Detailed Investigations into PV Cell Cracks – Why Some Cracks Can Lead to Power Loss

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DuraMAT Monthly Webinar Series

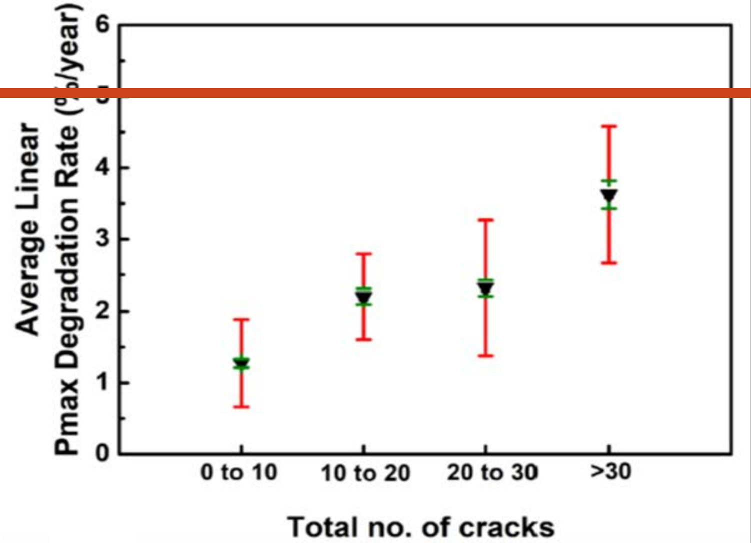
Nov. 9, 2020

Agenda

- Research gaps
- Desired outcomes of DuraMAT research
- Ways to detect and characterize cracks
- Things that matter
- EPRI project updates
- Sandia project updates

Research gaps

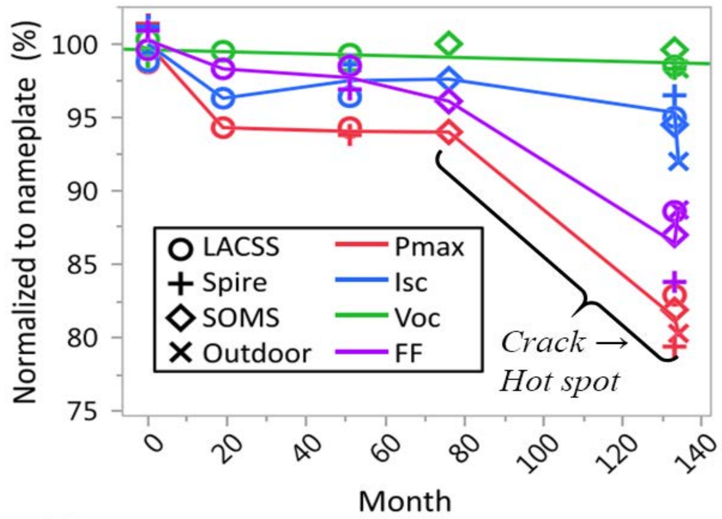
- *Expectation based on new module qualification tests*: Cracks have minimal impact on power loss
- *Real world*: Cracks may cause performance degradation and safety issues (hot spots)
- Environmental stressors, damage during installation or maintenance, or extreme weather may introduce new cracks and/or lead to unanticipated crack progression
- Linkage between cracks and performance loss are not fully understood, leading to project financial uncertainty.



Source: N. Shiradkar, PVRW 2018.

Field measurements link cracks to increased degradation

Delayed formation of a hot spot

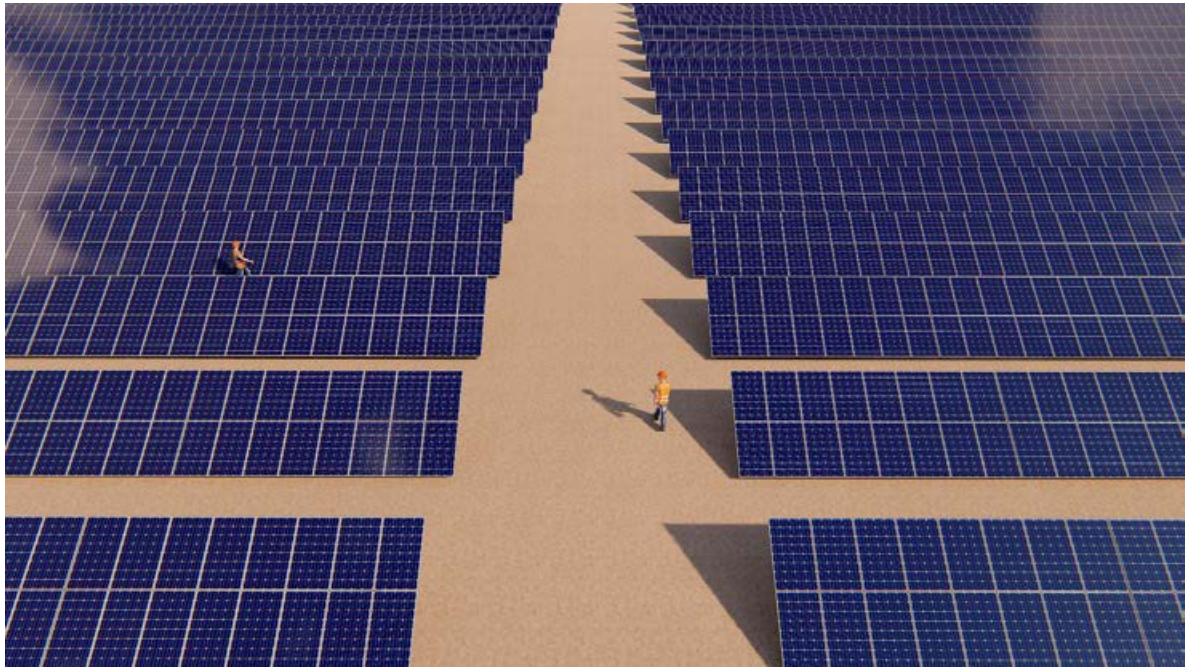


Source: D. Jordan, et al. *Prog. Photovolt.*, 2017.

Research is needed to understand what is happening in the field and reproduce it in physical testing and modeling simulations.

Desired outcomes

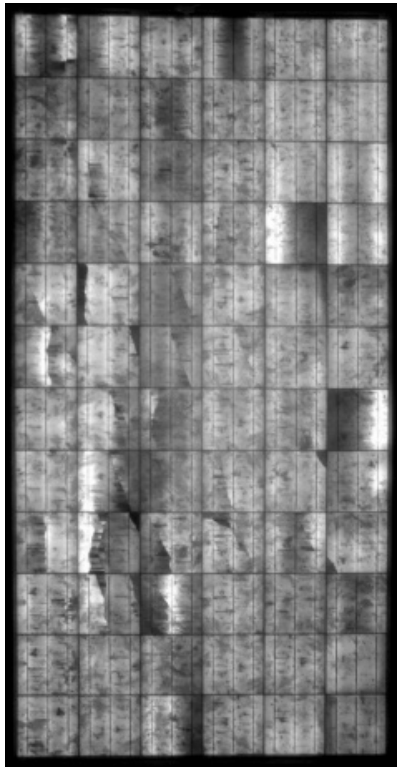
- Set crack thresholds for large-scale PV plant commissioning, operations, and maintenance
- Reduce uncertainty in levelized cost of electricity (LCOE) predictions
- Inform new module designs
- Enable improved qualification test procedures
- Improve simulation capabilities



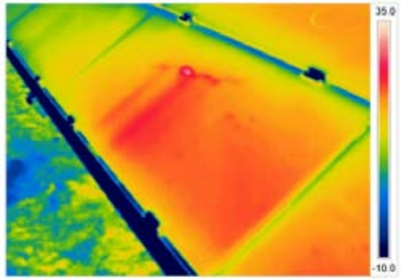
Understanding crack impacts reduces lifetime PV plant performance risk.

Ways to detect and characterize crack features

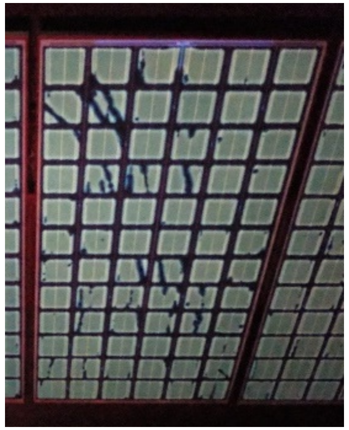
Visually



Electroluminescence (EL)



Infrared

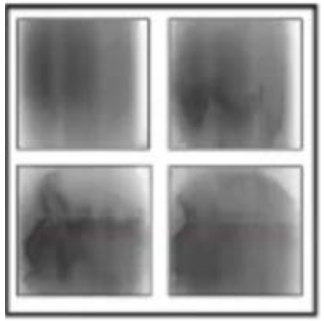


Source: Southern Company

Ultraviolet Fluorescence (UV-F)

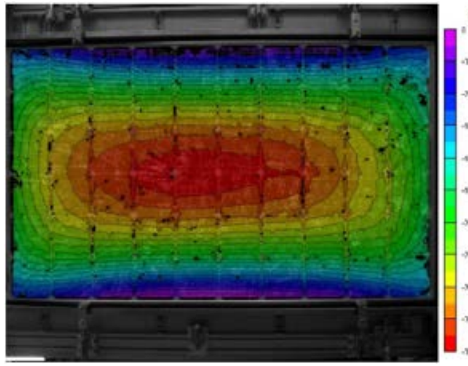
Source: NREL

Photoluminescence (PL)



Source: ASU

X-ray topography



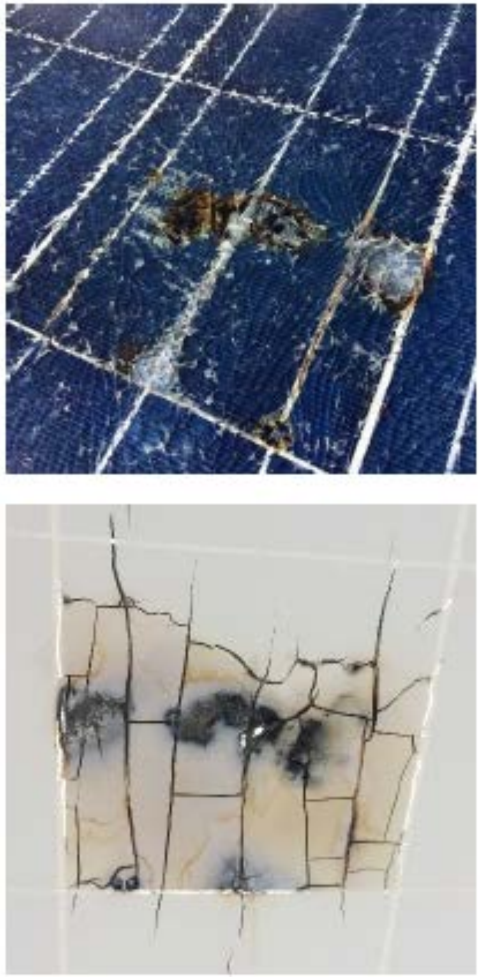
Source: Sandia

Digital Image Correlation (DIC)

Each option (and variations of these options) has benefits and limitations in terms of ease of use, speed, resolution, and other capabilities.

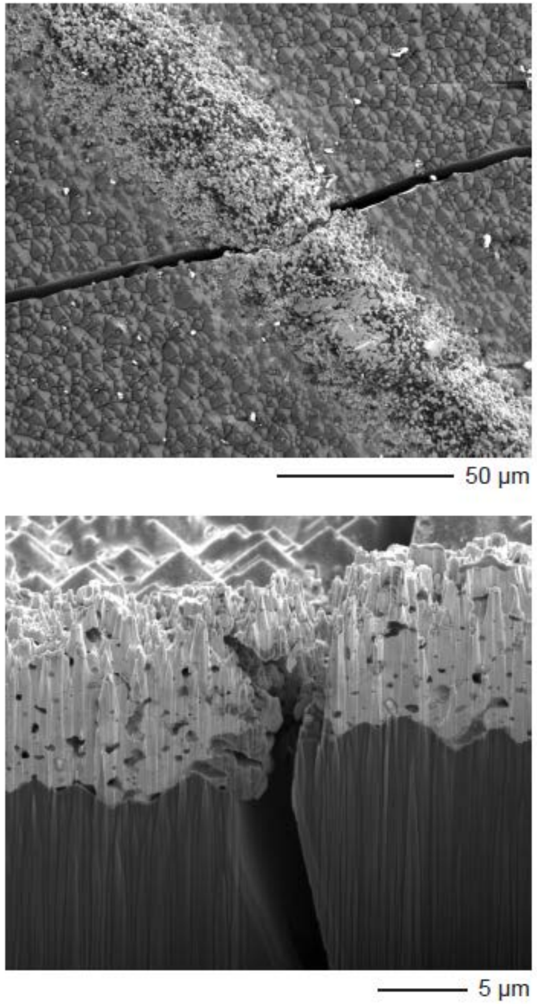
Things that matter

- Cracks that cause hot spots
- Movement within the laminate
  - Temperature
  - Mechanical stress
- Irradiance
- Crack width



Source: Southern Company

Cracked cell with multiple hot spots



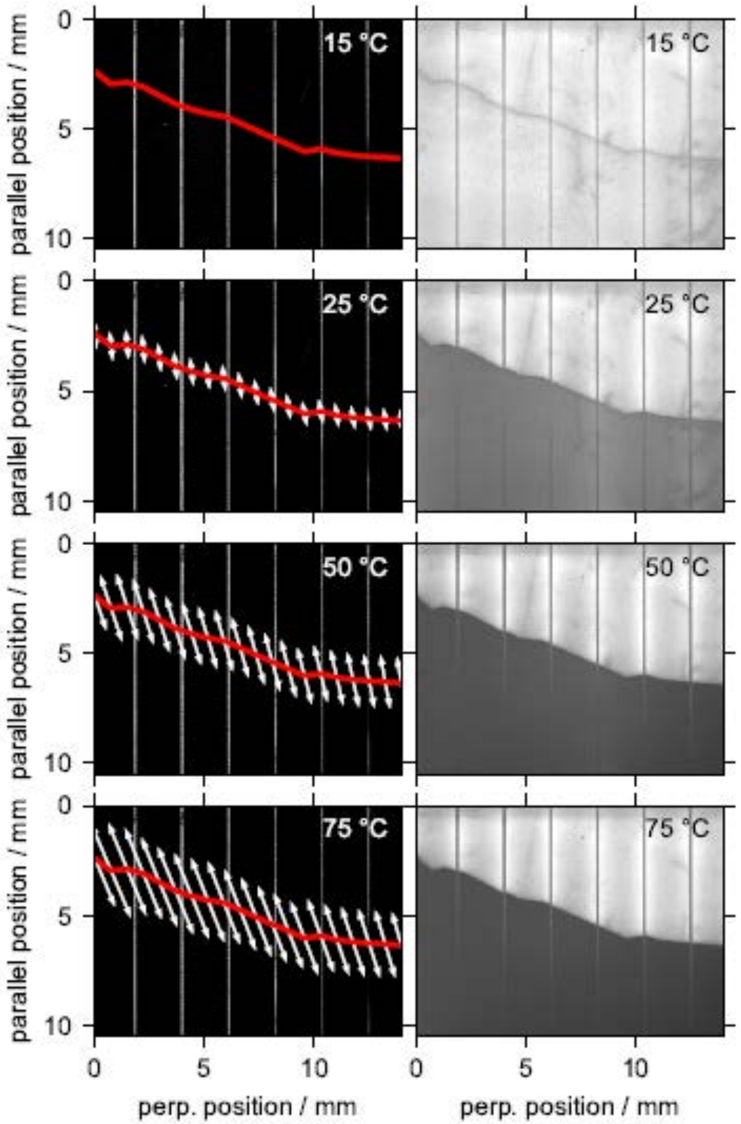
Source: T. Silverman, et al. *PVSC*, 2019.

SEM images of metalization bridge over cell crack

Movement within the laminate

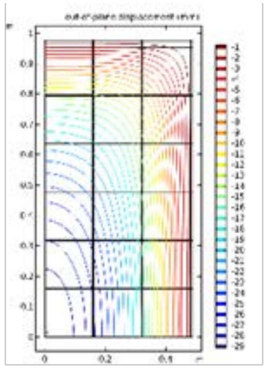
- Thermal cycling and mechanical loading cause movement within the laminate that can stress metallization across cracked cells
- Shifting and rotation of fragments has been observed
- Material properties of the encapsulant and other materials can change

Understanding and quantifying the relative movement of cell fragments is essential to predicting the progress of performance loss



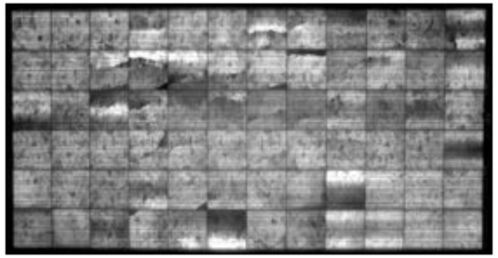
Source: T. Silverman, et al. *PVSC*, 2019.

EPRI project approach



Predictive simulation using finite element modeling (full modules)

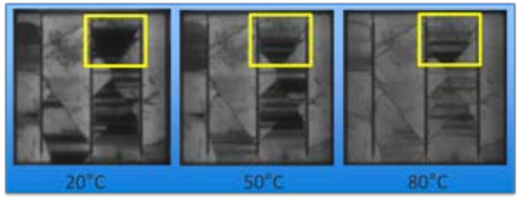
Field testing at NREL's small-scale outdoor test array



Data management and analytics for crack detection and analysis

Accelerated aging (full modules)

Field testing at two large-scale PV plants

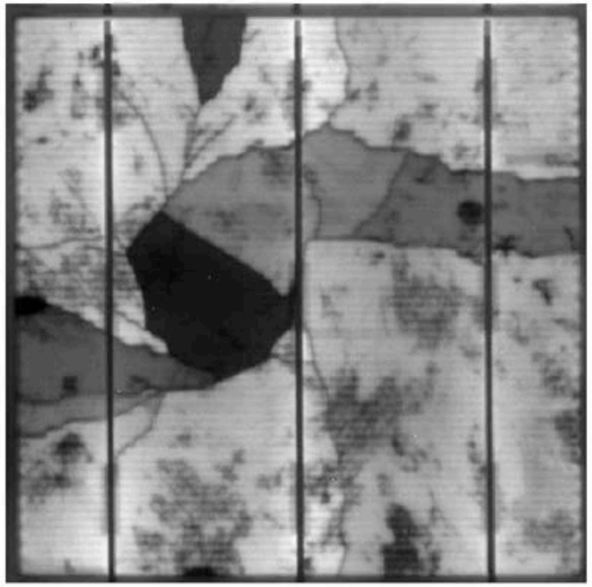


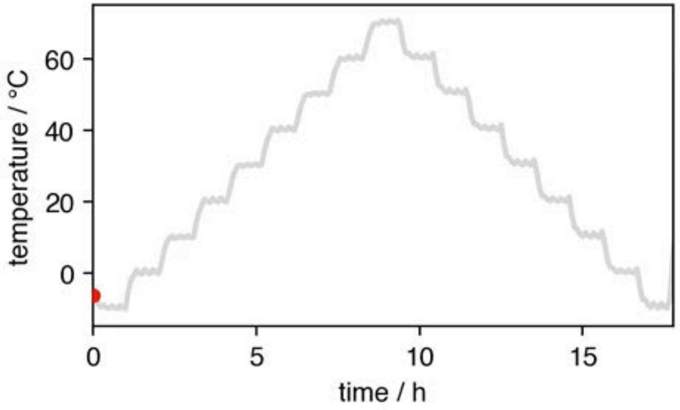
Temperature-dependent electroluminescence imaging

- Understand what is happening in the field
- Reproduce it in physical testing and modeling simulations
- Correlate crack features with degradation (or probability of developing safety issues)
- Identify relevant accelerated test protocols

Temperature-dependent EL imaging

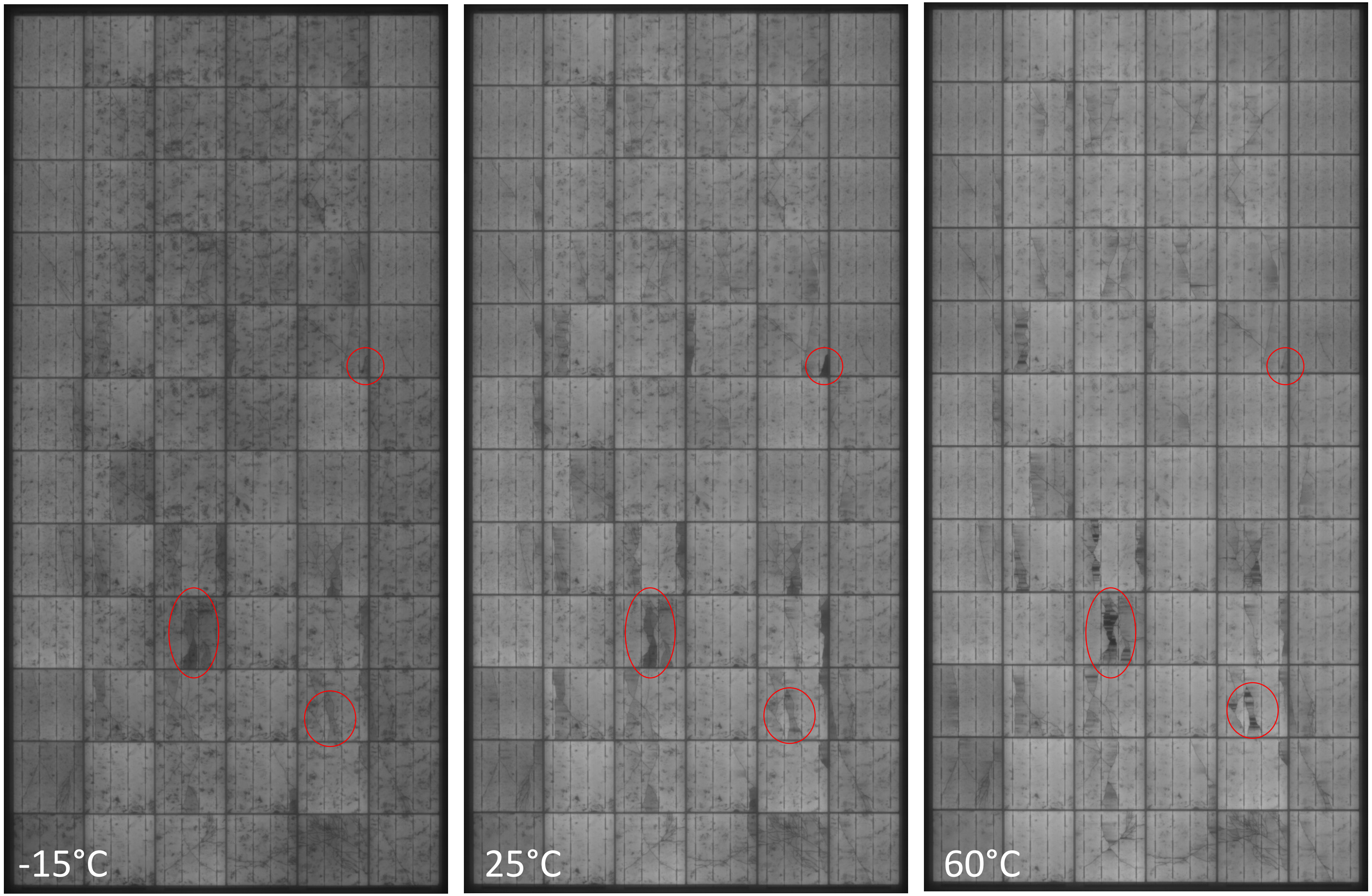
- The electrical contact to cell fragments changes with temperature as the fragments move
- Full understanding of crack impact under field conditions must include different temperatures





Application of temperature-dependent EL

- New capability:
  - Automated full-module EL images at varying temperature
- Apply throughout the project as a routine measurement

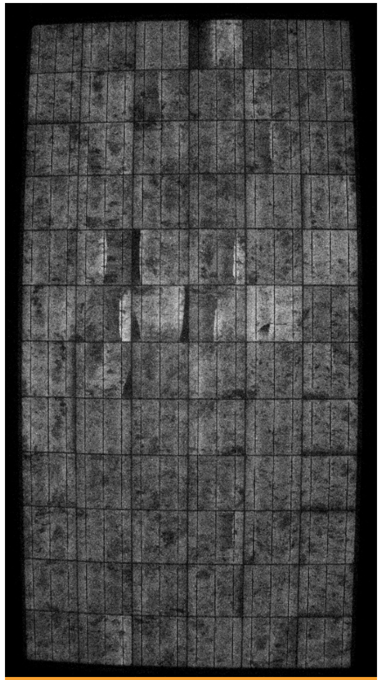


Field testing at commercial plants

- Outdoor testing commenced in February 2020 at a commercial PV power plant
- 4 modules that have been operating outdoors for several years were instrumented to monitor crack progression in response to wind loading
- A lookup table will correlate wind conditions with loading / vibration on the modules
- Data will be used in modeling to inform accelerated testing procedure
- The system will be replicated at a second PV plant

Electronics enclosure to support autonomous PV + battery power supply, data acquisition, and modem

Installation of back of module sensors: two potentiometers along the centerline to measure displacement, an accelerometer to measure vibration, and a thermocouple



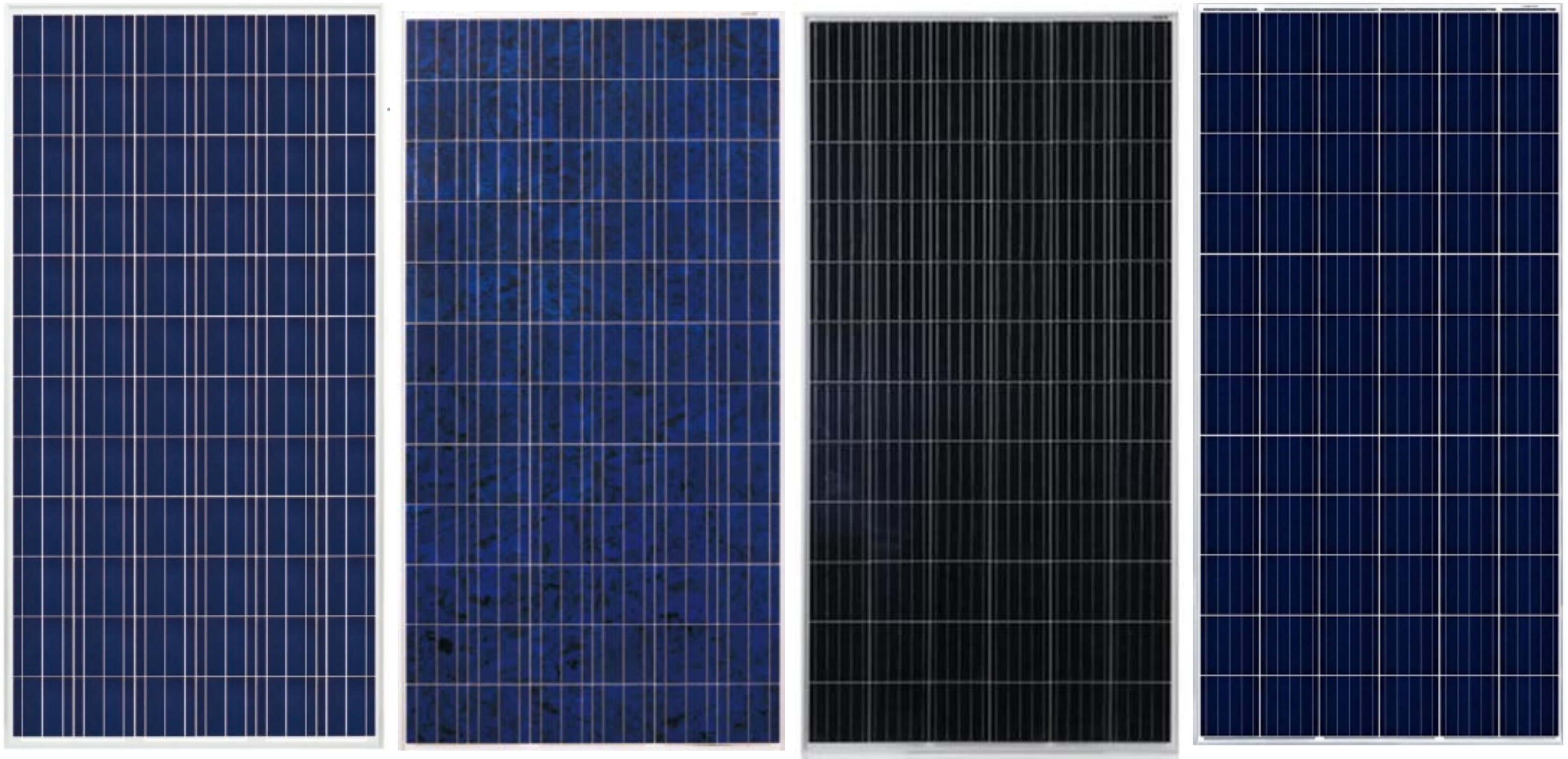
Fielded module EL images reveal different types and numbers of cell cracks

Field testing at NREL

- Test modules: 4 sets of 4 poly c-Si 72-cell modules (½ pristine condition, ½ pre-cracked)

Lazy installer drop

- Half of modules from each source will be pre-cracked
- Drop dummy modules of each type from successive heights until ~1/3 of cells are damaged. Test modules are then cracked with a single drop from the determined height.



3 busbar

4 busbar

5 busbar

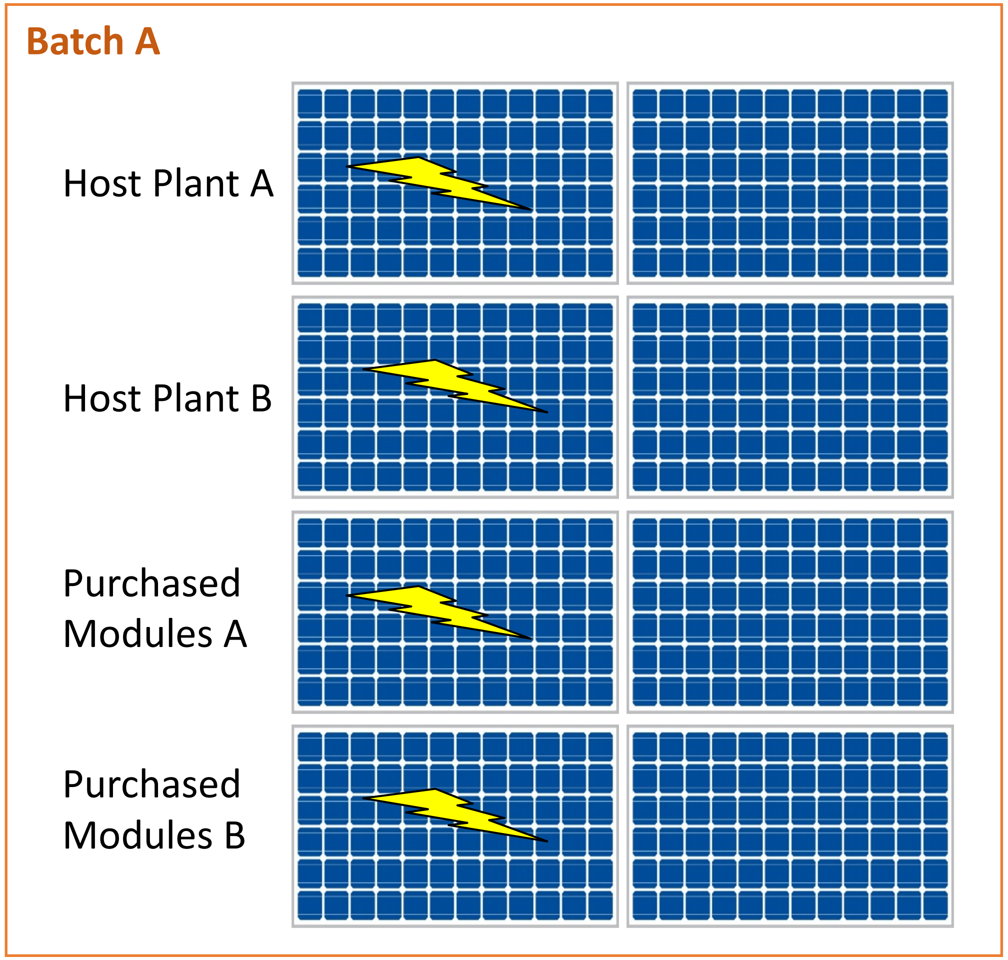
NREL outdoor testbed

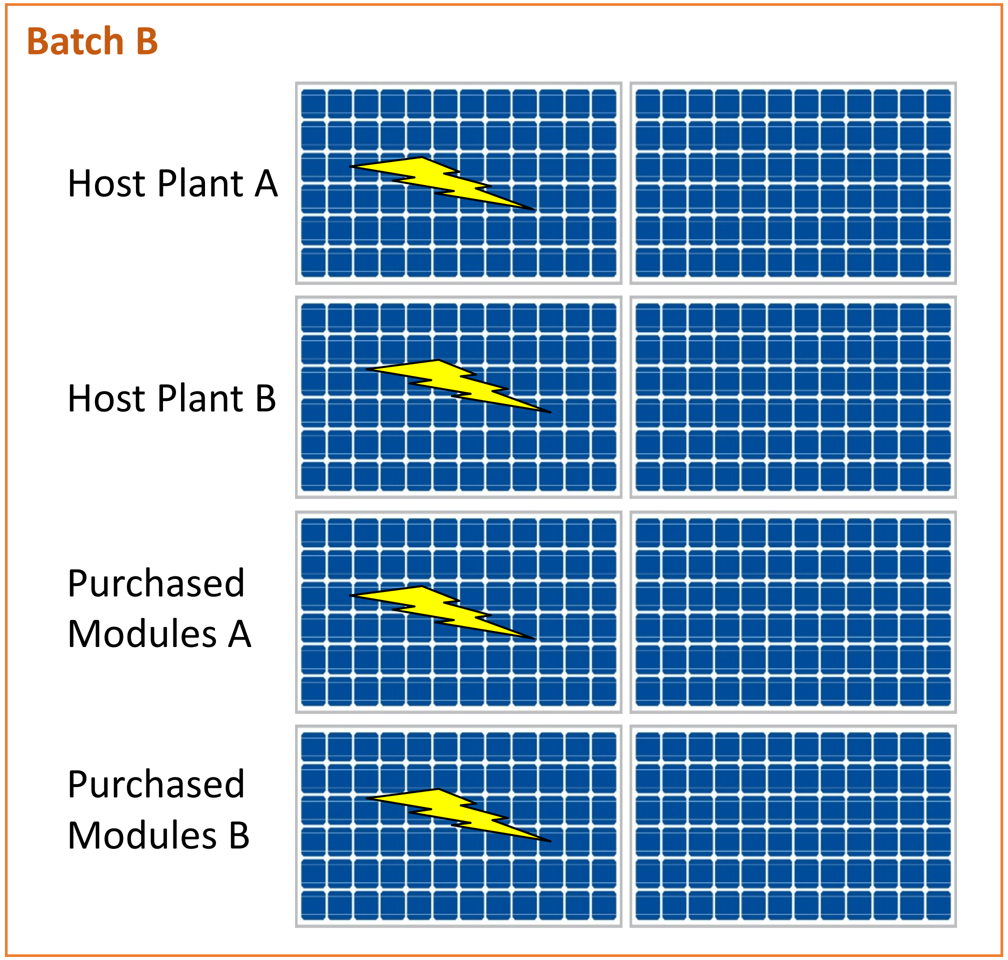
On-sun testing of DuraMAT modules

Potentiometer to measure displacement and accelerometer to measure vibration

Accelerated testing plans under development

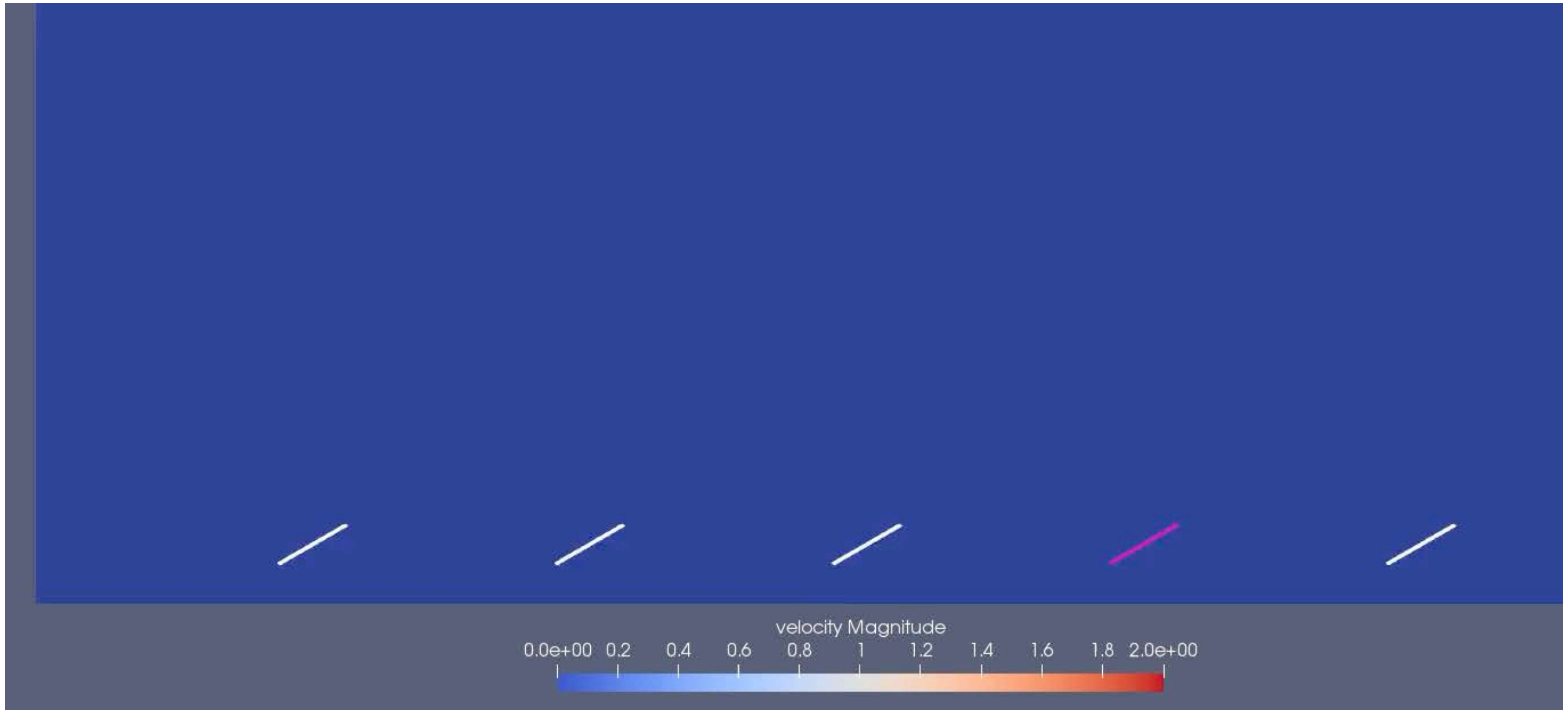
- Additional 4 sets of 4 modules (½ pristine condition, ½ pre-cracked) will be split into two identical batches
- Batch A and Batch B represent distinct test protocols, each with 2 levels, to be completed serially

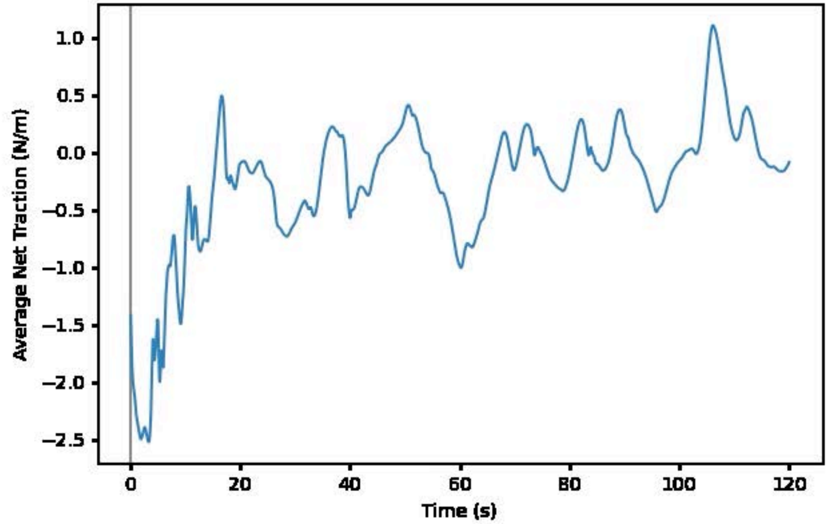


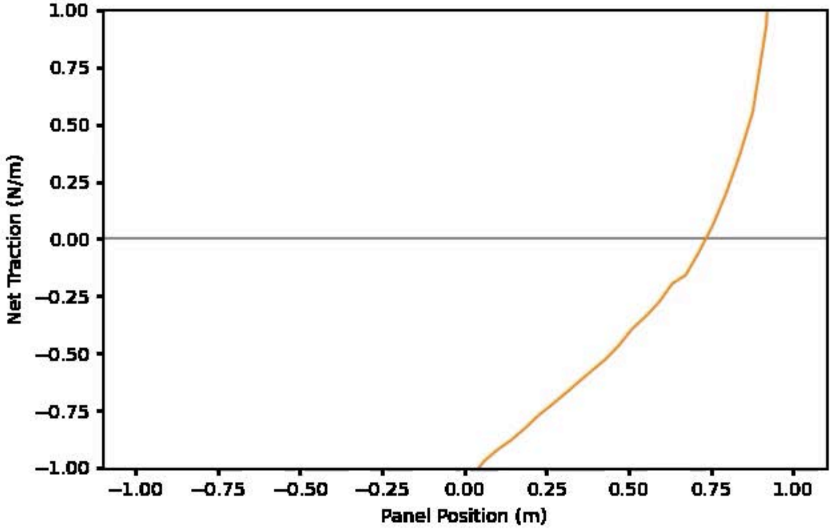


Wind pressure modeling

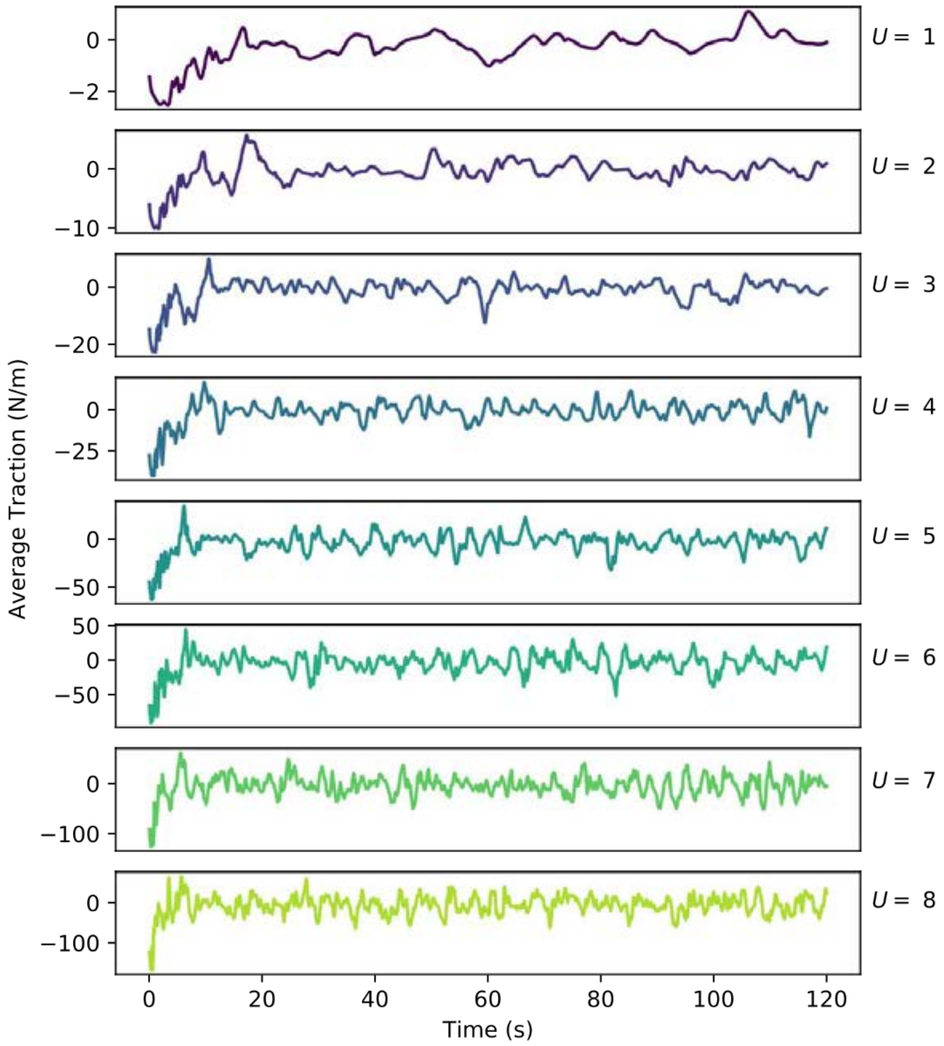
Unsteady Results, $\theta = +30, U_{ref} = 1$



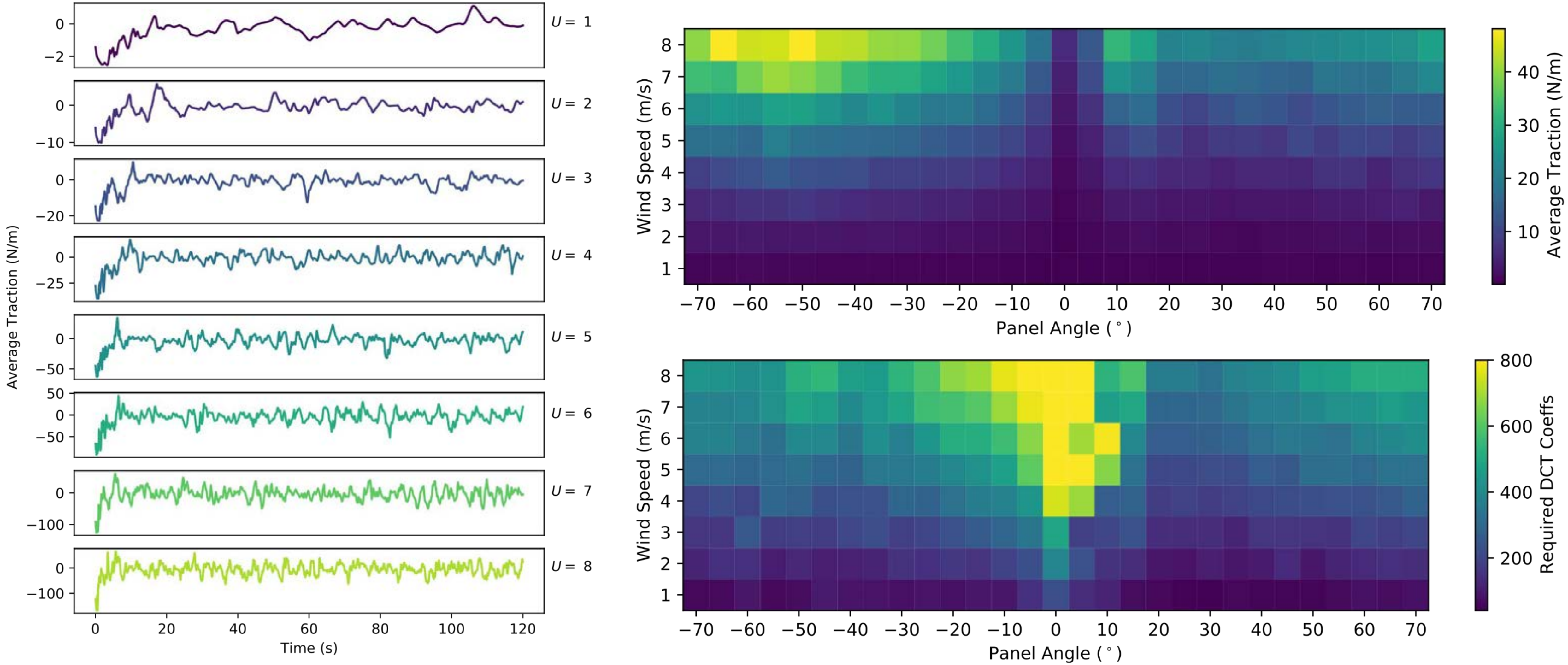




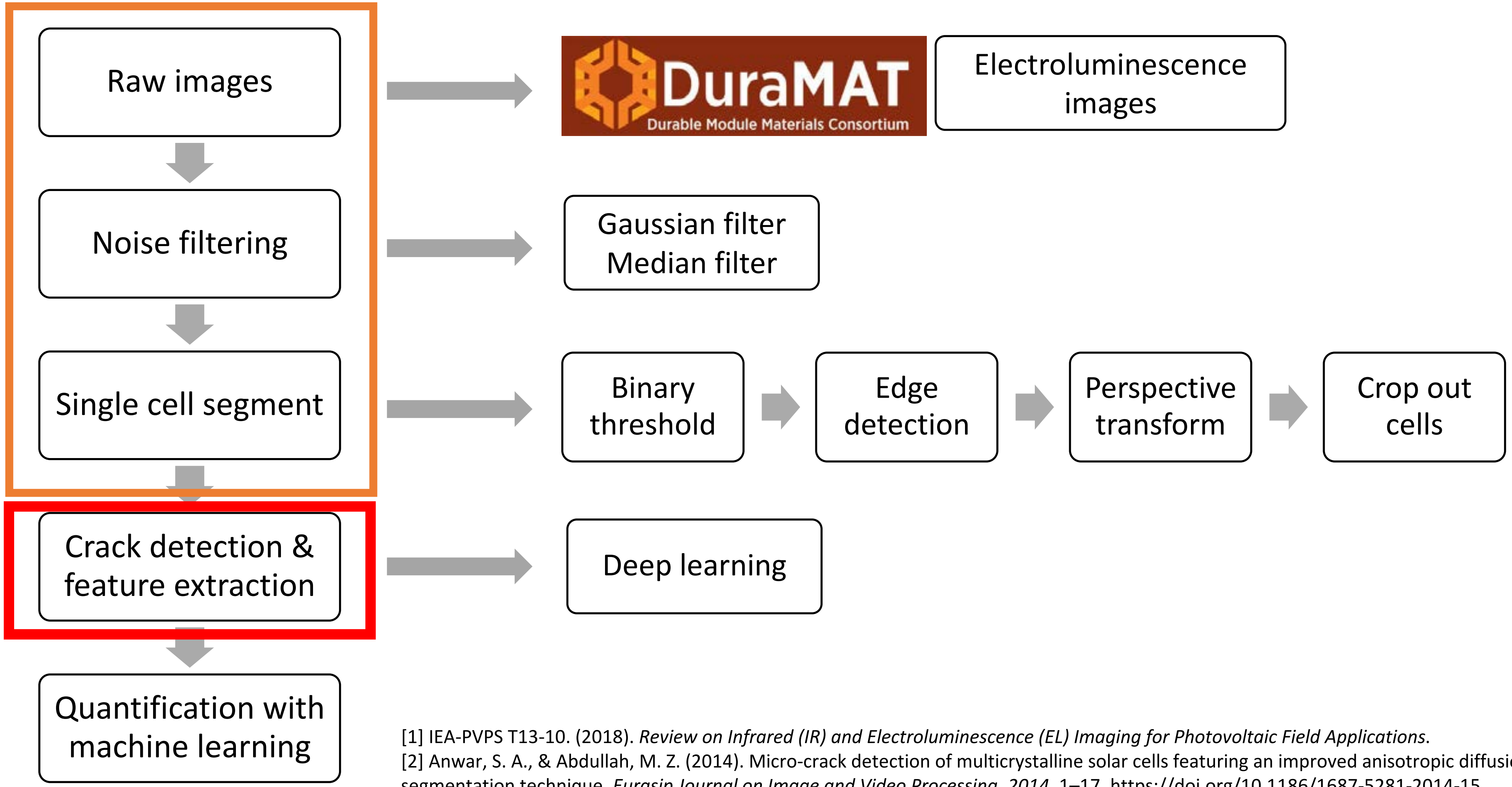
Average traction vs. wind speed, $\theta = +30$



Average traction vs. (wind speed, angle)



General process of automatic processing[1-3]

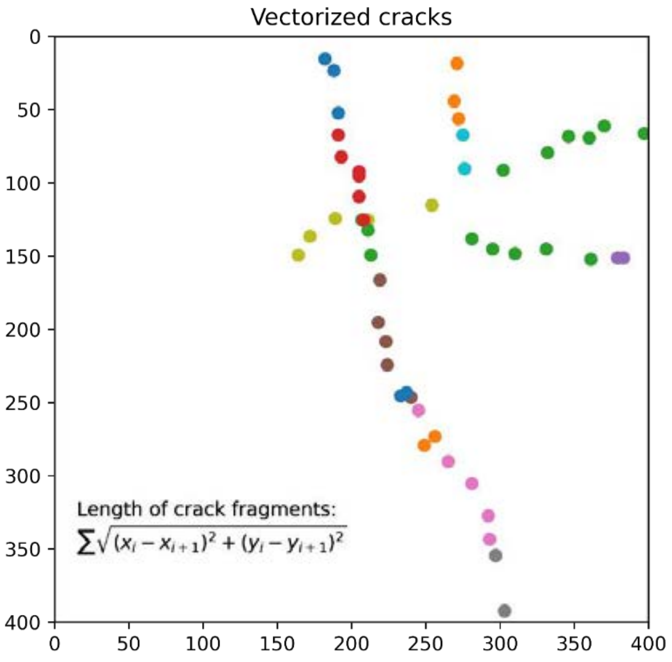


[1] IEA-PVPS T13-10. (2018). *Review on Infrared (IR) and Electroluminescence (EL) Imaging for Photovoltaic Field Applications*.

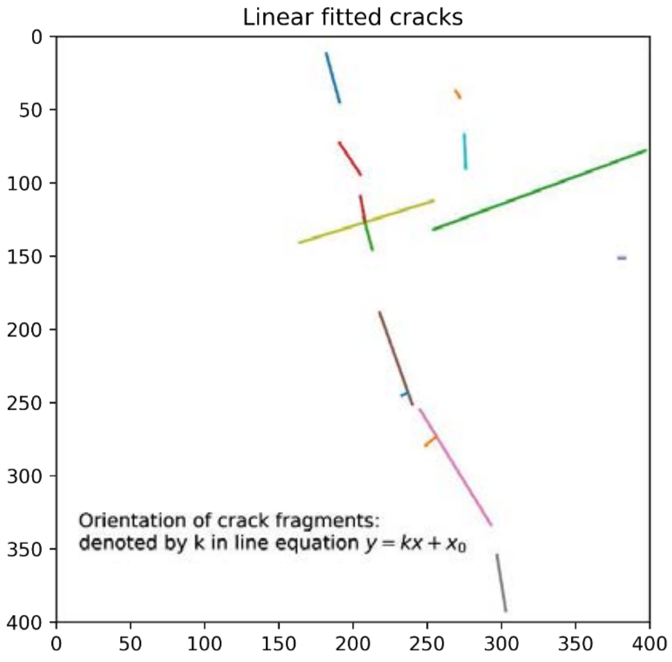
[2] Anwar, S. A., & Abdullah, M. Z. (2014). Micro-crack detection of multicrystalline solar cells featuring an improved anisotropic diffusion filter and image segmentation technique. *Eurasip Journal on Image and Video Processing*, *2014*, 1–17. https://doi.org/10.1186/1687-5281-2014-15

[3] Spataru, S., Hacke, P., & Sera, D. (2017). Automatic detection and evaluation of solar cell micro-cracks in electroluminescence images using matched filters. *2017 IEEE 44th Photovoltaic Specialist Conference, PVSC 2017*, 1–6. https://doi.org/10.1109/PVSC.2017.8366343

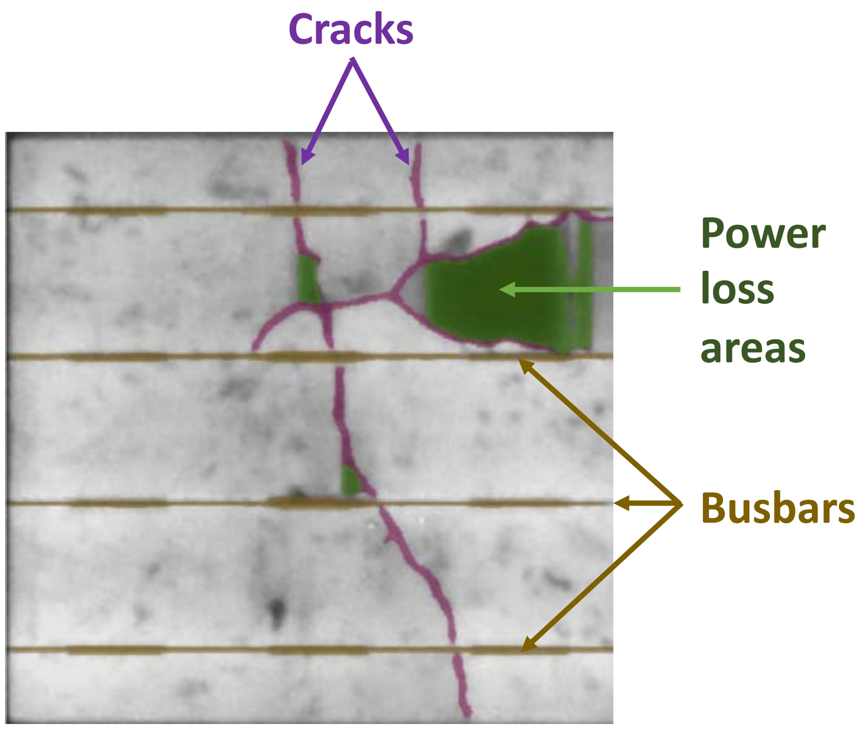
Extract features from masks of cracks



Crack vectors to compute lengths



Polyfitted cracks to compute orientations



Masks predicted by convolutional neural network

Machine learning algorithms will be used to correlate cell crack features with power loss.

Summary and future work

- Temperature dependent EL set up has been implemented for 72-cell modules as a routine capability.
- Outdoor testing is almost at a point where we can develop a lookup table of wind conditions vs. module stress; 2nd plant installation to occur once travel restrictions are lifted
- Wind modeling is being pursued to inform choice of test protocols
- Crack detection algorithm testing and training continues to improve accuracy

Acknowledgements

The following team members were instrumental in this work:

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- LBNL: Todd Karin, Anubhav Jain, Xin Chen
- Southern Company: Will Hobbs
- EPRI: Michael Bolen, Daniel Fregosi, Bijaya Paudyal

Measurement of PV cell crack characteristics in PV modules using digital image correlation

PI: Joshua Stein, Sandia

Team: Jenifer Braid, Charles Robinson, and Philip Reu

DuraMAT Monthly Webinar Series

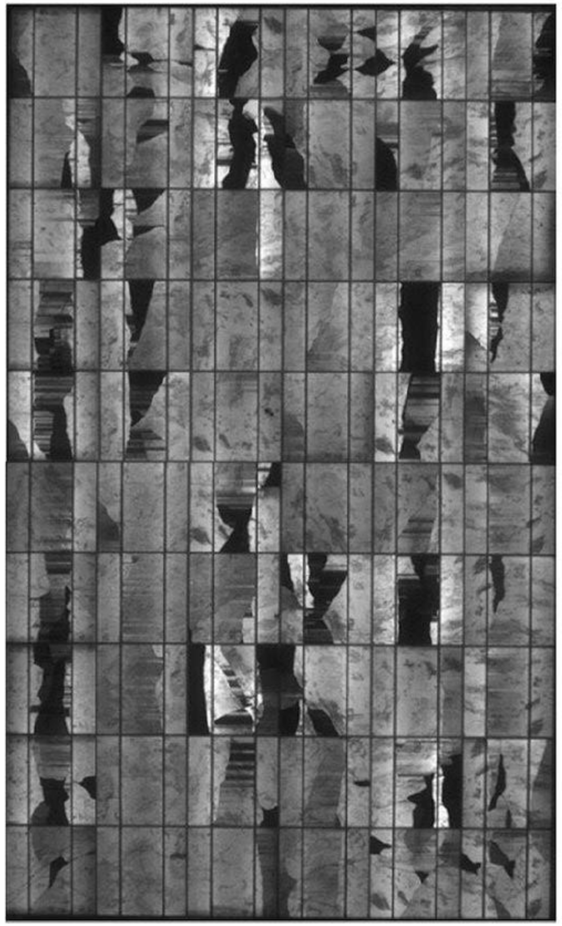
Nov. 9, 2020

Agenda

- Goals and objectives
- Stereo Digital Image Correlation (sDIC)
- Application of sDIC to module mechanical loading tests
- Application of sDIC to characterizing PV cell cracks (Future work)

Goals and Objectives

- *PV cell cracks are easy to find using EL*
- *Crack apertures or displacements are more difficult to characterize.*
- *Use stereo DIC method to measure crack apertures in **full-sized, laminated PV modules***
- *Study effects of **mechanical and thermal stresses**.*



Cracks are easy to see in EL, but difficult to characterize in detail

Digital Image Correlation

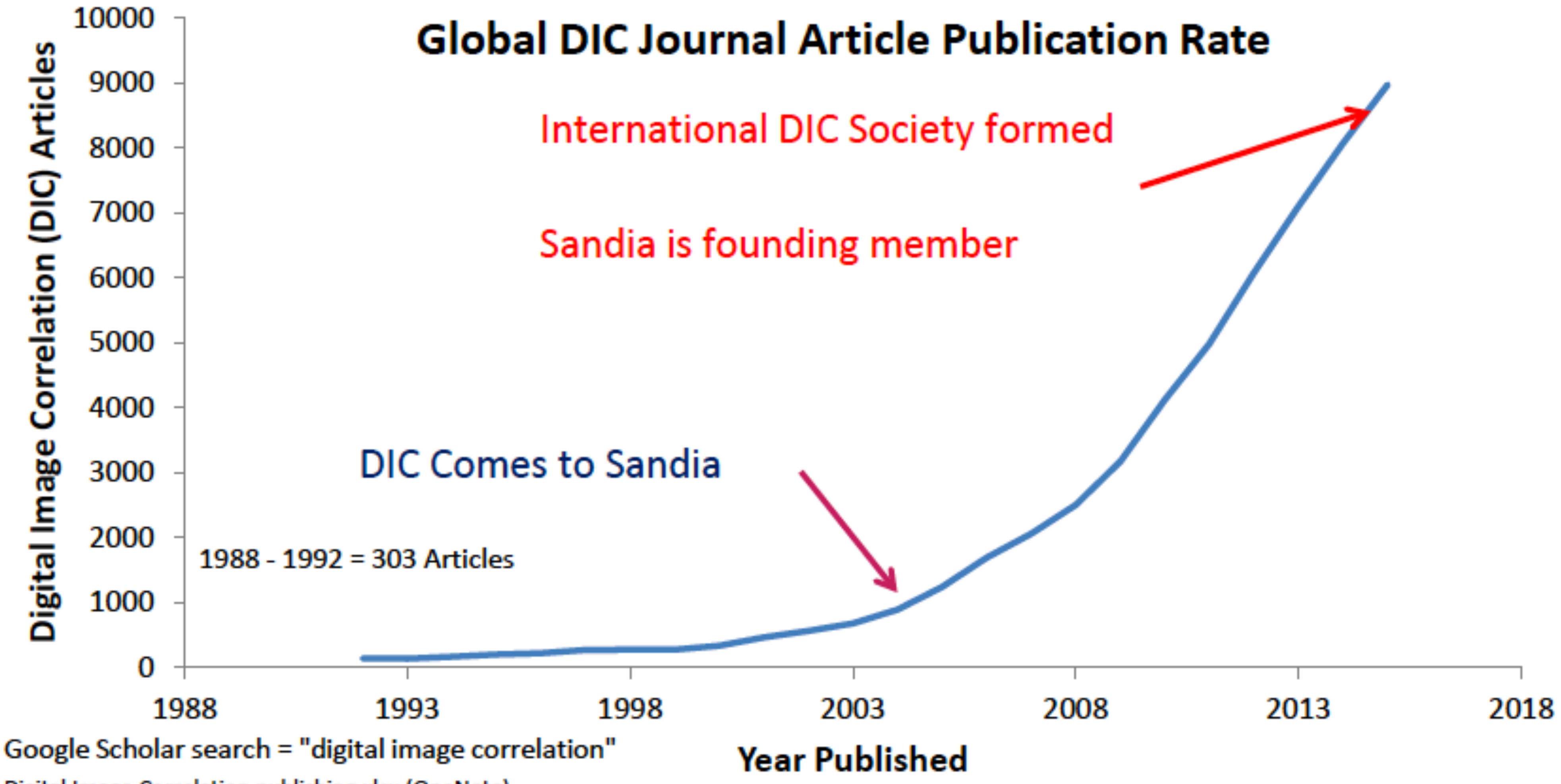
- DIC is a full-field image based shape, deformation and strain measurement technique.
- DIC is rapidly gaining in popularity for numerous applications.

Diagnostic	Measured	Resolution	Point Grid	Rate	Comments
Laser Doppler Velocimeter (LDV)	Out-of-plane Transient/periodic	20 m/s to 1 µm/s	1 µm	MHz	Single spot measurement Specular or diffuse
LDV – Displacement	Out-of-plane or in-plane	8 nm	1 µm	MHz	Single spot measurement Specular or diffuse
Classical Interferometry	Shape	2.5 nm	1 µm	Hz	Assuming λ/200. Specular surface.
Electronic Speckle Pattern Interferometry (ESPI)	Out-of-plane or In-plane. Quasi-static	2.5 nm/ 10 nm	10 µm	Hz	Diffuse surface preferred
Strobe Interferometry	Out-of-plane Periodic	2.5 nm	1 µm	MHz	Specular surface required
High speed imaging	In-plane transient	1/1000 FOV	10 µm	MHz	Structure/pattern required
Digital Image Correlation	3D Shape or motion	1/20 to 1/100 pixel	5 pixels	MHz	Surface must be patterned
Moire					

DIC Usage is Expanding

- Uncertainty quantification
- High speed and ultra-high speed testing
- Material property measurements
- FE model validation

- 1st International DIC conference in 2016 – 200 attendees.

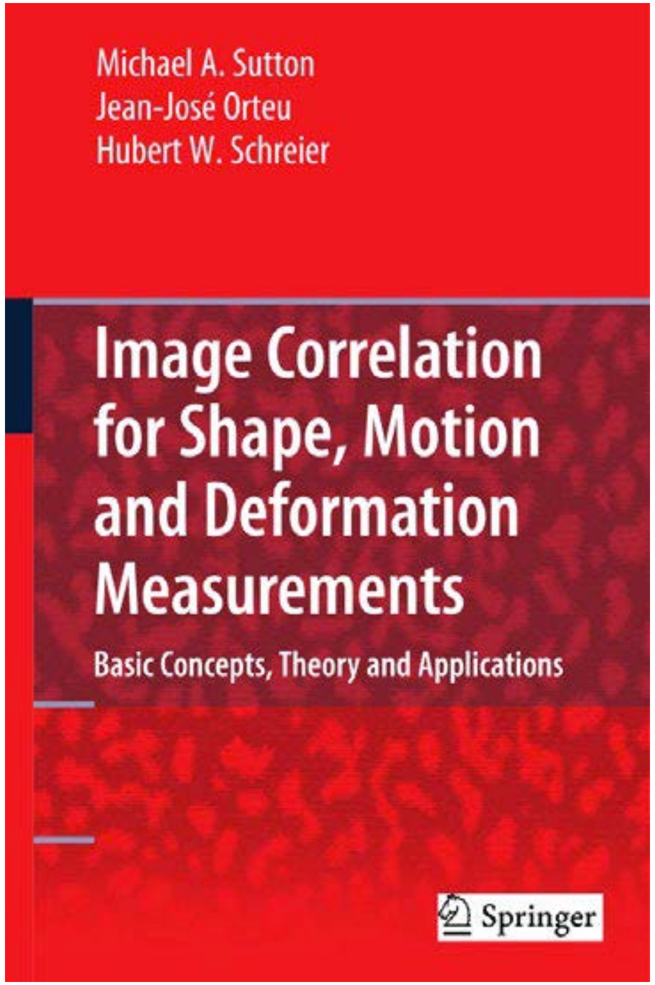


Google Scholar search = "digital image correlation"

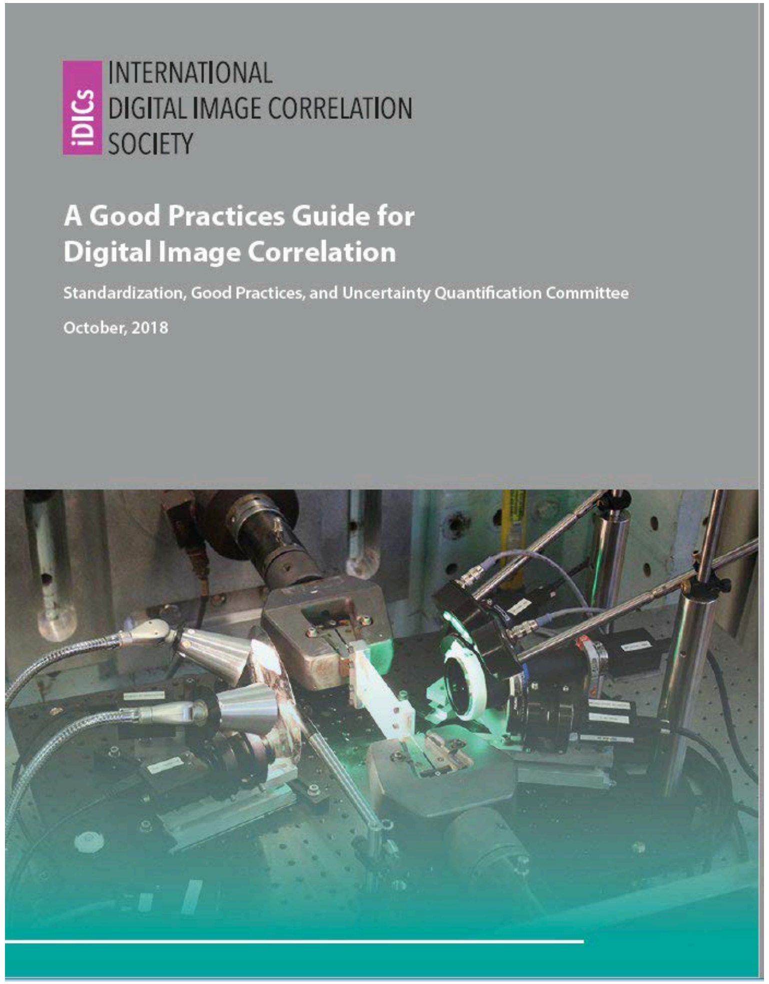
Digital Image Correlation publishing.xlsx (OneNote)

DIC Resources

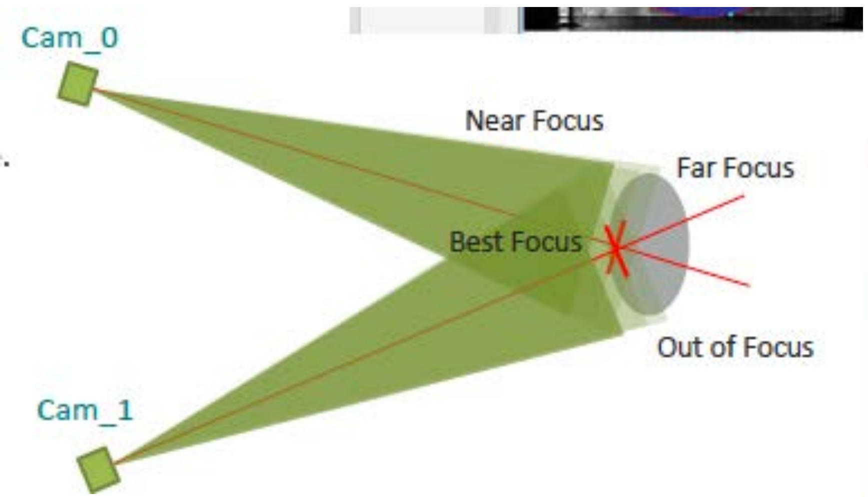
2009

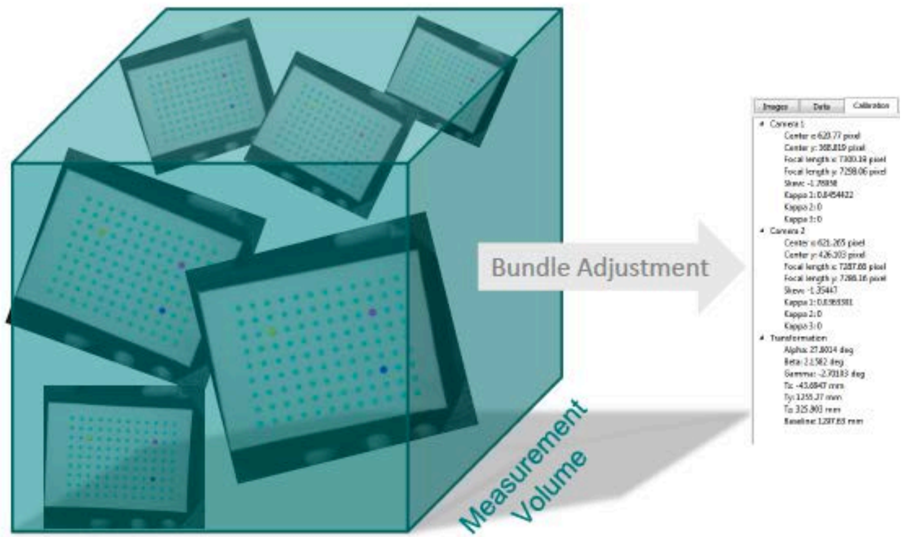


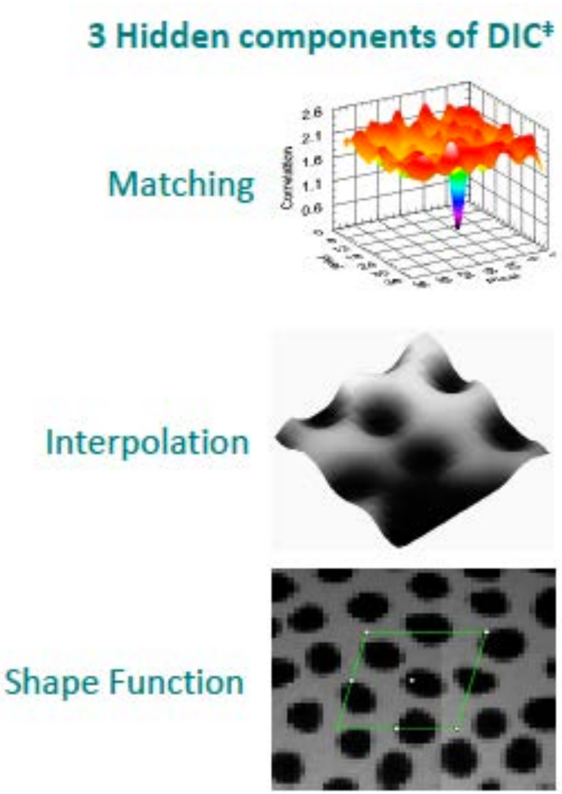
2018



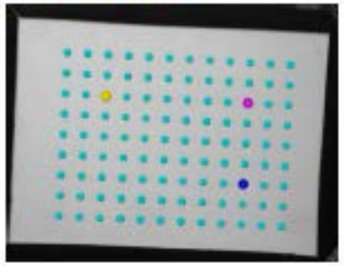
Steps of Stereo Digital Image Correlation







Calibration

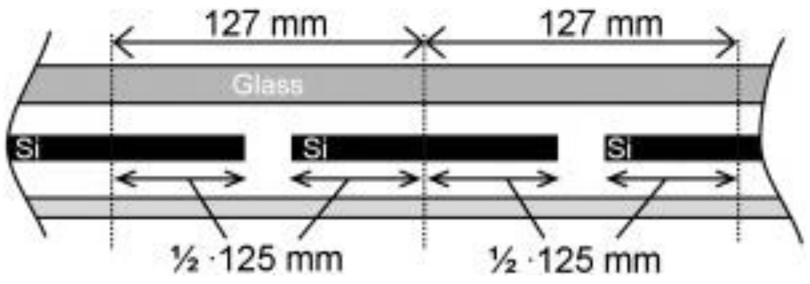


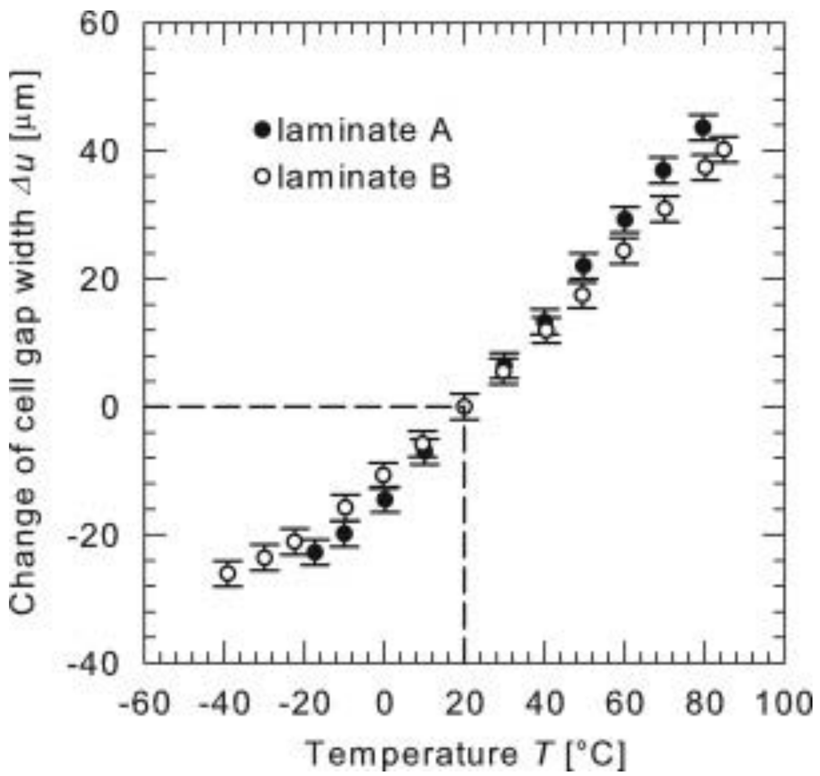
- Two cameras at **<u>fixed</u>** distance and angle
- Calibration board is moved in the FOV
- Sample has random pattern on surface
- Analysis matches patterns in each camera’s image.
- Interpolation and shape function transformations are used to measure displacements and deformation.

Stereo DIC Applications in Photovoltaics

- 2010, Eitner, Köntges, and Brendel, “Use of digital image correlation technique to determine thermomechanical deformations in photovoltaic laminates: Measurements and accuracy”, Solar Energy Materials and Solar Cells, https://doi.org/10.1016/j.solmat.2010.03.028

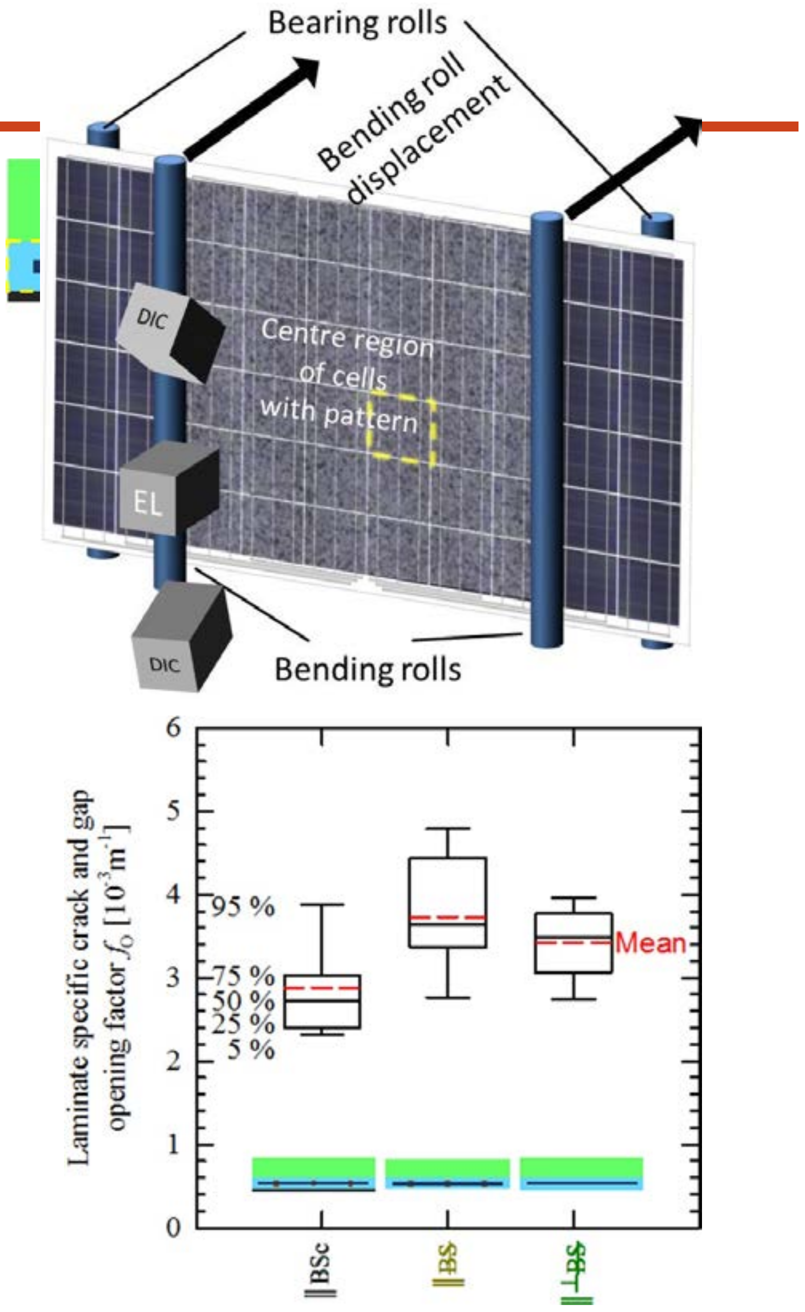
- The used Stereo DIC to measure deformation in transparent PV modules.
- Measured PV cell gaps changing due to temperature.
- Results: Gap between cells changed by 66.3 µm between 79.6 and -17.3 °C
- Resolution of 1 µm for a 40 x 15 cm sized test sample.





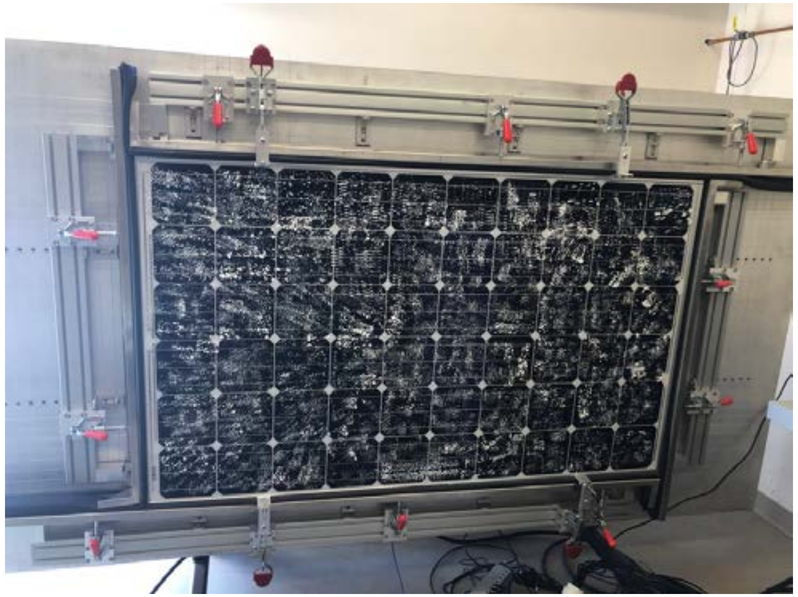
Stereo DIC Applications in Photovoltaics

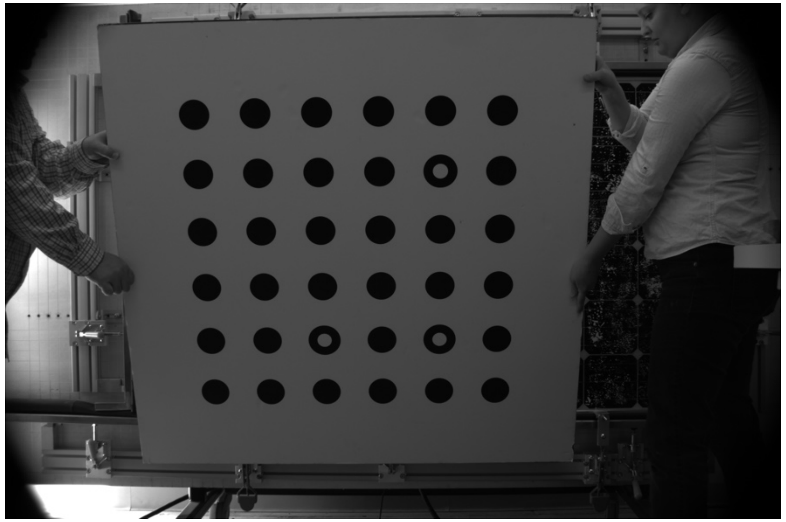
- Haase, F., et al. (2018). "Fracture Probability, Crack Patterns, and Crack Widths of Multicrystalline Silicon Solar Cells in PV Modules During Mechanical Loading." <u>Journal of Photovoltaics</u> **8**(6): 1510-1524.
- Result: In the standard module, the crack width of a single crack is 3.4 µm at loads comparable to the IEC 61215 5400 Pa test.

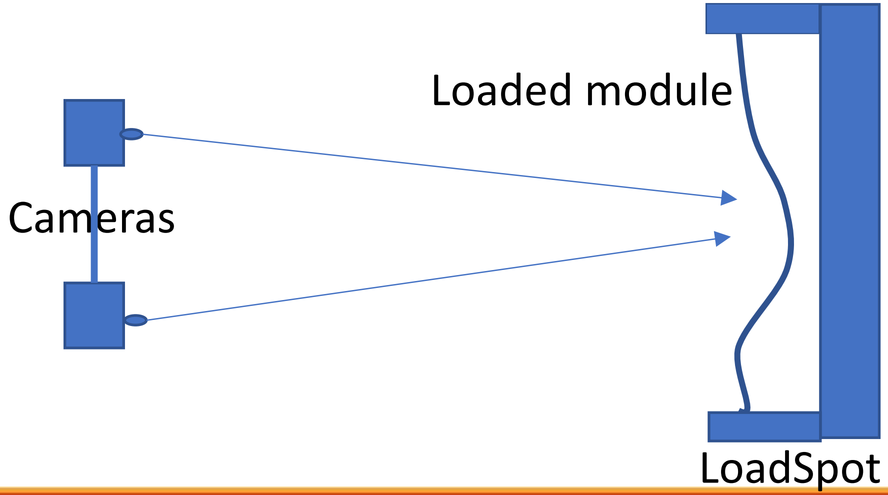


DuraMAT SPARK: Phase 1: Measure Module Displacement

- Standard 60-cell PV module was painted with a white speckle pattern.
- After DIC calibration, module was loaded using a LoadSpot mechanical tester from BrightSpot Automation.
- DIC images were taken as the module was loaded to -4000 Pa.

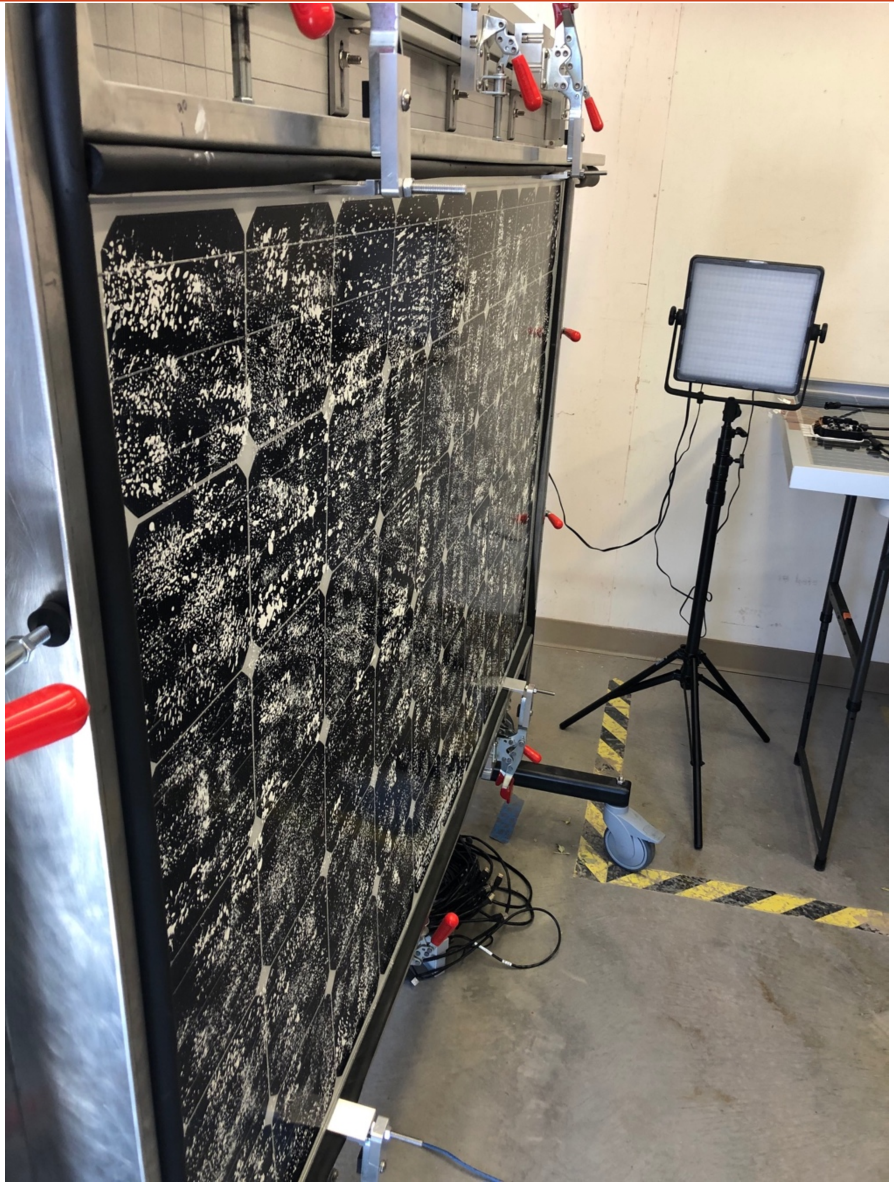






Applying the Load using the LoadSpot

- Test applied 0 Pa to -4000 Pa to back of module in approximately -500 Pa increments.
- LoadSpot has optical displacement sensors but we did not hook them up for this initial test.
- We averaged 10 images at each pressure increment.
- We processed the images using Vic3D software to calculate displacement in Z (into and out of the plane of the module.
- The next slides show the results of the test.
- We believe this may be the first example of using DIC to measure full module displacement under loading.

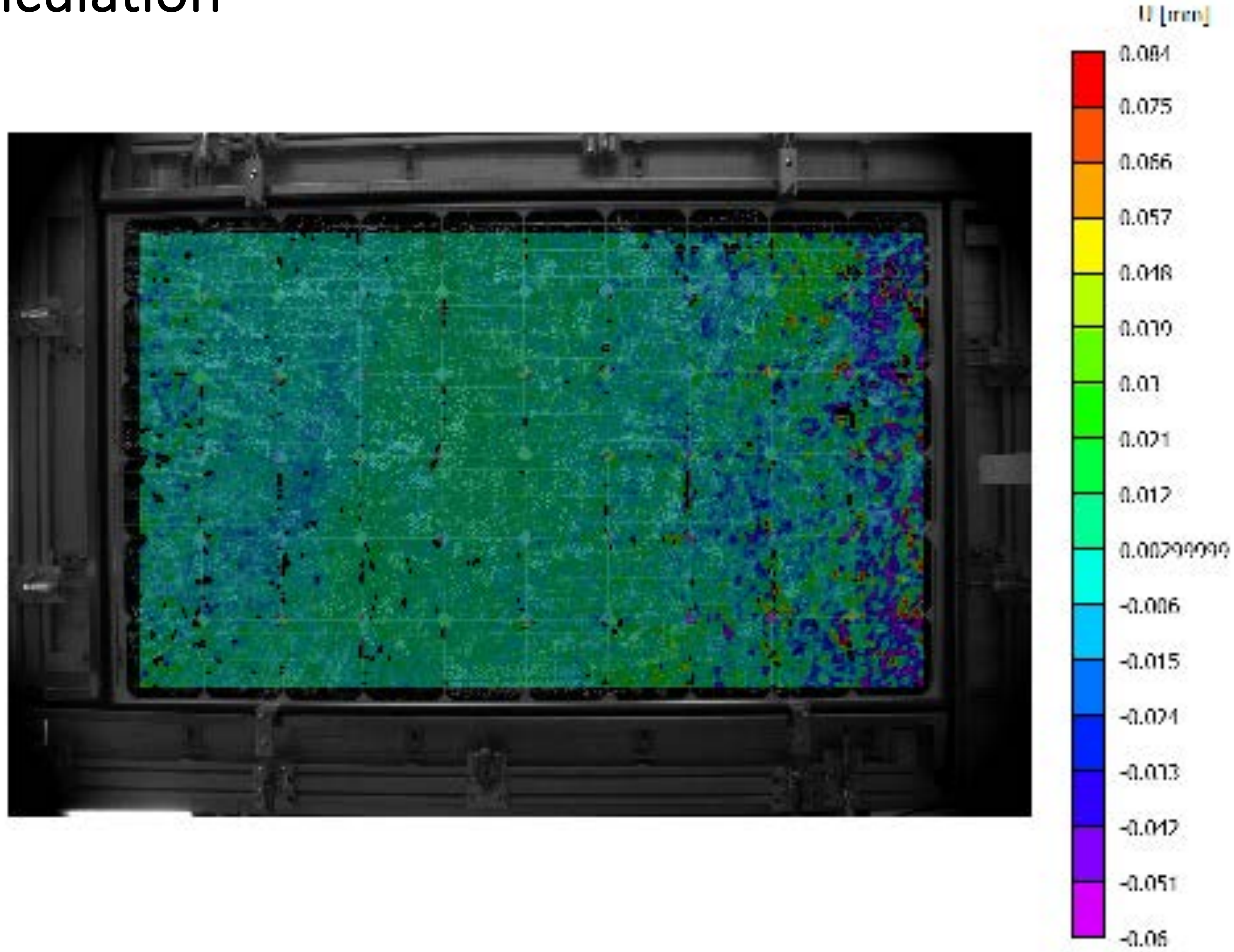


Noise Floor Error Calculation

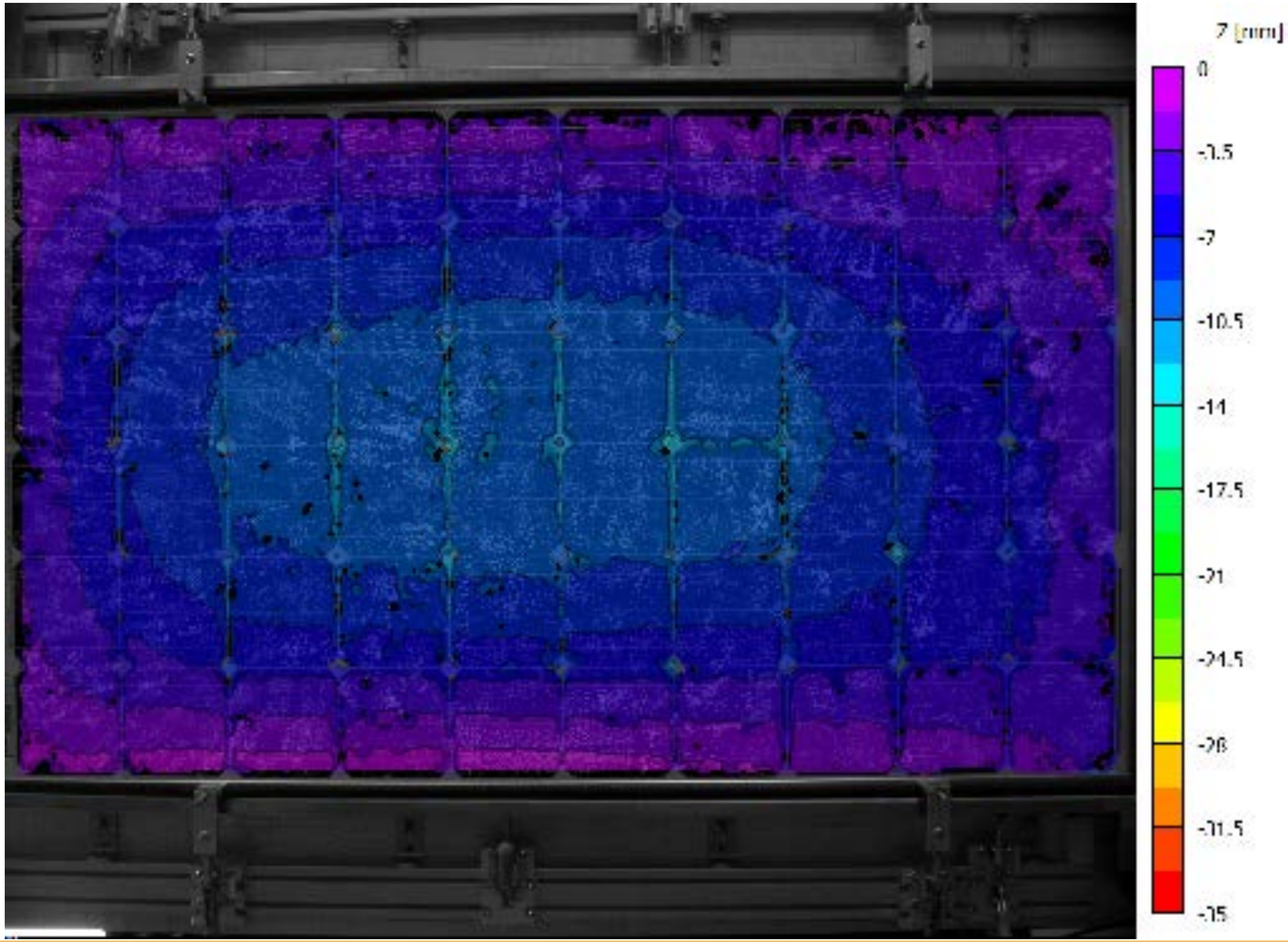
- Thermal plumes in the air can cause optical distortions and introduce errors in DIC.
- “Noise floor” test takes many images with no stress and evaluates these uncertainties.
- Heat from lighting is a common source of these errors.

Results:

- Stdev = 0.058 mm (out of plane direction)
- Average of 10 images – 0.02 mm
- Highest errors are associated with cell edges (white cell corners and edges cannot be matched)



-600 Pa



Legend

0 mm

-7 mm

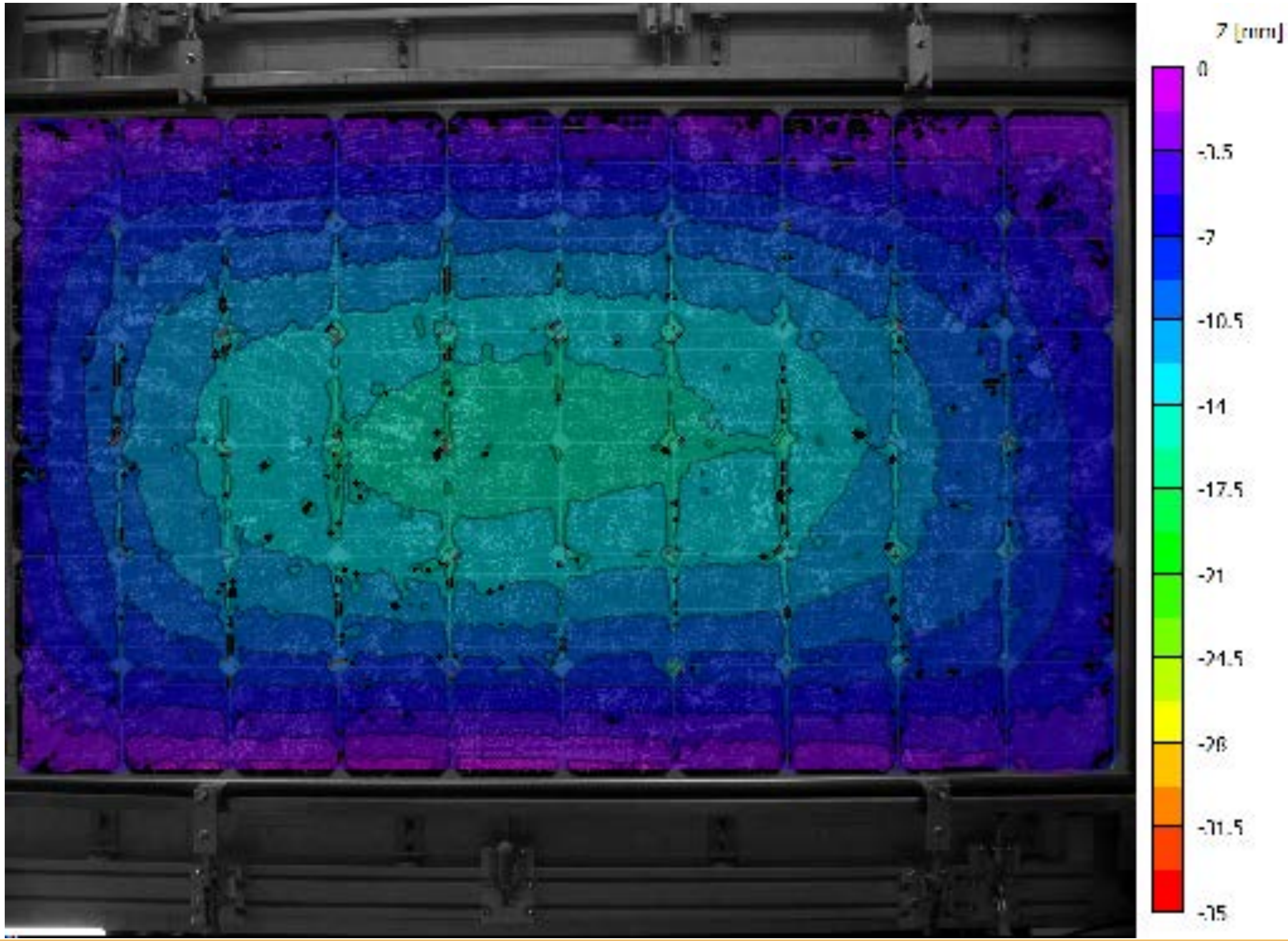
-14 mm

-21 mm

-26 mm

-35mm

-1000 Pa



Legend

0 mm

-7 mm

-14 mm

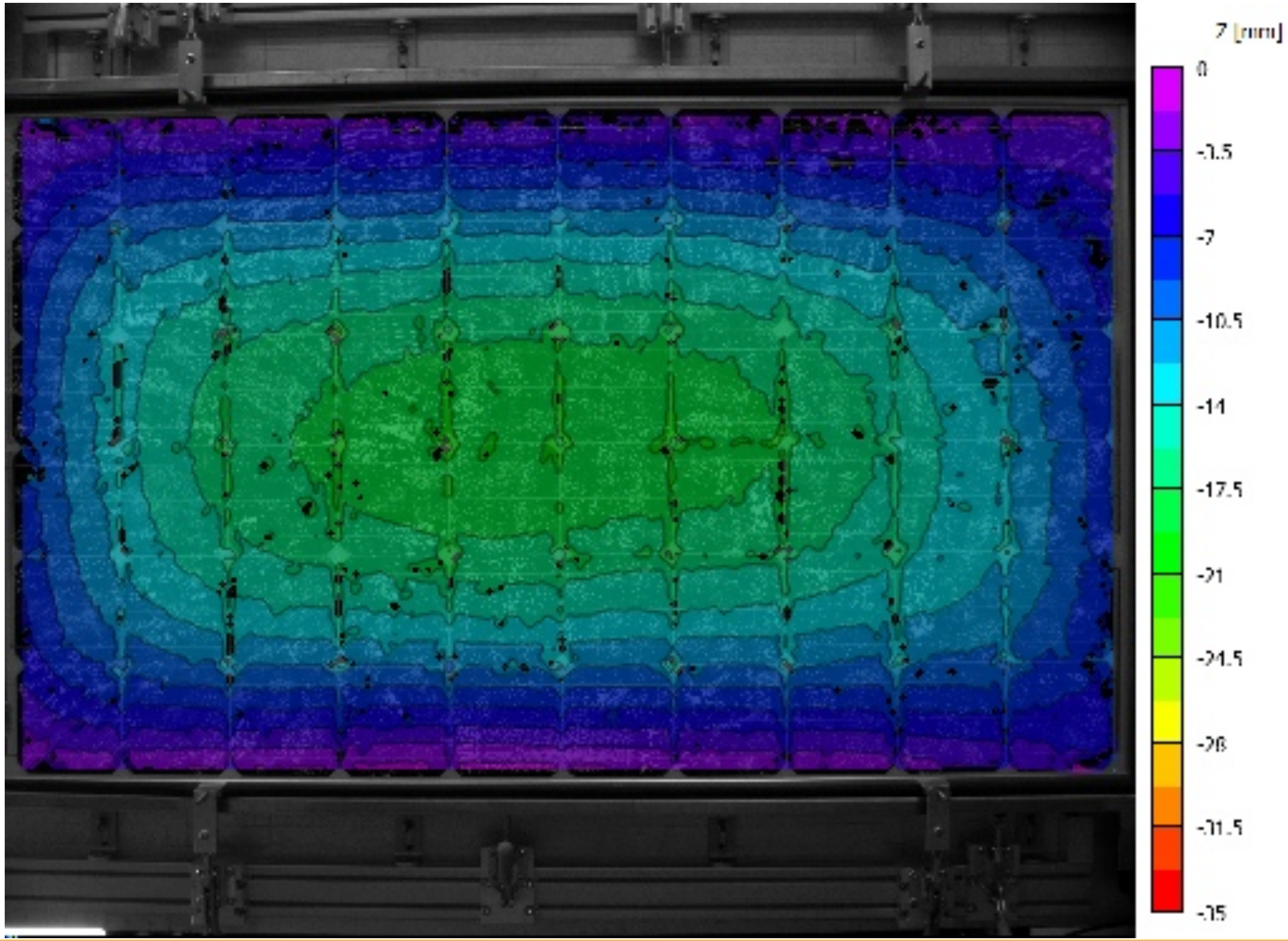
-21 mm

-26 mm

-35mm

-1500 Pa

Legend



0 mm

-7 mm

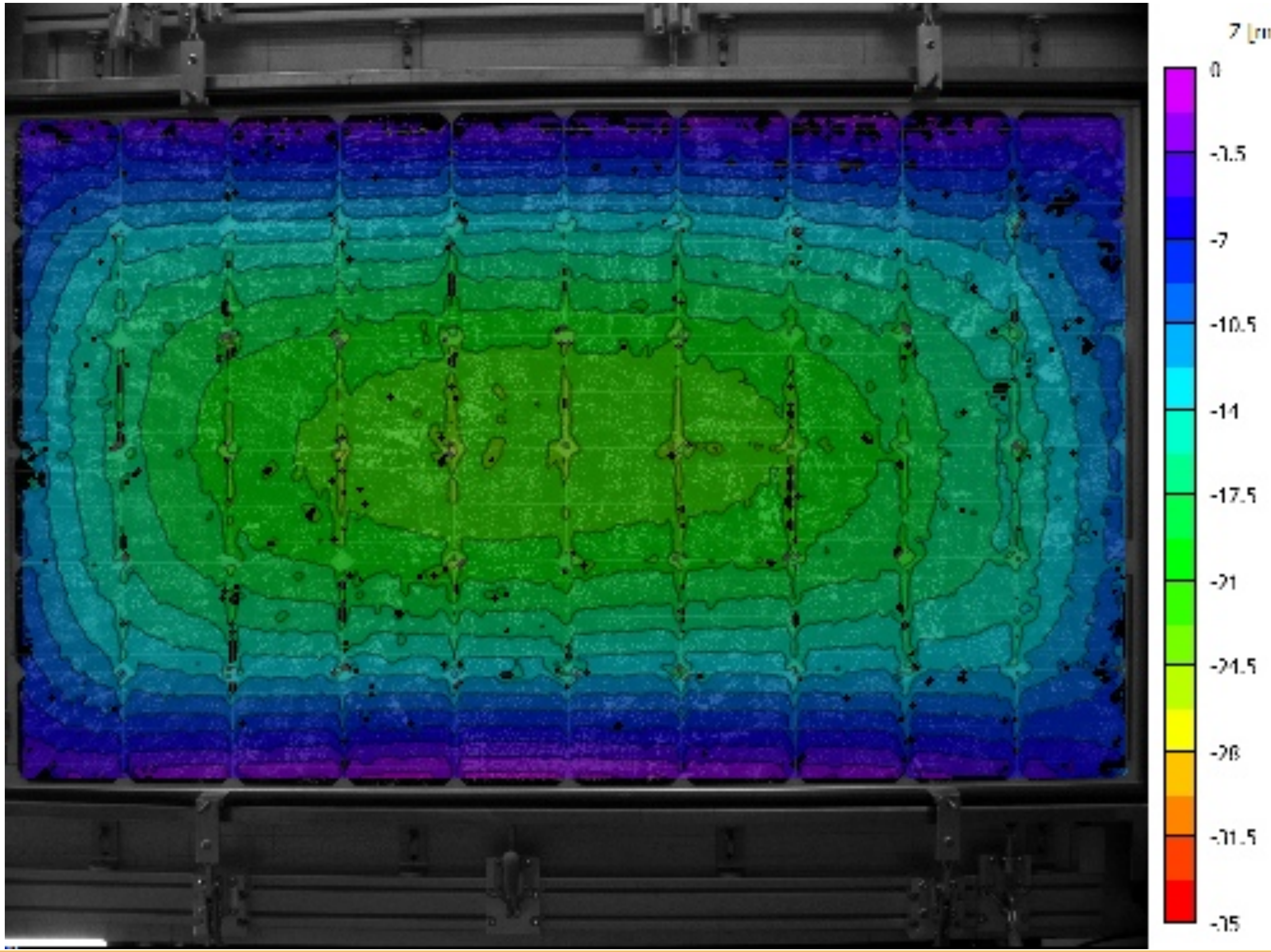
-14 mm

-21 mm

-26 mm

-35mm

-2000 Pa



Legend

0 mm

-7 mm

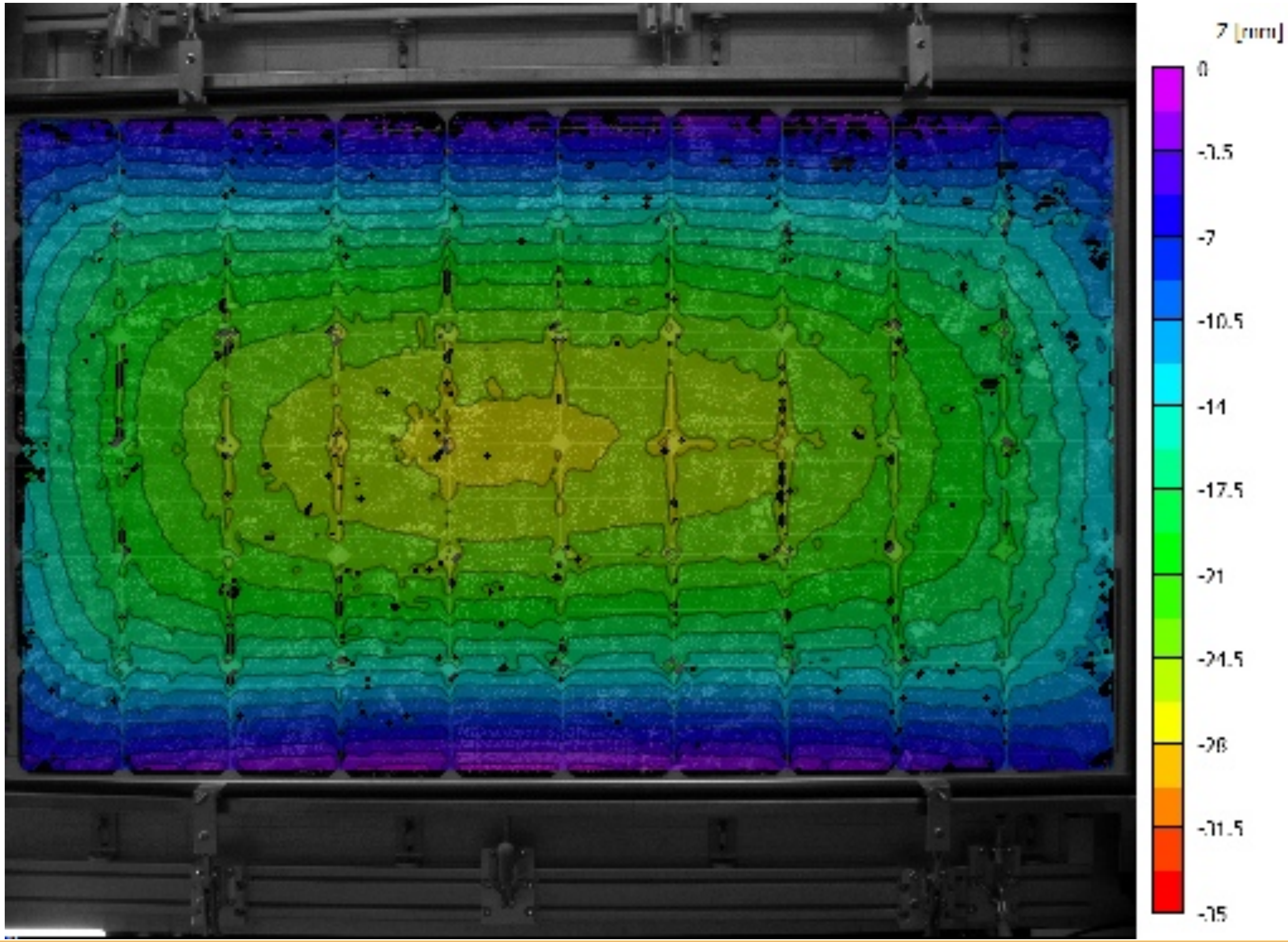
-14 mm

-21 mm

-26 mm

-35mm

-2500 Pa



Legend

0 mm

-7 mm

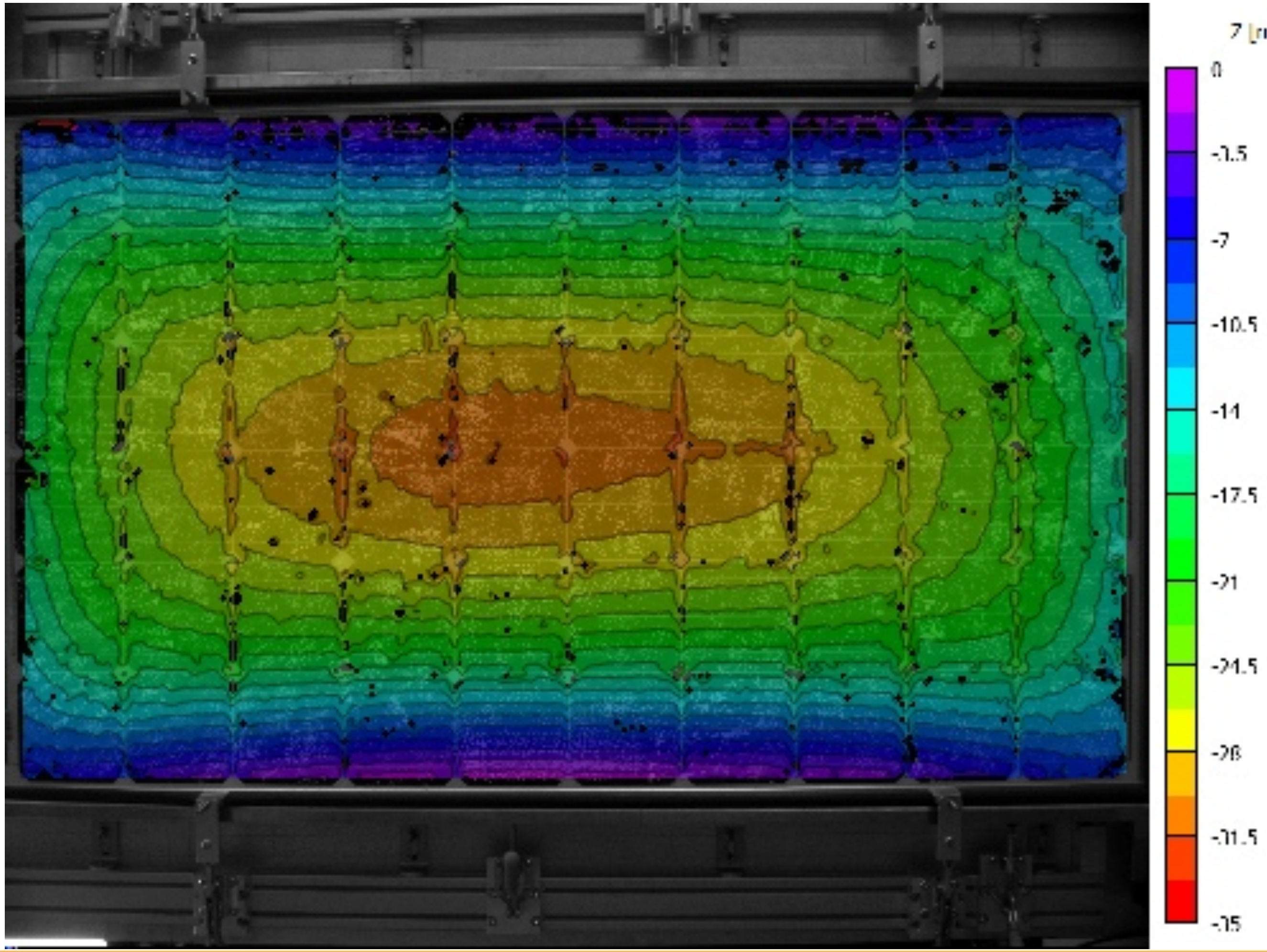
-14 mm

-21 mm

-26 mm

-35mm

-3000 Pa



Legend

0 mm

-7 mm

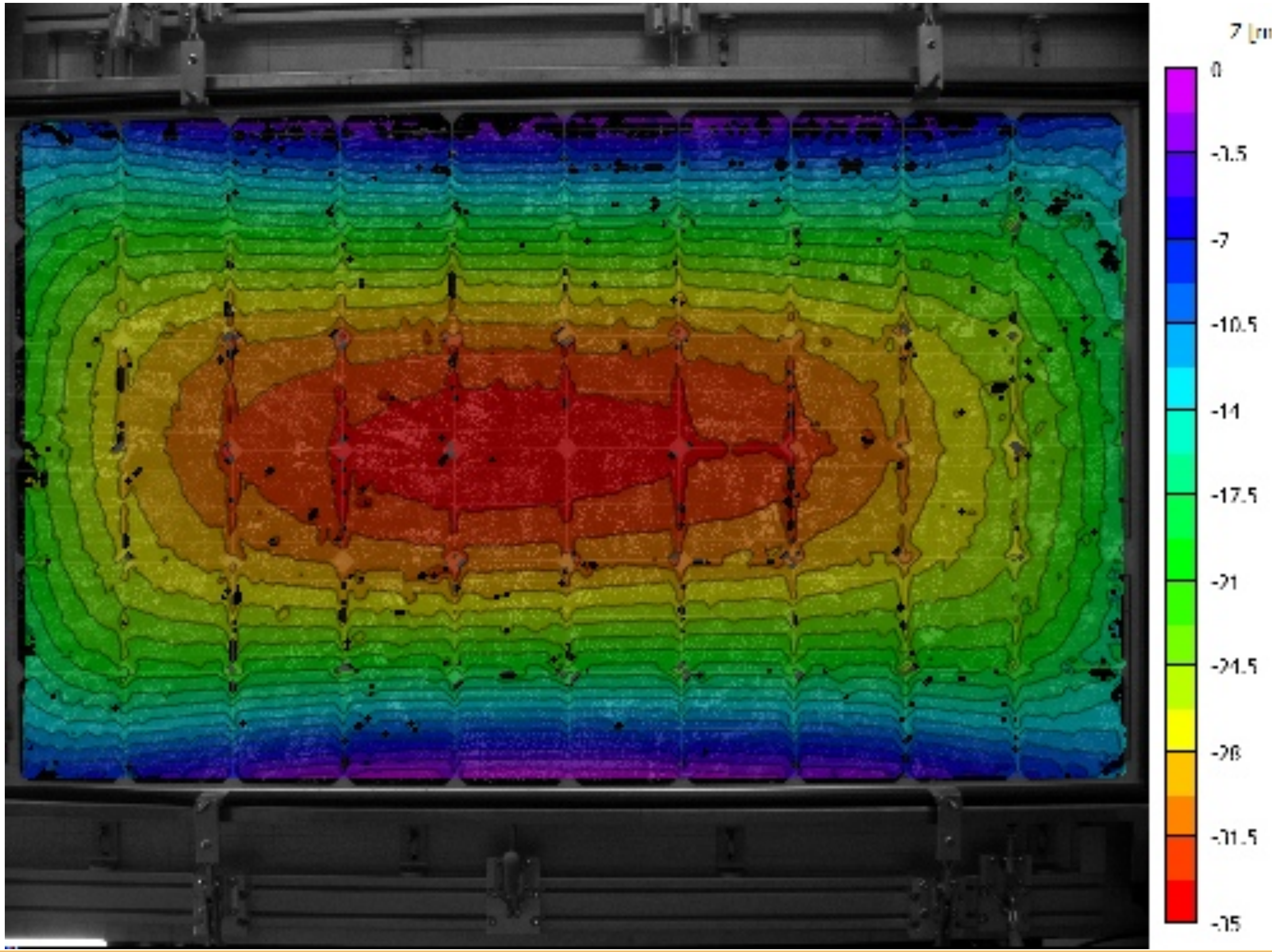
-14 mm

-21 mm

-26 mm

-35mm

-3500 Pa



Legend

0 mm

-7 mm

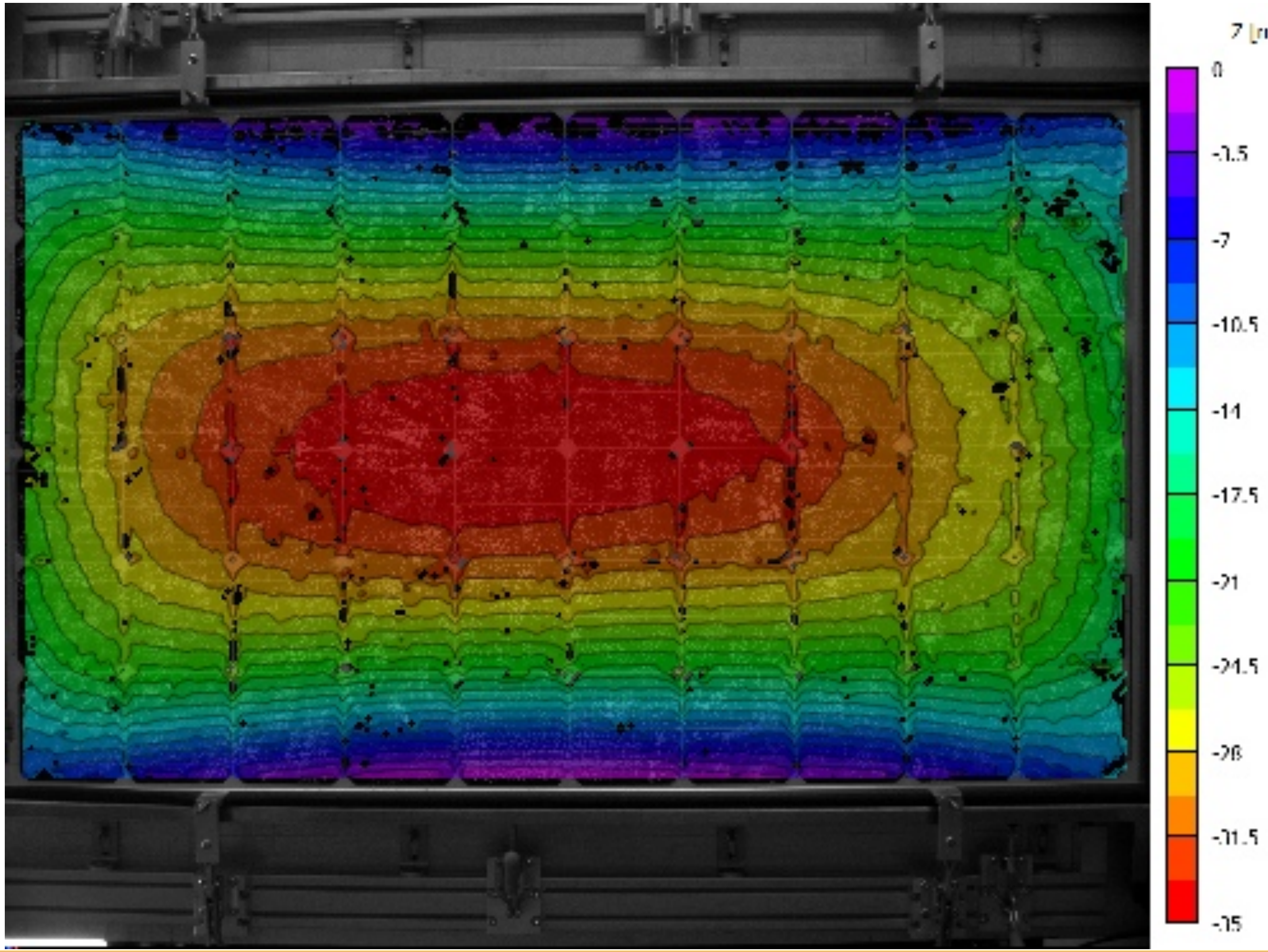
-14 mm

-21 mm

-26 mm

-35mm

-4000 Pa



Legend

0 mm

-7 mm

-14 mm

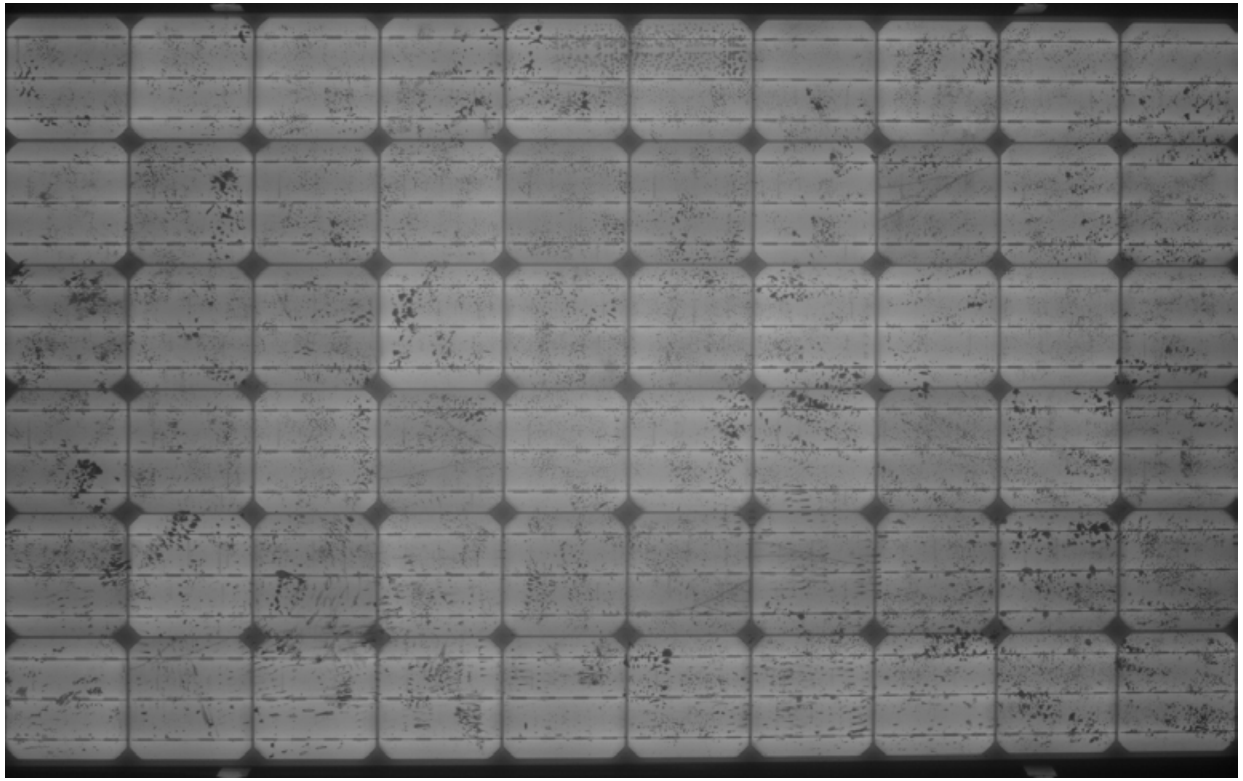
-21 mm

-26 mm

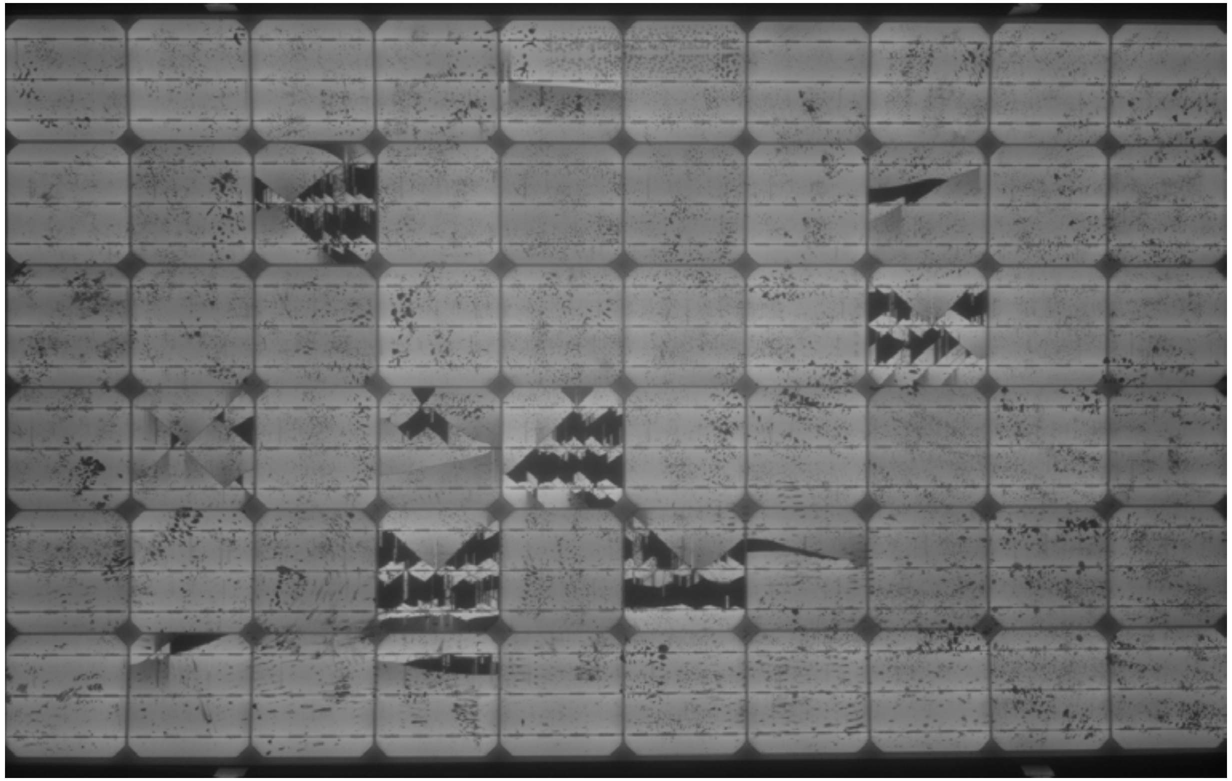
-35mm

EL performed after initial loading DIC shows cell cracking

No cracks visible



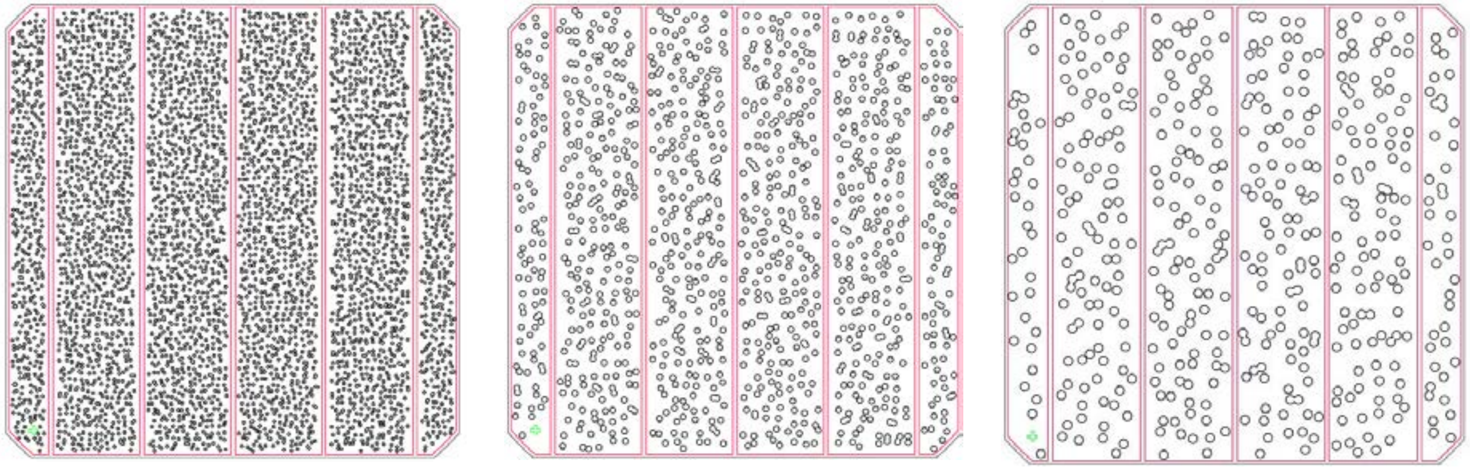
-5400 Pa load



Speckle patter is visible in EL images but does not interfere with crack detection

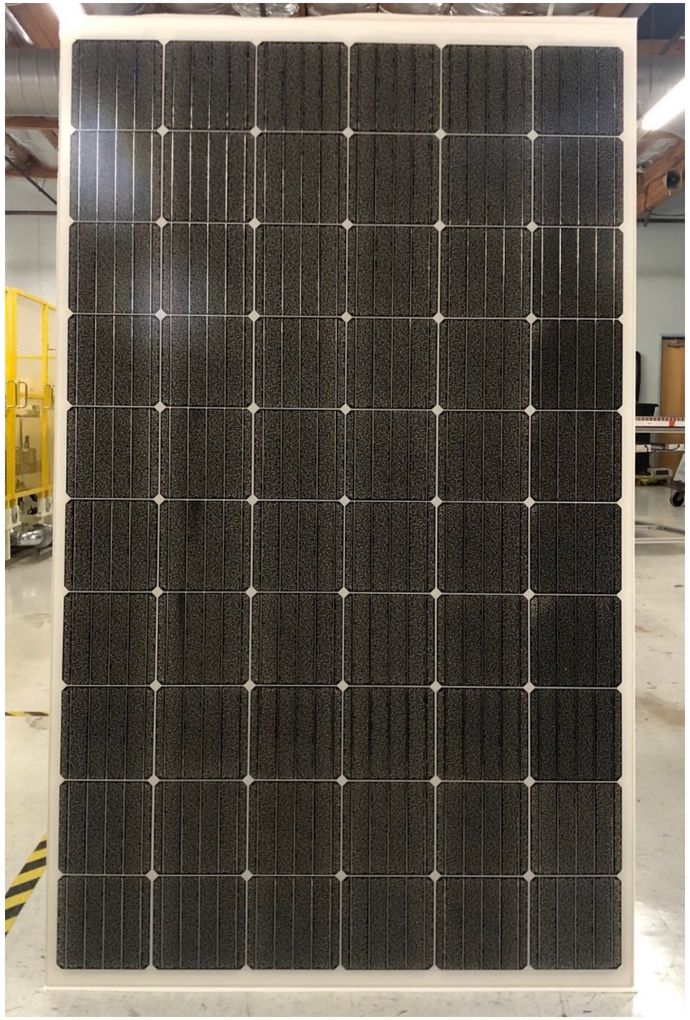
Phase 2: Measuring PV Cell Crack Widths using DIC

- Screen print the speckle patterns directly onto the PV cells
- Use those cells to build encapsulated test modules
- Run test modules on LoadSpot to induce cell cracks and measure X and Y displacements using Stereo DIC.
- Expected resolution in X and Y directions with 5 megapixel cameras:
  - 2-6 µm for full module area
  - <1-2 µm for single cell areas with optimized speckle pattern
  - Ultimate resolution may be affected by distortions caused by looking through glass.

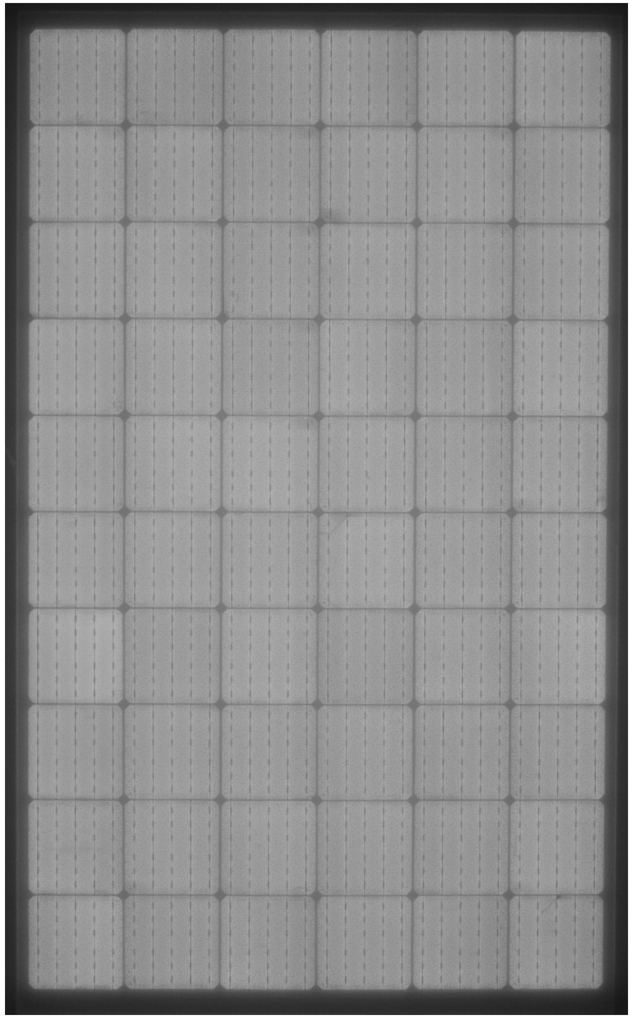


Three random dot screen patterns for different spatial resolutions

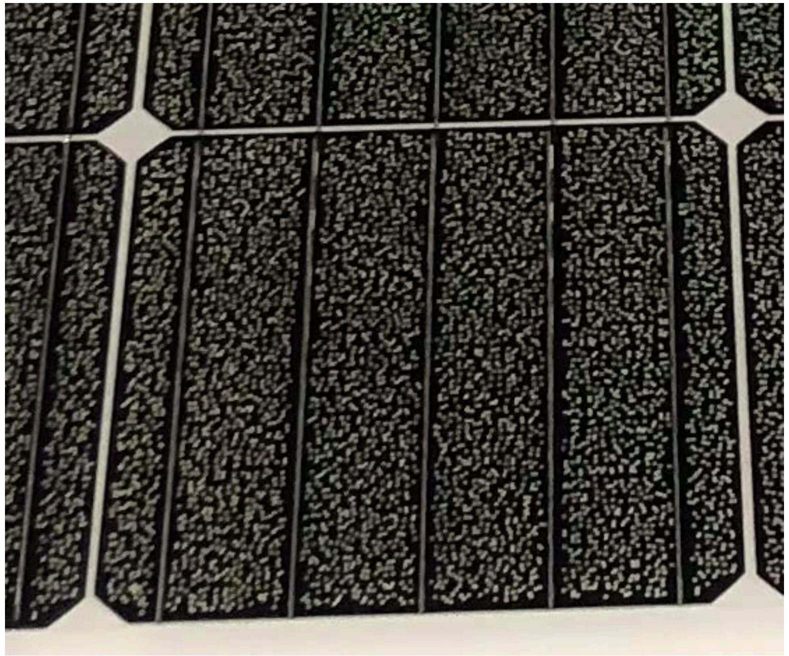
Phase 2: Status – 60 cell module with speckle pattern is complete



Visual image of 6x10 module (DIC pattern print)



EL image of 6x10 module (DIC pattern print)



Close-up of dot pattern on full module

DIC measurements of cell cracks will start soon. Waiting on delivery of new calibration board that is optimized for the experiment.

Summary and Future Work

- Stereo DIC is a full-field, image-based method to measure shape, deformation and strain.
- It is increasingly being applied to photovoltaics
- We have demonstrated its application to module mechanical load testing.
- We will attempt to use it to measure PV cell crack apertures as a function of mechanical and thermal loading.

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DuraMAT
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