CFV Labs

Irradiance Uniformity Mapping Module

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Outline

- Introduction
- Instrument Design and Construction
- Calibration
- Indoor Applications
- Outdoor Applications
- Summary

Introduction

- Irradiance uniformity is an important driver of PV performance
- Often assumed to be uniform in some cases (front-side POA)
- Calculated in other cases (rear-side POA in bifacial applications)
- Significant driver of solar simulator measurement uncertainty
- Component of solar simulator classification (IEC 60904)

$$Non - uniformity\ (\%) = \frac{(G_{max} - G_{min})}{(G_{max} + G_{min})} \times\ 100.0$$

- *Can the uniformity be measured in 2 dimensions quickly and accurately?*

Instrument Design and Construction

- 60 cells in a 1.0 m x 2.0 m form factor
- Cells are individually tabbed out through backsheet
- Isc values measured by DAQ boards behind each cell
- Modbus over RS-485, all cells are networked
- Simple interface using pymodbus
- Multiple measurement modes:
  - Slow: constant irradiance environments
  - High speed: Time resolved measurements of fast (≲35 ms) flash pulses with up to 256 measurements per flash

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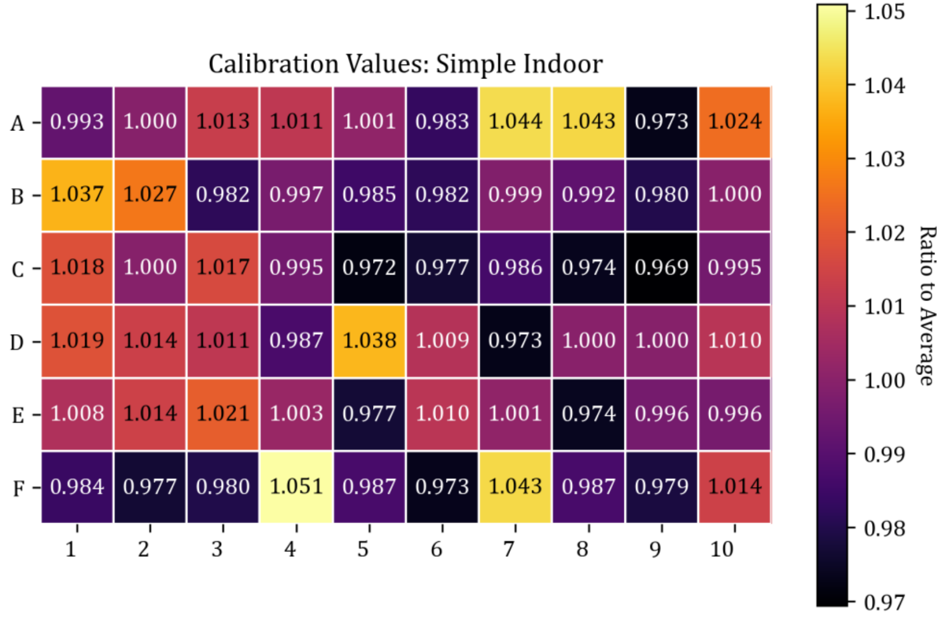
Calibration

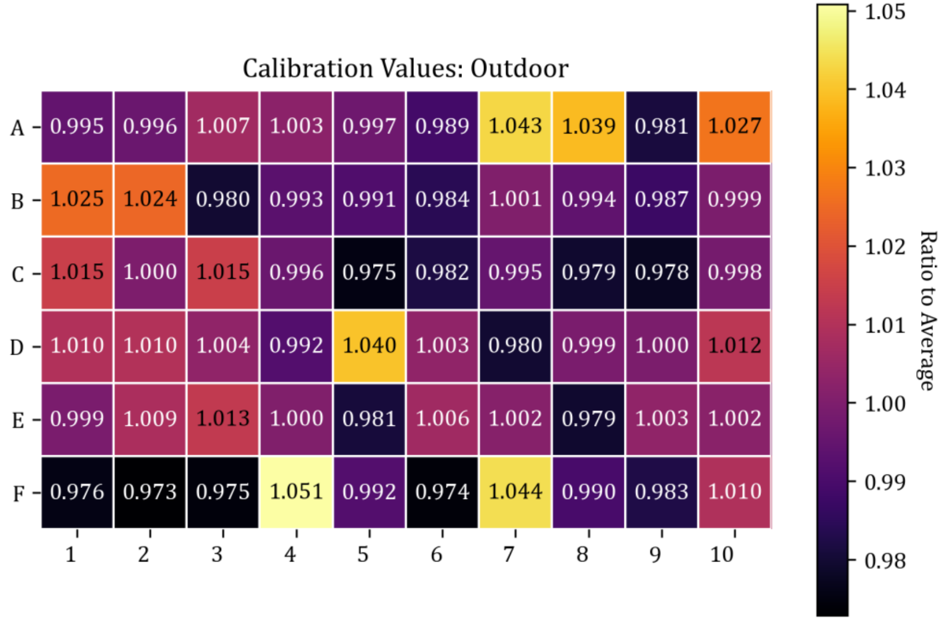
- Serves two functions:
  - ADU to W/m² (absolute; ~1.25 - 1.75% uncertainty)
  - Cell-to-Cell (relative; ~0.2 - 0.3% uncertainty)

Method	Irradiance Source	Description
Single Cell	Pulsed Simulator	Compare single cell map @ (X,Y) positions of cells in the module
Indoor Shift	Pulsed Simulator	Shift module in (X,Y) to sample the same points in irradiance field with different cells, then solve for both intrinsic field and the calibration values
Indoor Simple	Pulsed Simulator	Assume irradiance field is perfectly uniform (not true)
Outdoor	Natural Sunlight Two-Axis Tracker	Assume irradiance field is perfectly uniform (close approximation)

Calibration

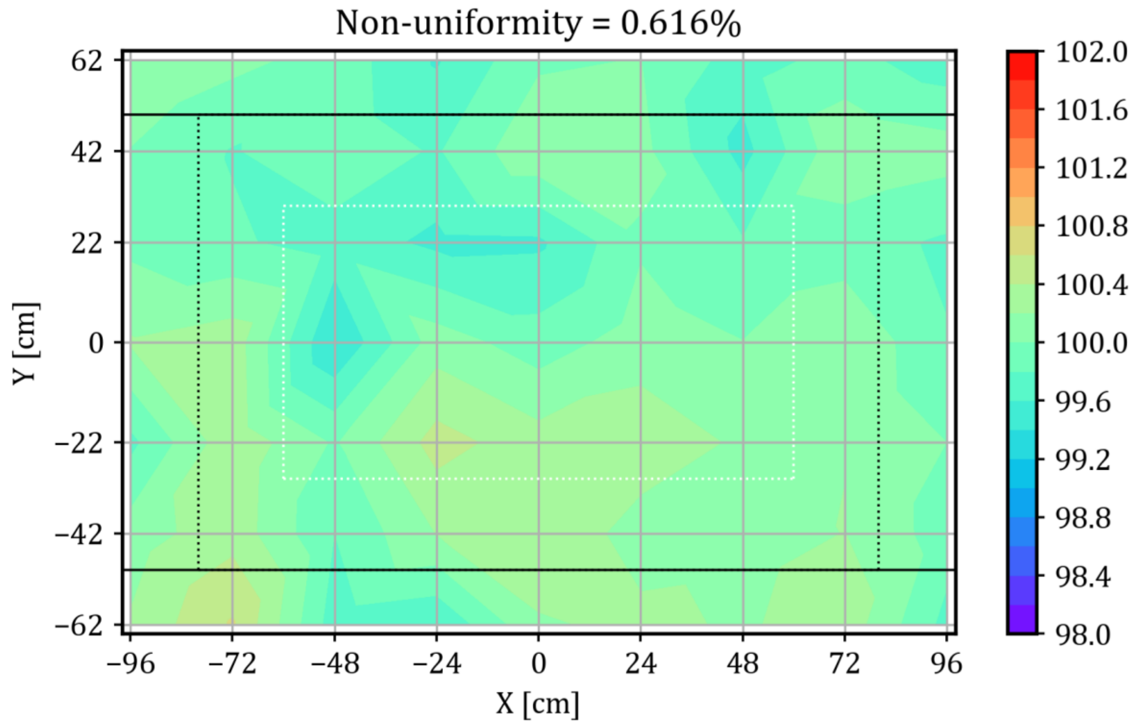
- Calibration is challenging!
- Indoor methods (pulsed simulator):
  - (+) Temperature controlled environment
  - (+) Flashes do not suffer from current shunt heating
  - (-) Time consuming (most methods)
- Outdoor method(s):
  - (+) One installation is needed, potentially faster
  - (-) Shunt resistors @ high temperature
  - (-) Input irradiance may not be perfectly uniform?





Indoor Applications: Pulsed Solar Simulator

- IEC 60904 method is time consuming (each point is one flash)
- IEC 60904 method not useful in the following cases:
  - Flash-to-flash (pulsed simulator)
  - Intraflash (pulsed simulator)
  - Time resolved continuous illumination
- New hardware and methods are required to characterize simulators in these regimes.



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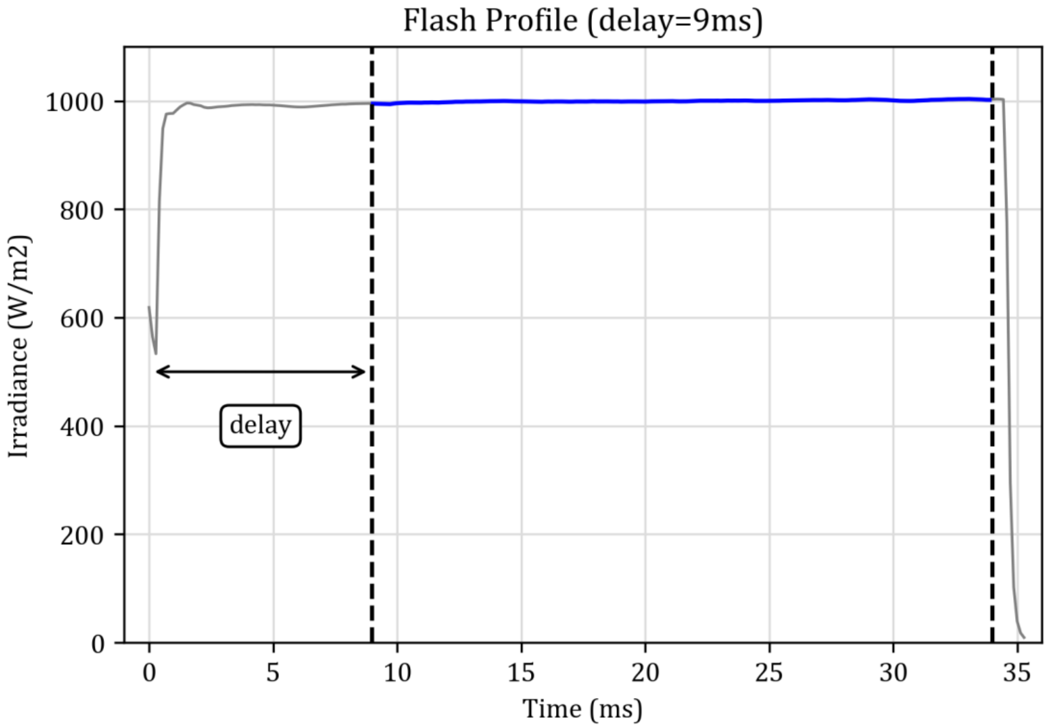
Indoor Applications: Pulsed Solar Simulator

How consistent is the uniformity during a flash?

- Flash Properties:
  - 1000 W/m² plateau
  - 35 ms duration, 25 ms measurement window
  - 5-12 ms delays tested (9 ms shown at right)
- SD of single-cell Isc < 0.3% over 25 ms
- Most flashes, SD of single-cell Isc < 0.2%



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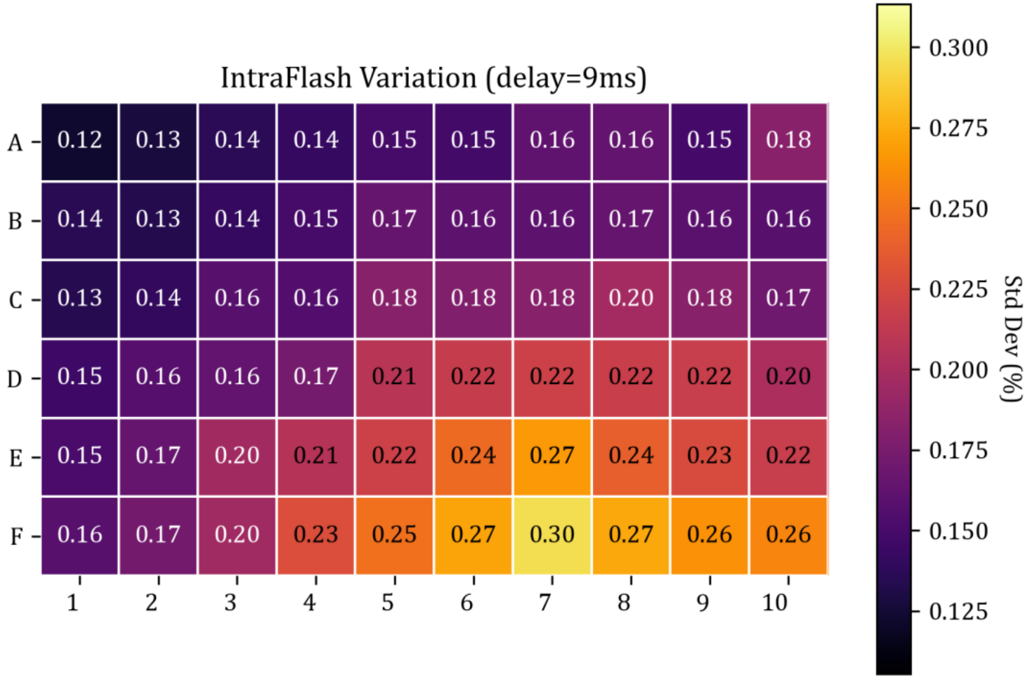

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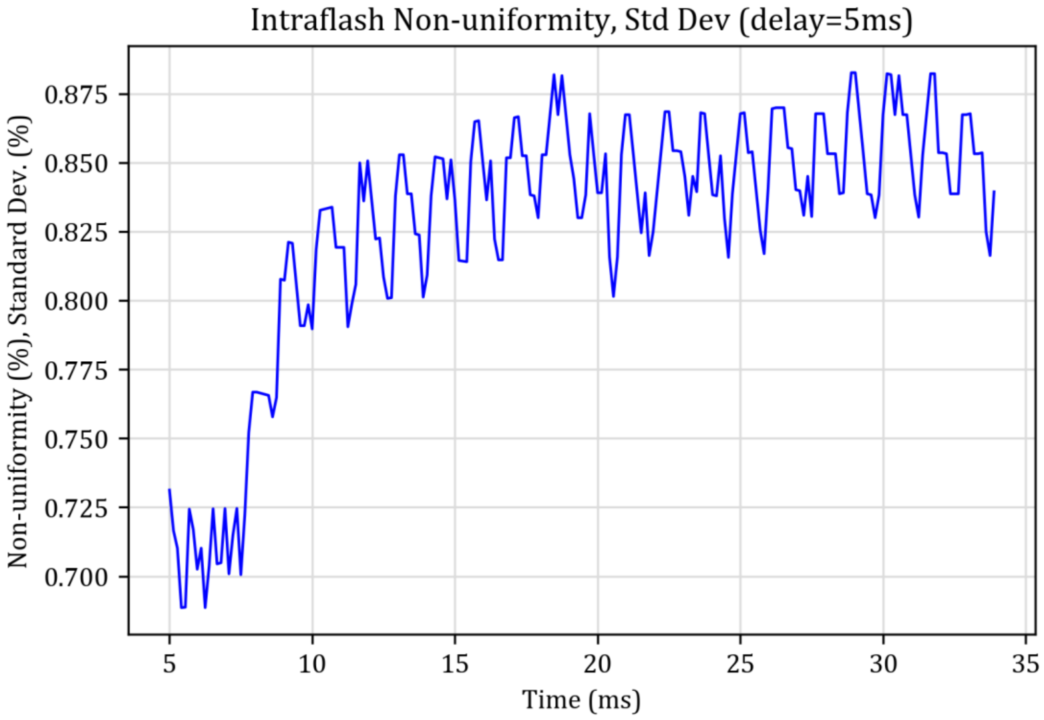
- Most flashes, SD of single-cell Isc < 0 2%
- NU variations when delay is short



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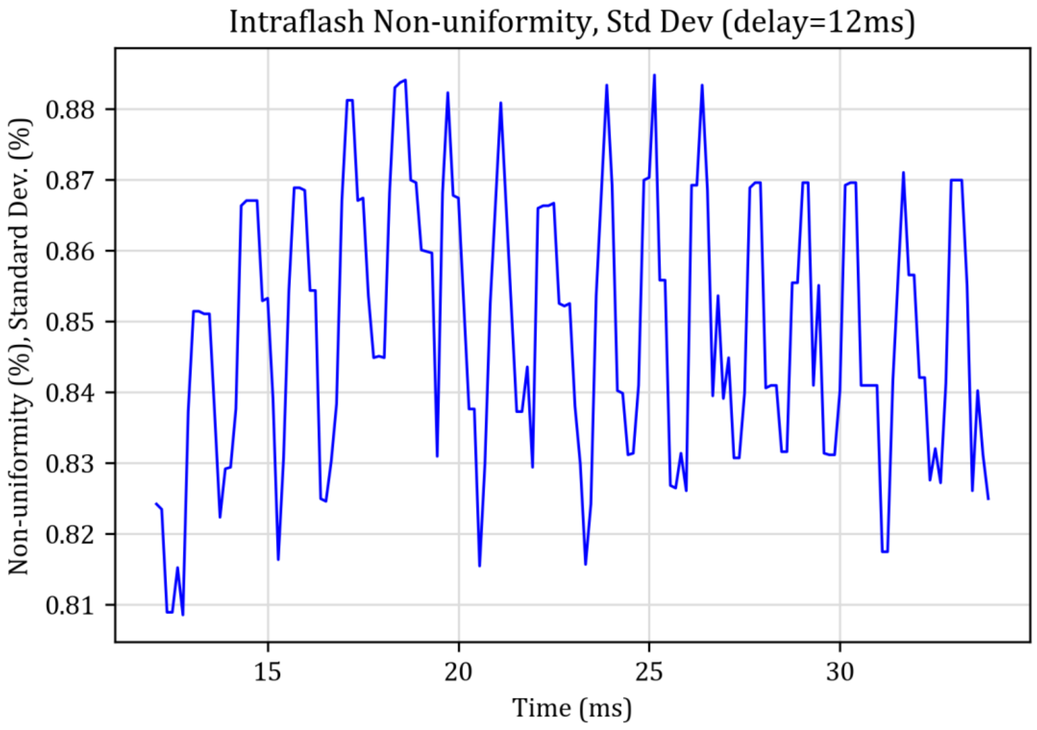
➢ Non-uniformity is stable during flash **<u>IF the delay is long enough.</u>**



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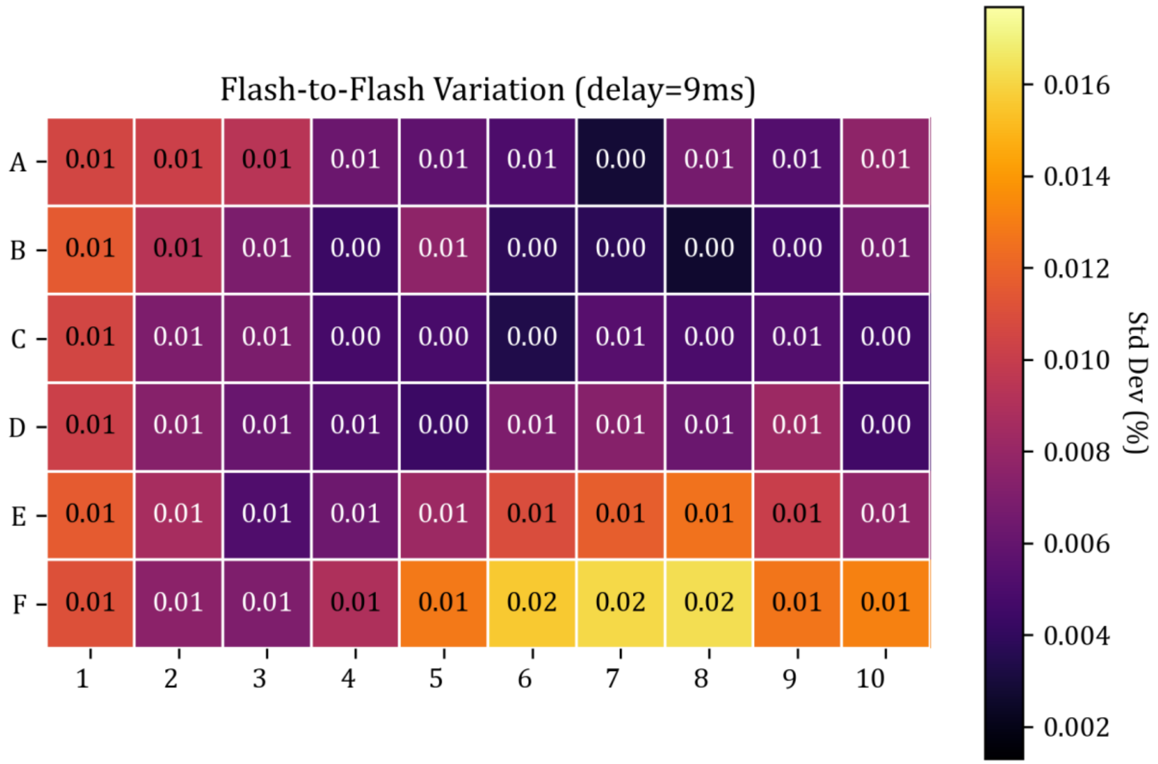
Indoor Applications: Pulsed Solar Simulator

How consistent is the uniformity from flash to flash?

- Flash-to-flash SD of the single-cell Isc <0.05%
- SD $NU_{FlashToFlash}$ < SD $NU_{IntraFlash}$
- Larger variations observed at the beginning of the flash
- Moving from 9 ms to 12 ms IV sweep delay reduces variation



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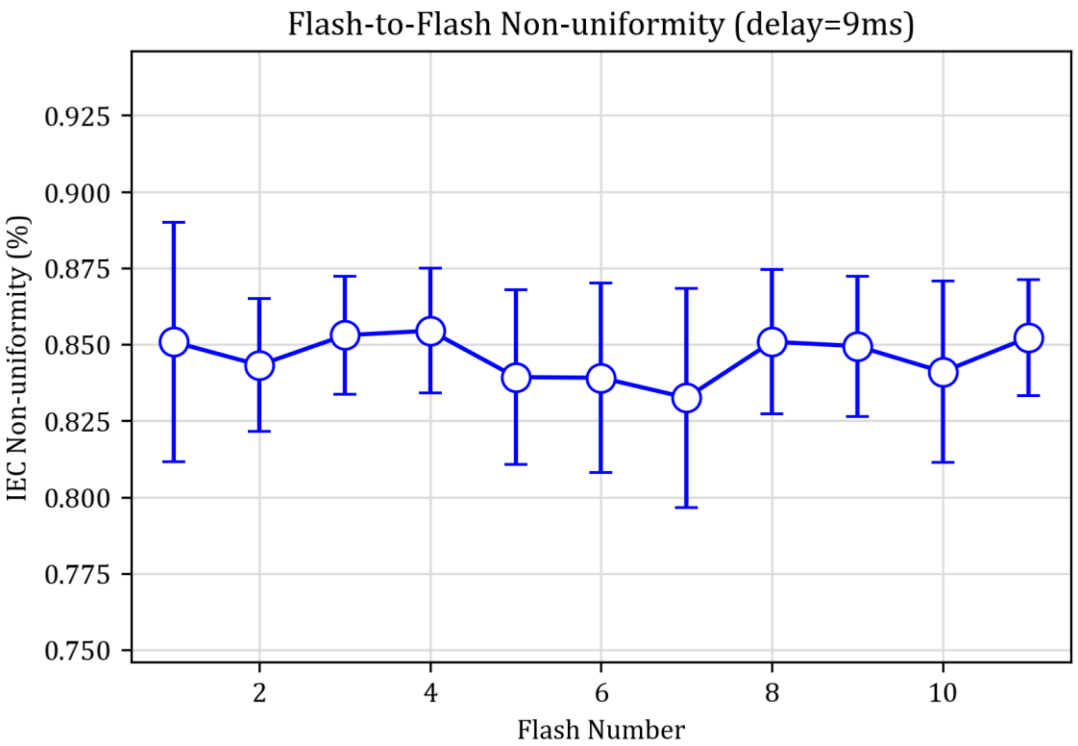

10 Flashes, 35 ms pulse duration with 9 ms delay. Flashes are 2 minutes apart.

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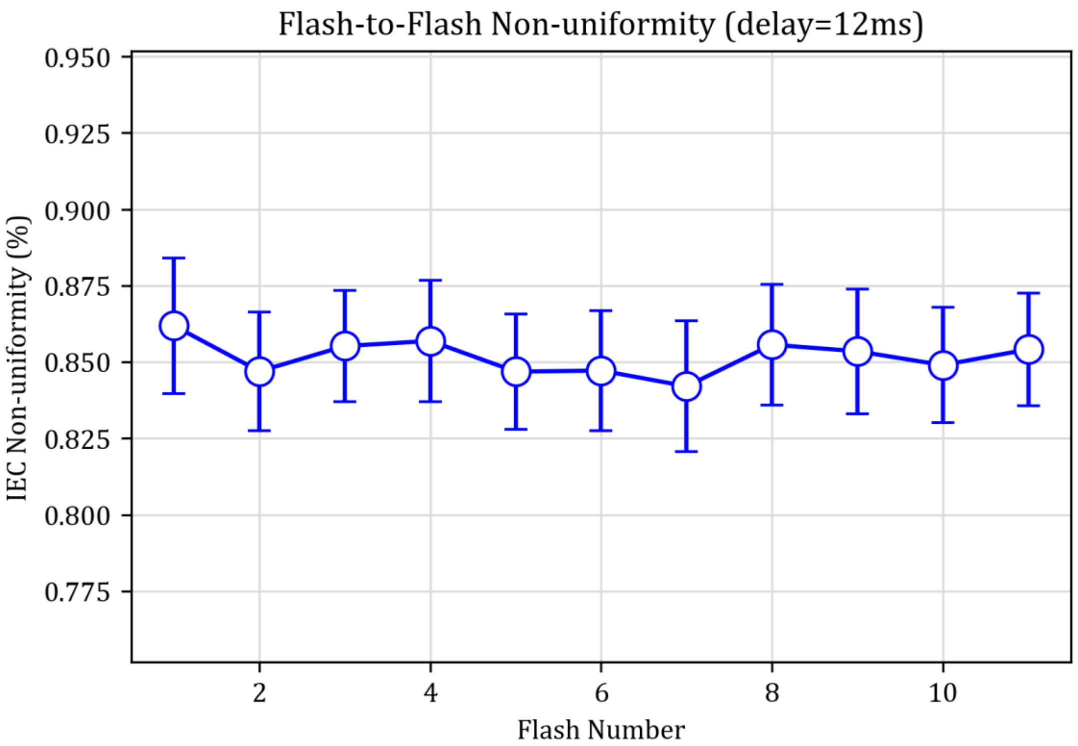

10 Flashes, 40 ms pulse duration with 12 ms delay. Flashes are 2 minutes apart.

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Indoor Applications: Pulsed Solar Simulator

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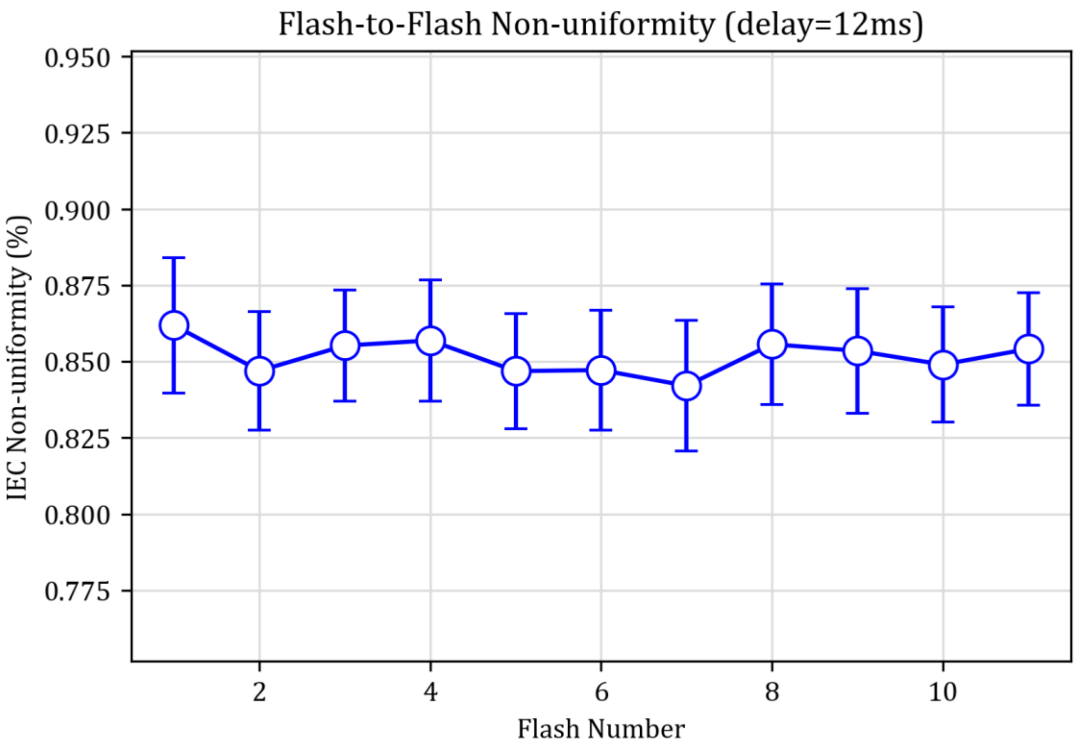
➢ Non-uniformity is stable from flash to flash



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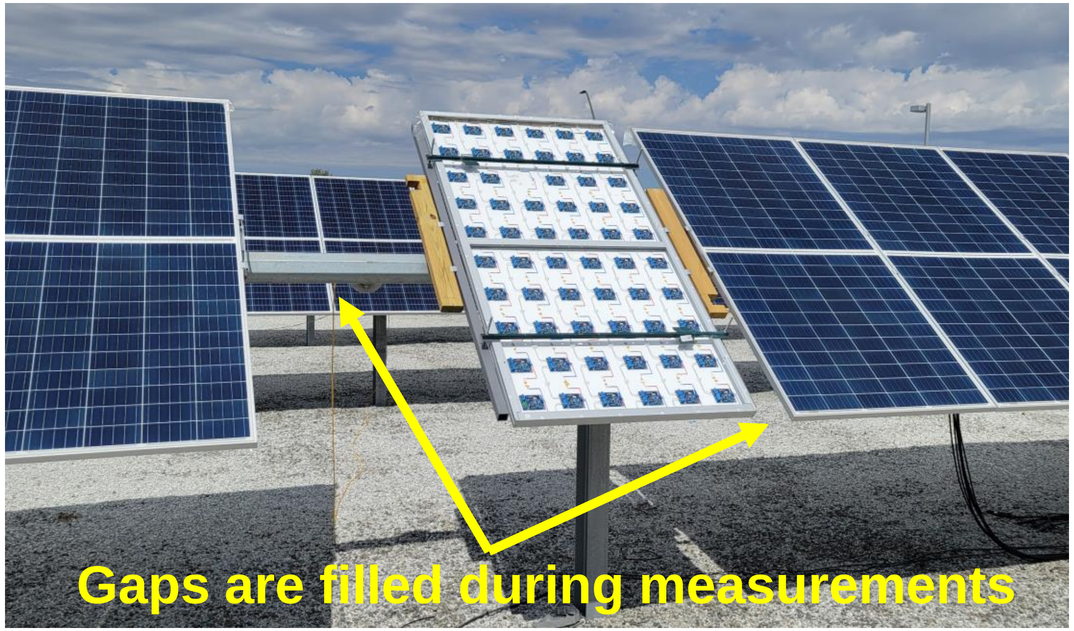
Outdoor Applications: Bifacial SAT Environments

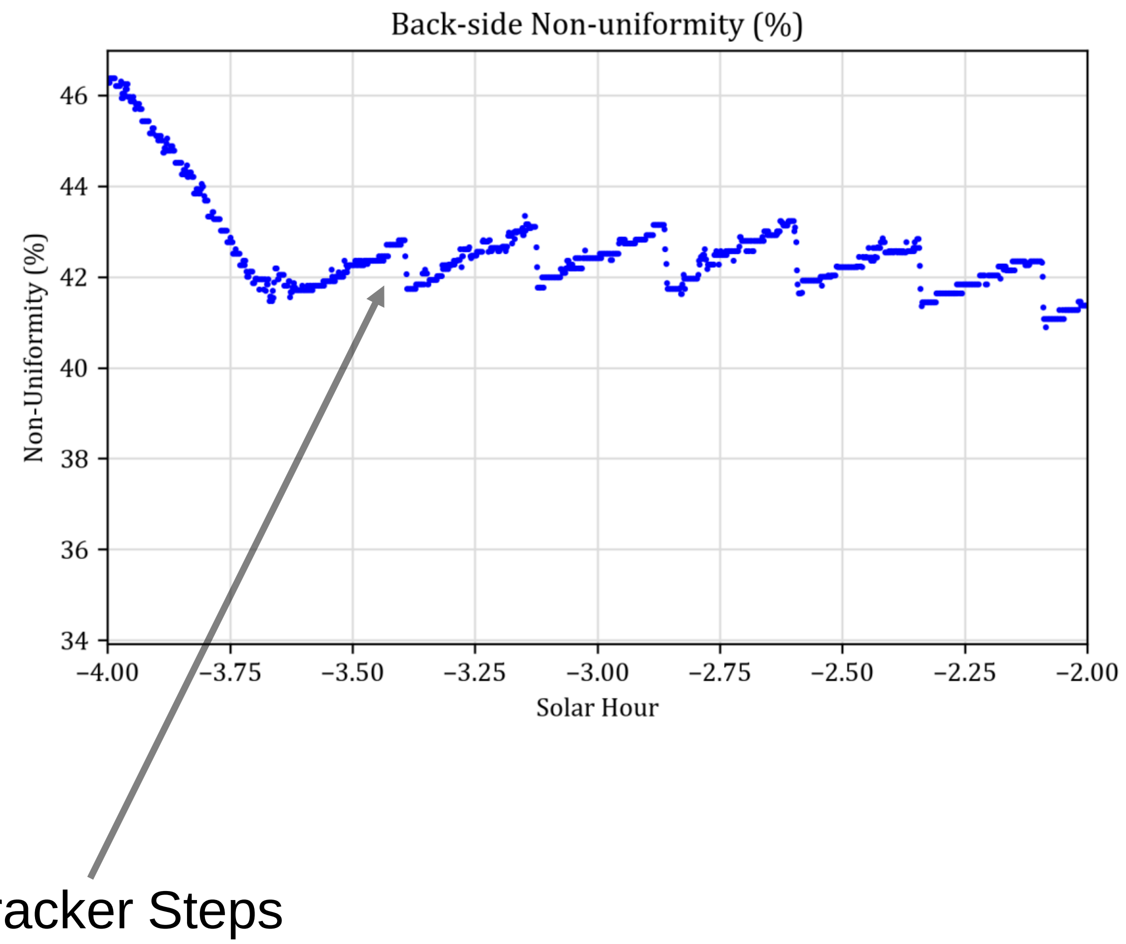
- Installed module in CFV's bifacial test yard to measure back-side irradiances
- Height-adjustable fixture, most standard module/clamp configurations can be tested
- Measurements within ±4 hours of solar noon for 2-3 days, three configurations:
  - Module-to-TT gap (51 mm), between piers
  - Module-to-TT gap (64 mm), between piers
  - Module-to-TT gap (64 mm), above pier
- Albedo ~28%, GCR ~ 0.37



Outdoor Applications: Bifacial SAT Measurements

- ➢2D time-resolved irradiance maps, 5 second sample frequency

- Factors that influence the irradiance non-uniformity include:
  - View factor (ground illumination, height, etc.)
  - Shading losses (torque tube, clamps, piers, etc.)



Outdoor Applications: Bifacial SAT Measurements

- 2D time-resolved irradiance maps, 5 second measurement interval

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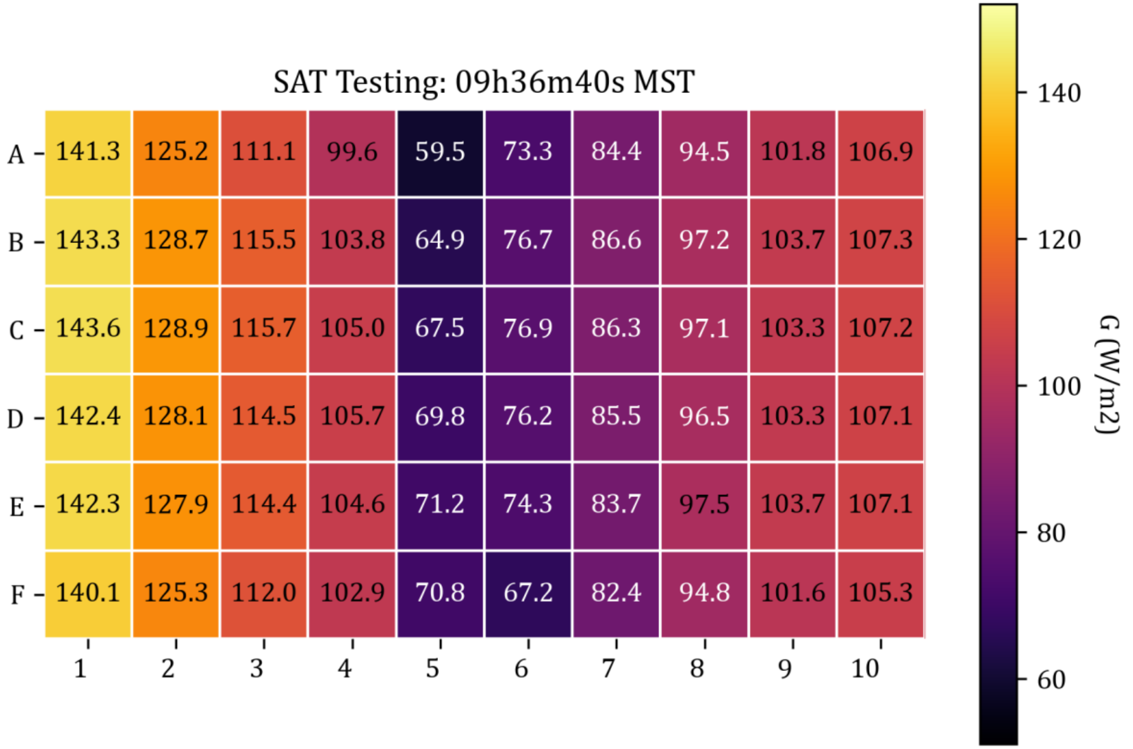

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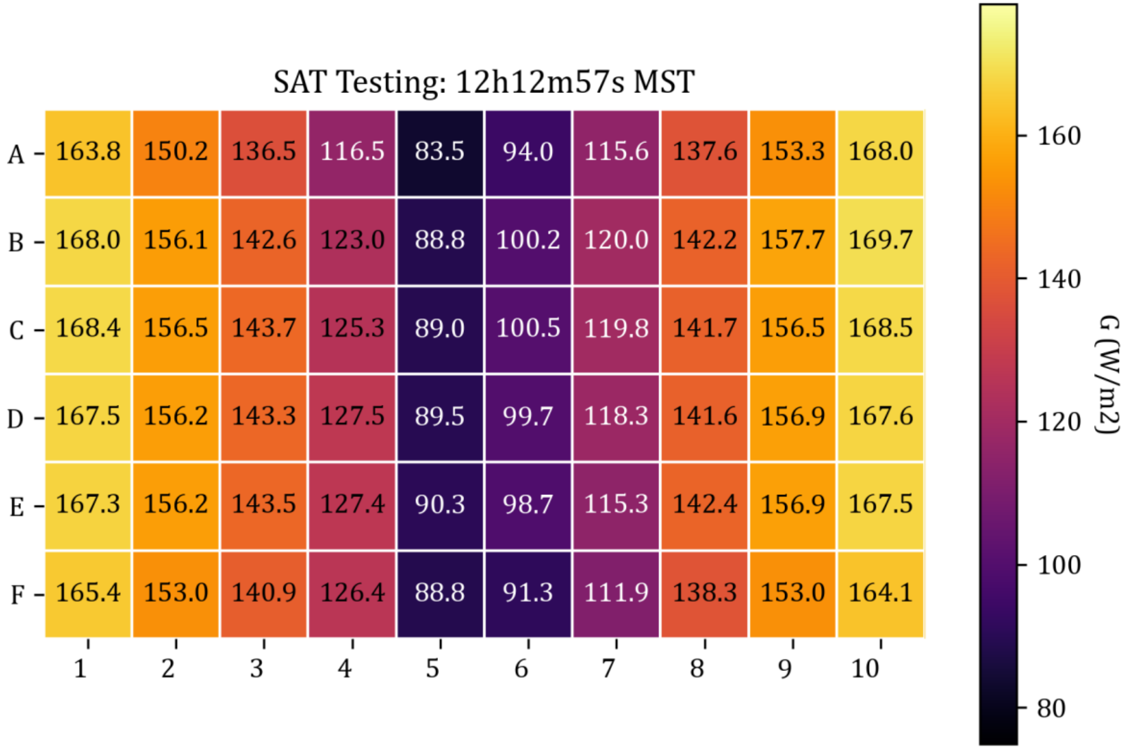

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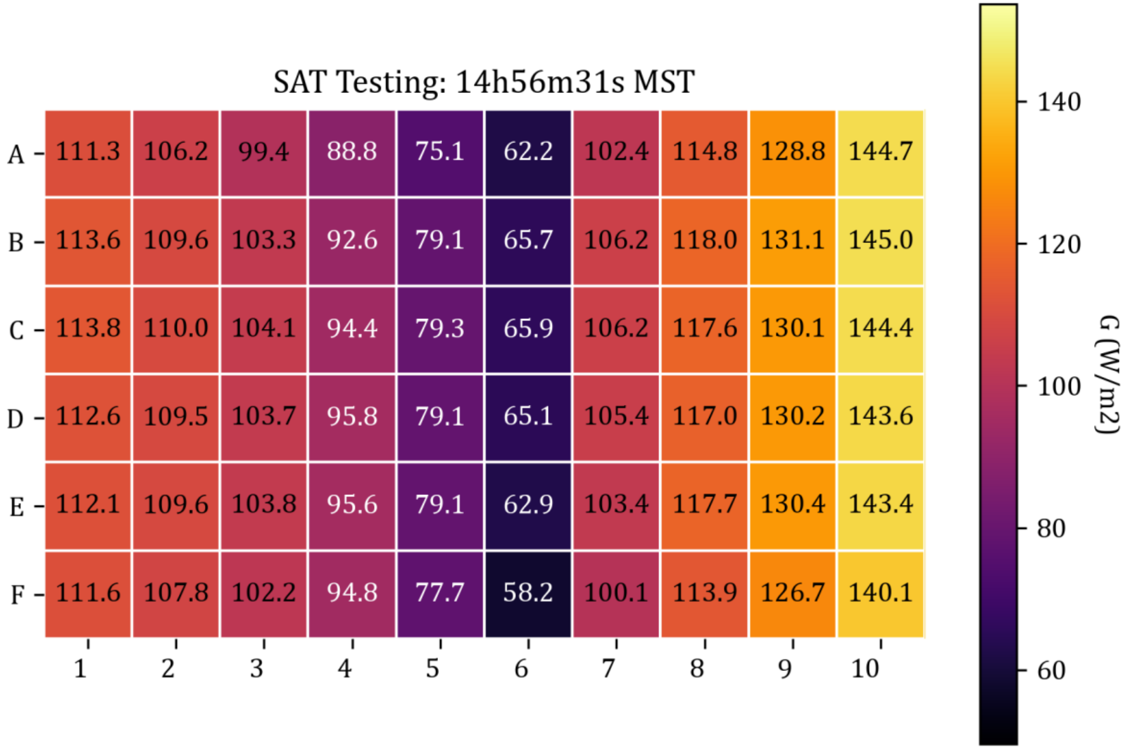

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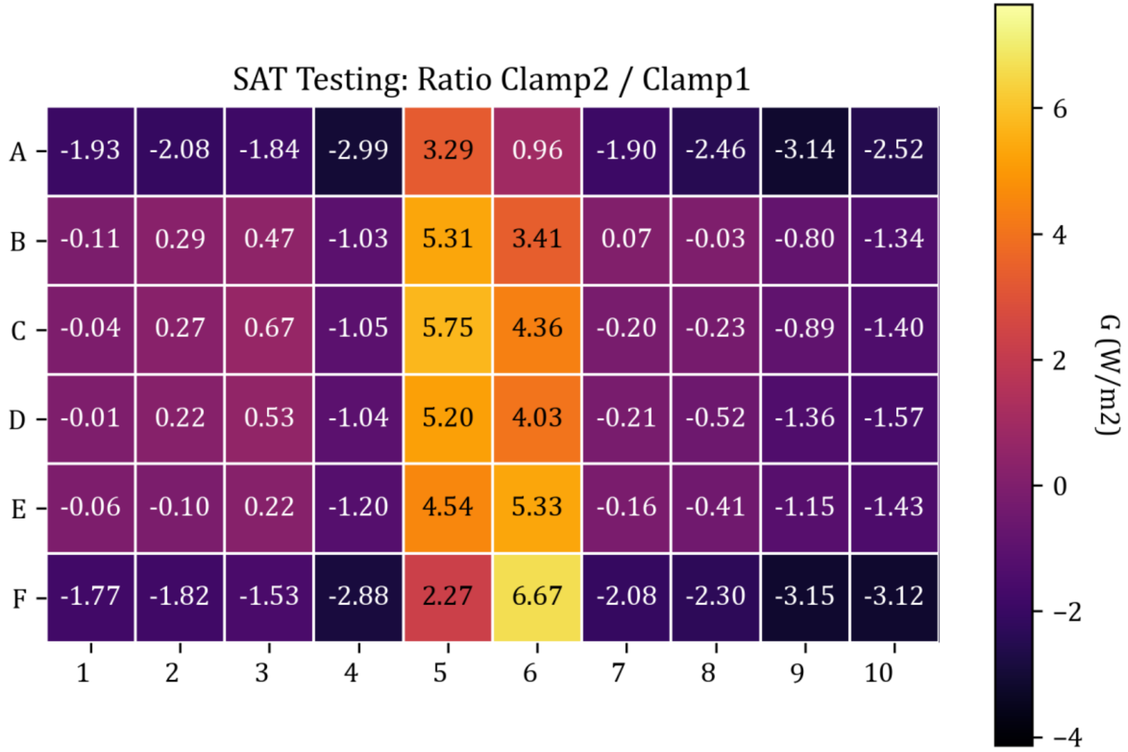
Outdoor Applications: Bifacial SAT Environment Comparisons

- ➢Ratios of the irradiance maps serve as a useful diagnostic
- ➢Clamp 2 / Clamp 1 isolates the effect of module height above the torque tube
  - The measured increase in the back-side irradiance over the torque tube is ~ 4.3% when increasing the gap from 51mm to 64mm



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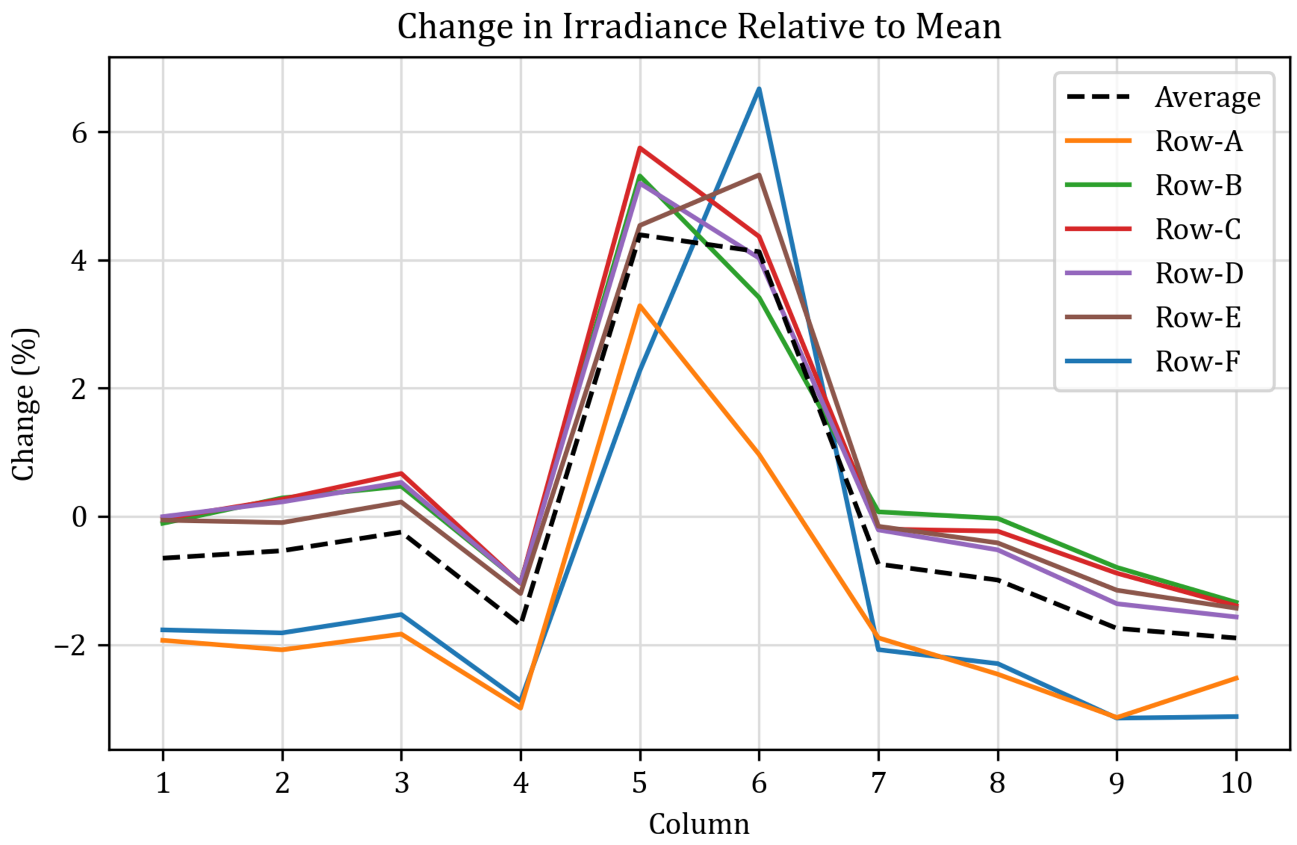

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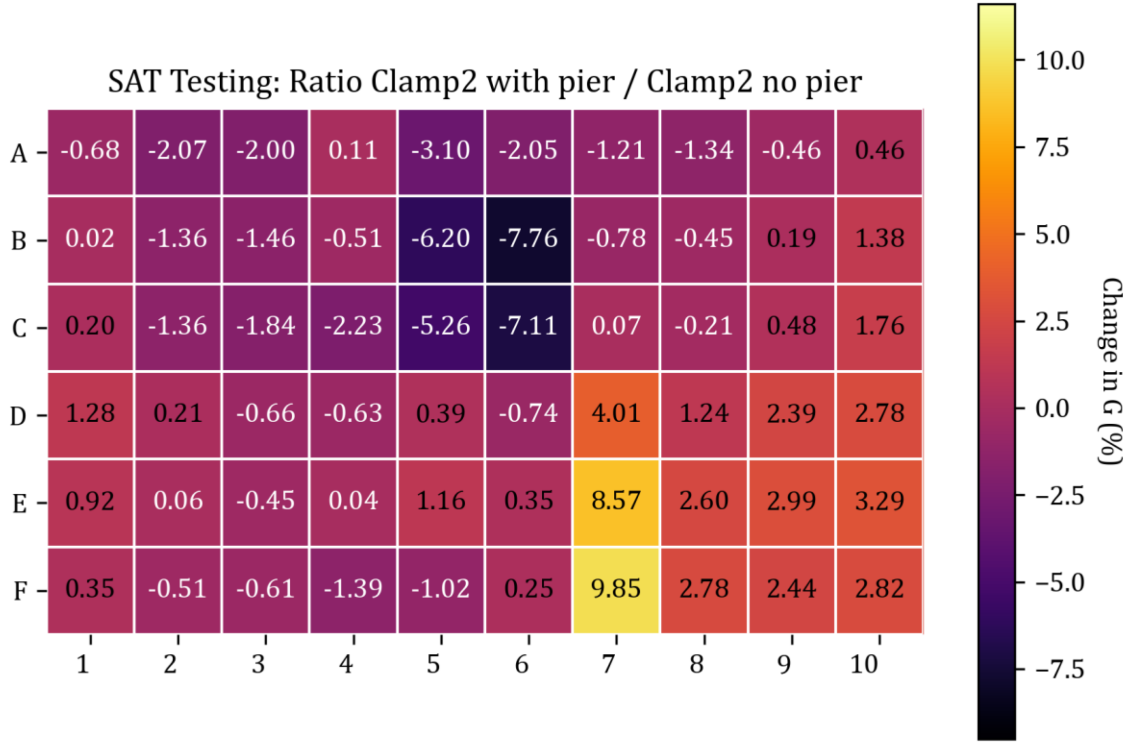
Outdoor Applications: Bifacial SAT Environment Comparisons

- Clamp 2 maps can be used to isolate the effect of the pier
  - Decrease of ~7.4% north of the pier
  - Increase of ~4-10% southeast of the pier
  - These measurements were taken over mixed weather conditions, additional data is required



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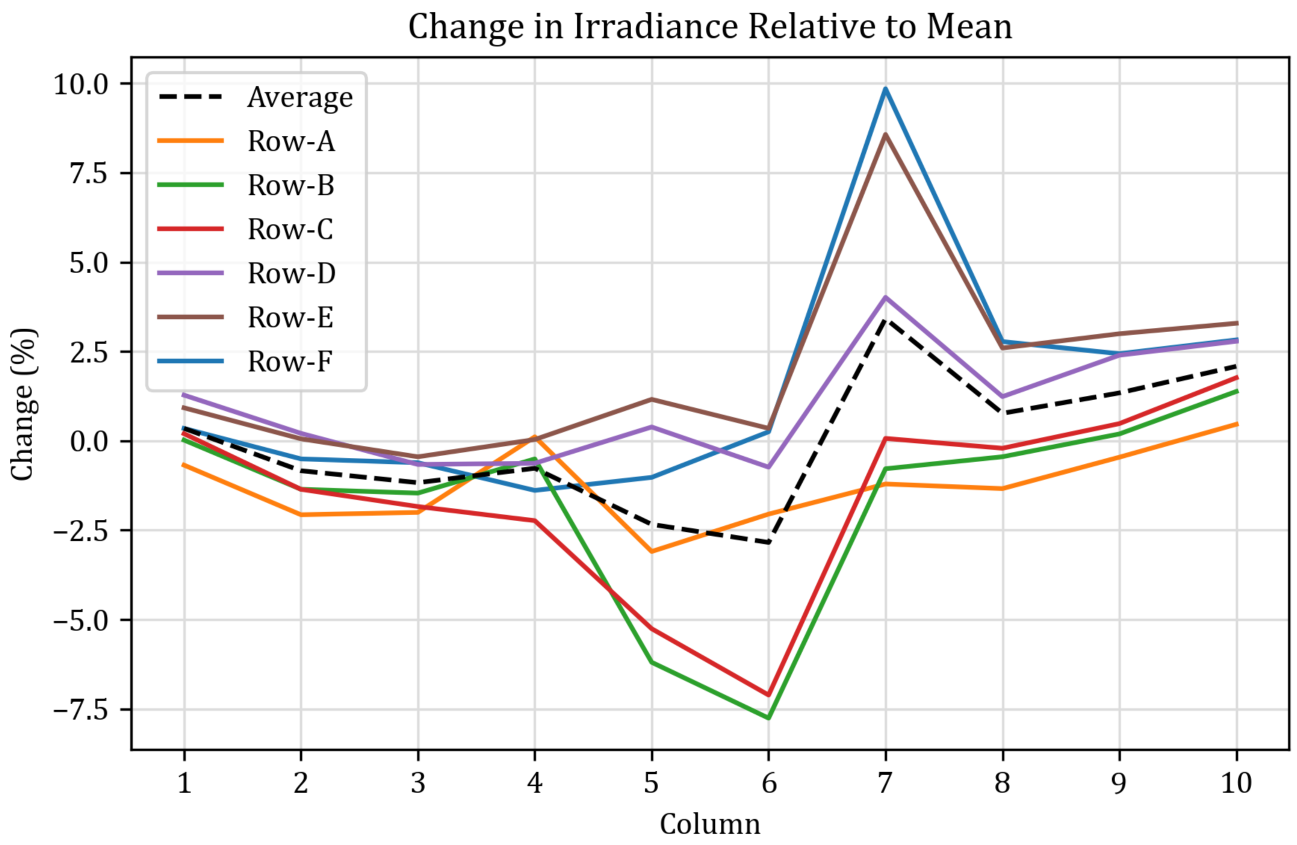

Summary

- A 2-dimensional uniformity mapping module was developed and tested at CFV
- The irradiance uniformity of a short pulse solar simulator was measured to be stable in the following regimes:
  - During a flash
  - Flash to flash
- Initial outdoor measurements demonstrate the ability to measure:
  - Time resolved intramodule variations in back-side irradiance
  - Sensitivity to different module clamping configurations and mounting locations

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Thank you!

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