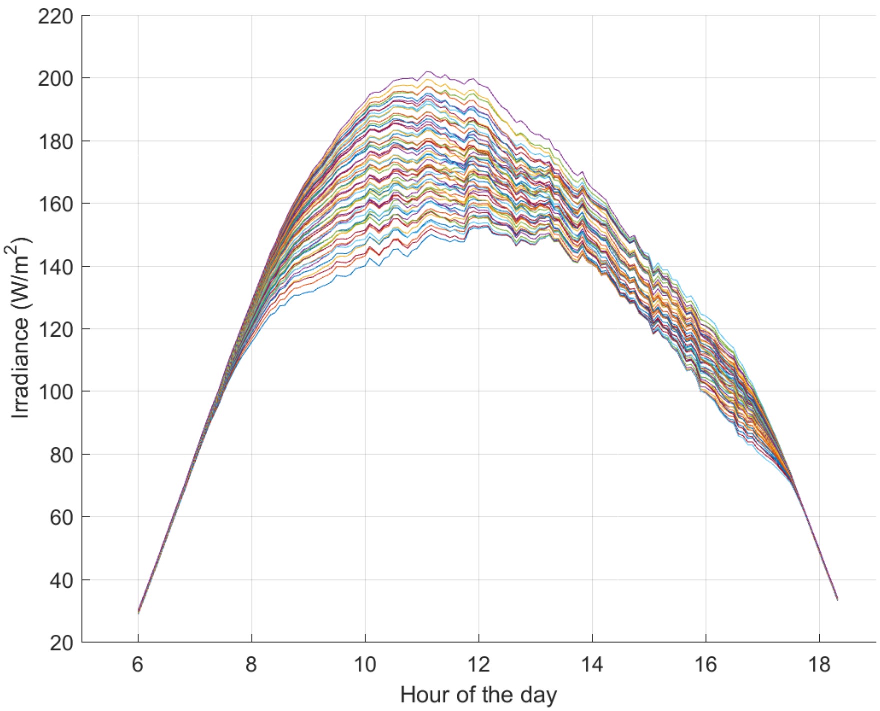




Cell to cell irradiance variability

- Clear-sky conditions
- 15° tilt, center at 1.63m

- Simulated irradiance for each of 60 cells
- Peak difference between cells on the order of 50 W/m^2
- Difference becomes negligible during cloudy sky conditions



Conclusions

- Cell-scale rear irradiance model with accuracy ±10%
- Model shows bias, appears related to sky diffuse fraction
  - Negative bias during clear skies
  - Positive bias sometimes present during cloudy conditions
- Computationally feasible but implementation matters
  - 3 cells, 10 objects, 700x700 grid, 150 time steps ~2 min on a typical PC with CPU processing
  - 14s with GPU processing