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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



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):

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- (+) One installation is needed, potentially faster
- (-) Shunt resistors @ high temperature
- (-) Input irradiance may not be perfectly uniform?



- 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.



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 lsc < 0.3% over 25 ms
- Most flashes, SD of single-cell lsc < 0.2%



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

SD of single-cell Isc < 0.3% over 25 ms
Most flashes, SD of single-cell Isc < 0.2%

| | IntraFlash Variation (delay=9ms) | | | | | | | | | | | | | | |
|-----|----------------------------------|------|------|------|--------|------|--------|--------|--------|---------|--|--|---------------|--|--|
| A - | 0.12 | 0.13 | 0.14 | 0.14 | 0.15 | 0.15 | 0.16 | 0.16 | 0.15 | 0.18 | | | - 0.275 | | |
| В - | 0.14 | 0.13 | 0.14 | 0.15 | 0.17 | 0.16 | 0.16 | 0.17 | 0.16 | 0.16 | | | - 0.250 | | |
| С- | 0.13 | 0.14 | 0.16 | 0.16 | 0.18 | 0.18 | 0.18 | 0.20 | 0.18 | 0.17 | | | - 0.225 Std L | | |
| D - | 0.15 | 0.16 | 0.16 | 0.17 | 0.21 | 0.22 | 0.22 | 0.22 | 0.22 | 0.20 | | | - 0.200 🛞 | | |
| E - | 0.15 | 0.17 | 0.20 | 0.21 | 0.22 | 0.24 | 0.27 | 0.24 | 0.23 | 0.22 | | | - 0.175 | | |
| F - | 0.16 | 0.17 | 0.20 | 0.23 | 0.25 | 0.27 | 0.30 | 0.27 | 0.26 | 0.26 | | | - 0.150 | | |
| | 1 | 2 | 3 | 4 | י 5 | 6 | ' 7 | і 8 | י 9 | 10 1 | | | - 0.125 | | |

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
- SD of single-cell lsc < 0.3% over 25 ms
- Most flashes, SD of single-cell lsc < 0 2%
- NU variations when delay is short



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
- SD of single-cell lsc < 0.3% over 25 ms
- Most flashes, SD of single-cell lsc < 0.2%
- Non-uniformity is stable during flash IF the delay is long enough.



How consistent is the uniformity from flash to flash?

Flash-to-flash SD of the single-cell lsc <0.05%</p>

- SD NU_{FlashToFlash} < SD NU_{IntraFlash}
- Larger variations observed at the beginning of the flash

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• Moving from 9 ms to 12 ms IV sweep delay reduces variation

| | Flash-to-Flash Variation (delay=9ms) | | | | | | | | | | | | | | |
|-----|--------------------------------------|------|------|------|------|------|------|------|------|------|--|--|--|--|--|
| A - | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | | | | | |
| в - | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | | | | | |
| с - | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | | | | | |
| D - | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | | | | | |
| E - | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | | | | | |
| F - | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | | | |



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How consistent is the uniformity from flash to flash?

- Flash-to-flash SD of the single-cell lsc <0.05%
- SD NU_{FlashToFlash} < SD NU_{IntraFlash}
- Larger variations observed at the beginning of the flash

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 Moving from 9 ms to 12 ms IV sweep delay reduces variation



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

How consistent is the uniformity from flash to flash?

- Flash-to-flash SD of the single-cell lsc <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



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

How consistent is the uniformity from flash to flash?

- Flash-to-flash SD of the single-cell lsc <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
- Non-uniformity is stable from flash to flash



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

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





>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.)



- 2D time-resolved irradiance maps, 5 second measurement interval
- Factors that influence the irradiance non-uniformity include:
 - View factor (ground illumination, height, etc.)
 - Shading losses (torque tube, clamps, piers, etc.)

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| | SAT Testing: 09h36m40s MST | | | | | | | | | | | | | | |
|-----|----------------------------|-------|-------|-------|------|------|------|------|-------|-------|--|---|-------|--|--|
| A - | 141.3 | 125.2 | 111.1 | 99.6 | 59.5 | 73.3 | 84.4 | 94.5 | 101.8 | 106.9 | | | | | |
| В - | 143.3 | 128.7 | 115.5 | 103.8 | 64.9 | 76.7 | 86.6 | 97.2 | 103.7 | 107.3 | | ŀ | - 120 | | |
| C - | 143.6 | 128.9 | 115.7 | 105.0 | 67.5 | 76.9 | 86.3 | 97.1 | 103.3 | 107.2 | | | | | |
| D - | 142.4 | 128.1 | 114.5 | 105.7 | 69.8 | 76.2 | 85.5 | 96.5 | 103.3 | 107.1 | | | - 100 | | |
| E - | 142.3 | 127.9 | 114.4 | 104.6 | 71.2 | 74.3 | 83.7 | 97.5 | 103.7 | 107.1 | | | - 80 | | |
| F - | 140.1 | 125.3 | 112.0 | 102.9 | 70.8 | 67.2 | 82.4 | 94.8 | 101.6 | 105.3 | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | - 60 | | |

G(W/m2)

- 2D time-resolved irradiance maps, 5 second measurement interval
- \succ Factors that influence the irradiance non-uniformity include:
 - View factor (ground illumination, height, etc.)
 - Shading losses (torque tube, clamps, piers, etc.)

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| | SAT Testing: 12h12m57s MST | | | | | | | | | | | | | |
|-----|----------------------------|-------|-------|-------|------|-------|-------|-------|-------|-------|--|--|---------|--|
| A - | 163.8 | 150.2 | 136.5 | 116.5 | 83.5 | 94.0 | 115.6 | 137.6 | 153.3 | 168.0 | | | • 160 | |
| В - | 168.0 | 156.1 | 142.6 | 123.0 | 88.8 | 100.2 | 120.0 | 142.2 | 157.7 | 169.7 | | | - 140 | |
| C - | 168.4 | 156.5 | 143.7 | 125.3 | 89.0 | 100.5 | 119.8 | 141.7 | 156.5 | 168.5 | | | G (W | |
| D - | 167.5 | 156.2 | 143.3 | 127.5 | 89.5 | 99.7 | 118.3 | 141.6 | 156.9 | 167.6 | | | · 120) | |
| E - | 167.3 | 156.2 | 143.5 | 127.4 | 90.3 | 98.7 | 115.3 | 142.4 | 156.9 | 167.5 | | | | |
| F - | 165.4 | 153.0 | 140.9 | 126.4 | 88.8 | 91.3 | 111.9 | 138.3 | 153.0 | 164.1 | | | - 100 | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | - 80 | |

- 2D time-resolved irradiance maps, 5 second measurement interval
- Factors that influence the irradiance non-uniformity include:
 - View factor (ground illumination, height, etc.)
 - Shading losses (torque tube, clamps, piers, etc.)

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| | SAT Testing: 14h56m31s MST | | | | | | | | | | | | | |
|-----|----------------------------|-------|-------|------|------|------|-------|-------|-------|-------|--|--|------------|--|
| A - | 111.3 | 106.2 | 99.4 | 88.8 | 75.1 | 62.2 | 102.4 | 114.8 | 128.8 | 144.7 | | | | |
| В - | 113.6 | 109.6 | 103.3 | 92.6 | 79.1 | 65.7 | 106.2 | 118.0 | 131.1 | 145.0 | | | - 120 | |
| С - | 113.8 | 110.0 | 104.1 | 94.4 | 79.3 | 65.9 | 106.2 | 117.6 | 130.1 | 144.4 | | | G(W | |
| D - | 112.6 | 109.5 | 103.7 | 95.8 | 79.1 | 65.1 | 105.4 | 117.0 | 130.2 | 143.6 | | | - 100 /m2] | |
| E - | 112.1 | 109.6 | 103.8 | 95.6 | 79.1 | 62.9 | 103.4 | 117.7 | 130.4 | 143.4 | | | - 80 | |
| F - | 111.6 | 107.8 | 102.2 | 94.8 | 77.7 | 58.2 | 100.1 | 113.9 | 126.7 | 140.1 | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | - 60 | |

- 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 backside irradiance over the torque tube is ~ 4.3% when increasing the gap from 51mm to 64mm

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| | SAT Testing: Ratio Clamp2 / Clamp1 | | | | | | | | | | | | | |
|-----|------------------------------------|-------|-------|-------|------|------|-------|-------|-------|-------|--|--|--|--|
| A - | -1.93 | -2.08 | -1.84 | -2.99 | 3.29 | 0.96 | -1.90 | -2.46 | -3.14 | -2.52 | | | | |
| B - | -0.11 | 0.29 | 0.47 | -1.03 | 5.31 | 3.41 | 0.07 | -0.03 | -0.80 | -1.34 | | | | |
| C - | -0.04 | 0.27 | 0.67 | -1.05 | 5.75 | 4.36 | -0.20 | -0.23 | -0.89 | -1.40 | | | | |
| D - | -0.01 | 0.22 | 0.53 | -1.04 | 5.20 | 4.03 | -0.21 | -0.52 | -1.36 | -1.57 | | | | |
| E - | -0.06 | -0.10 | 0.22 | -1.20 | 4.54 | 5.33 | -0.16 | -0.41 | -1.15 | -1.43 | | | | |
| F - | -1.77 | -1.82 | -1.53 | -2.88 | 2.27 | 6.67 | -2.08 | -2.30 | -3.15 | -3.12 | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | | |

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G (W/m2)

- 0

- 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



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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| | SAT Testing: Ratio Clamp2 with pier / Clamp2 no pier | | | | | | | | | | | | | | |
|-----|--|-------|-------|-------|-------|-------|-------|-------|-------|------|--|--|-------|--|--|
| A - | -0.68 | -2.07 | -2.00 | 0.11 | -3.10 | -2.05 | -1.21 | -1.34 | -0.46 | 0.46 | | | - 7.5 | | |
| B - | 0.02 | -1.36 | -1.46 | -0.51 | -6.20 | -7.76 | -0.78 | -0.45 | 0.19 | 1.38 | | | - 5.0 | | |
| C - | 0.20 | -1.36 | -1.84 | -2.23 | -5.26 | -7.11 | 0.07 | -0.21 | 0.48 | 1.76 | | | - 2.5 | | |
| D - | 1.28 | 0.21 | -0.66 | -0.63 | 0.39 | -0.74 | 4.01 | 1.24 | 2.39 | 2.78 | | | - 0.0 | | |
| E - | 0.92 | 0.06 | -0.45 | 0.04 | 1.16 | 0.35 | 8.57 | 2.60 | 2.99 | 3.29 | | | 2.5 | | |
| F - | 0.35 | -0.51 | -0.61 | -1.39 | -1.02 | 0.25 | 9.85 | 2.78 | 2.44 | 2.82 | | | 5.0 | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | 7.5 | | |

Change in G (%)

- 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





- 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



Thank you!

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