Outdoor Inspection of PV Modules Using Drone-based Electroluminescence Imaging

Outline

- **Motivation**
  - **Electroluminescence imaging:**
    - **High accuracy**
    - **Fast acquisition**
    - **Less weather constrains**
  - **Drones:**
    - **Speed**
    - **Automation**

- **Drone-based EL**
  - **Nighttime and dusk-dawn**
  - **Daytime – Challenges**
    - **Signal Enhancement**
  - **Prototype and results**

- **Conclusions and Outlook**

PV Inspections: Fast and Accurate

- **Power and material integrity**

- **Warranted ~0,5% degradation rate per year**

- **Some faults impact the energy production:**
  – Linearly with time
  – <u>Exponentially</u> with time

- **Important to consider:**
  – Product variations
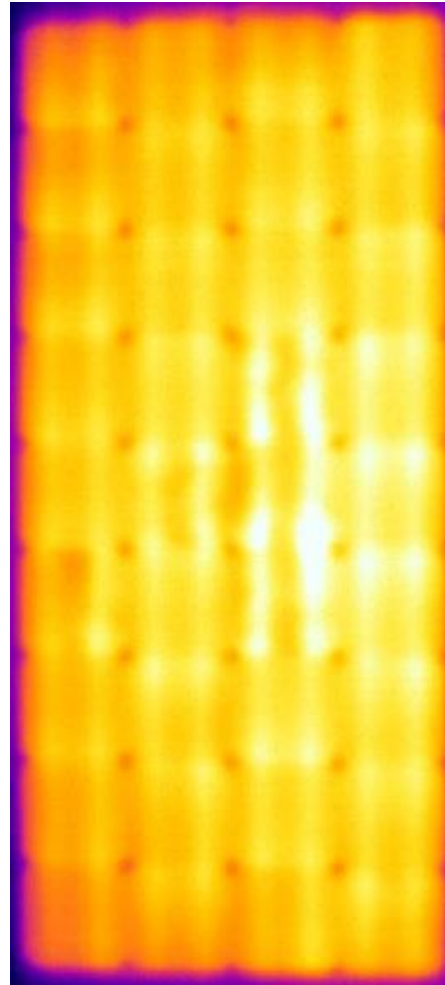 – Climate
  – Mounting configuration
  – Etc.

How to pinpoint failures?
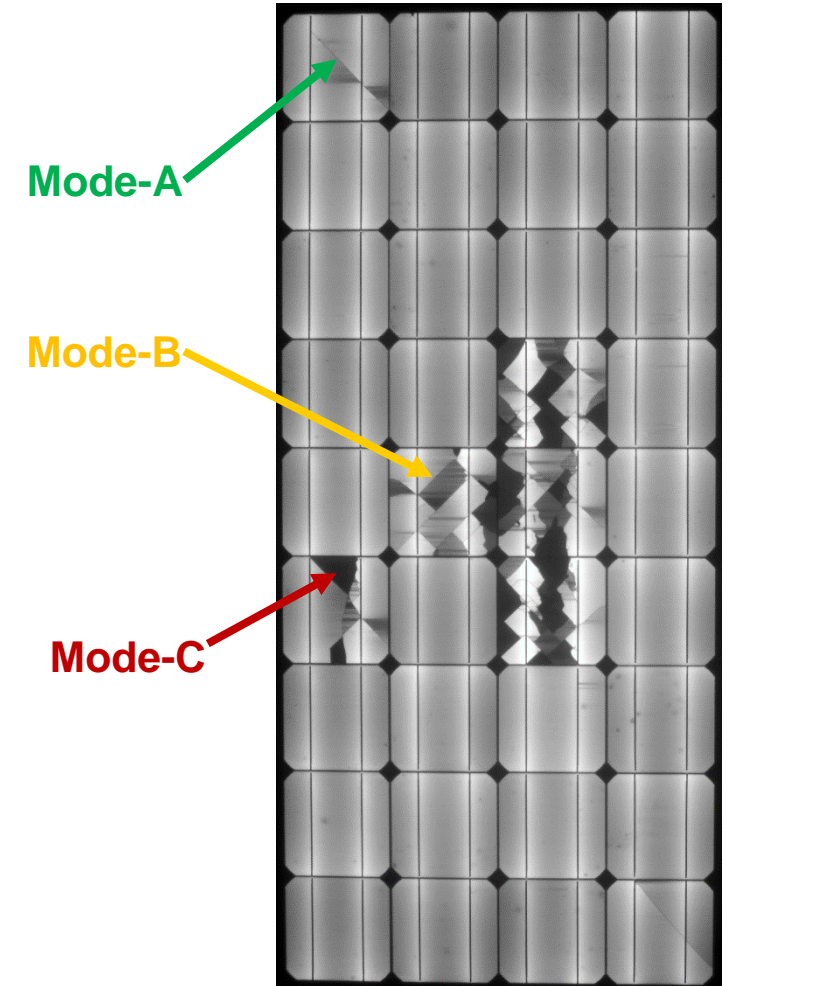
How to define their severity?

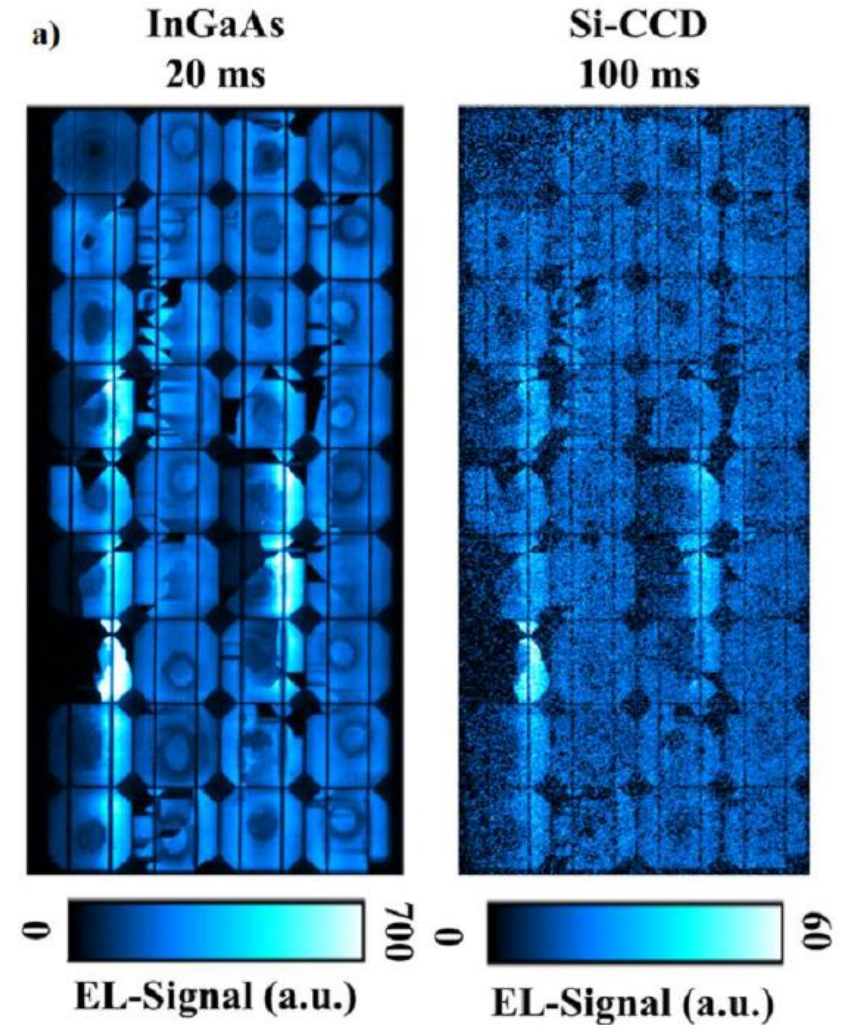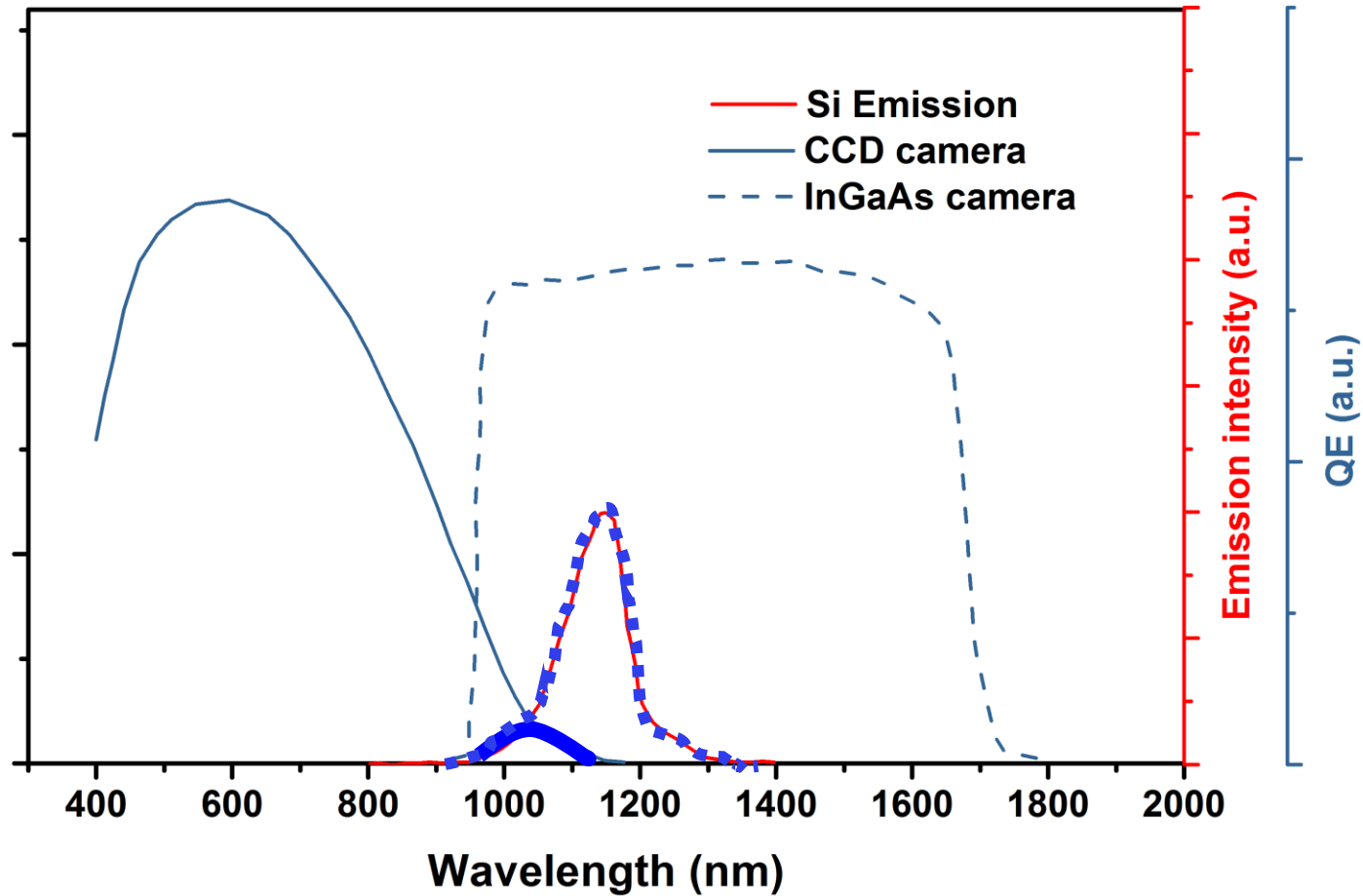# Inspection Techniques Comparison

Visual

IR Thermography (IRT)

Mode-A

Mode-B

Mode-C
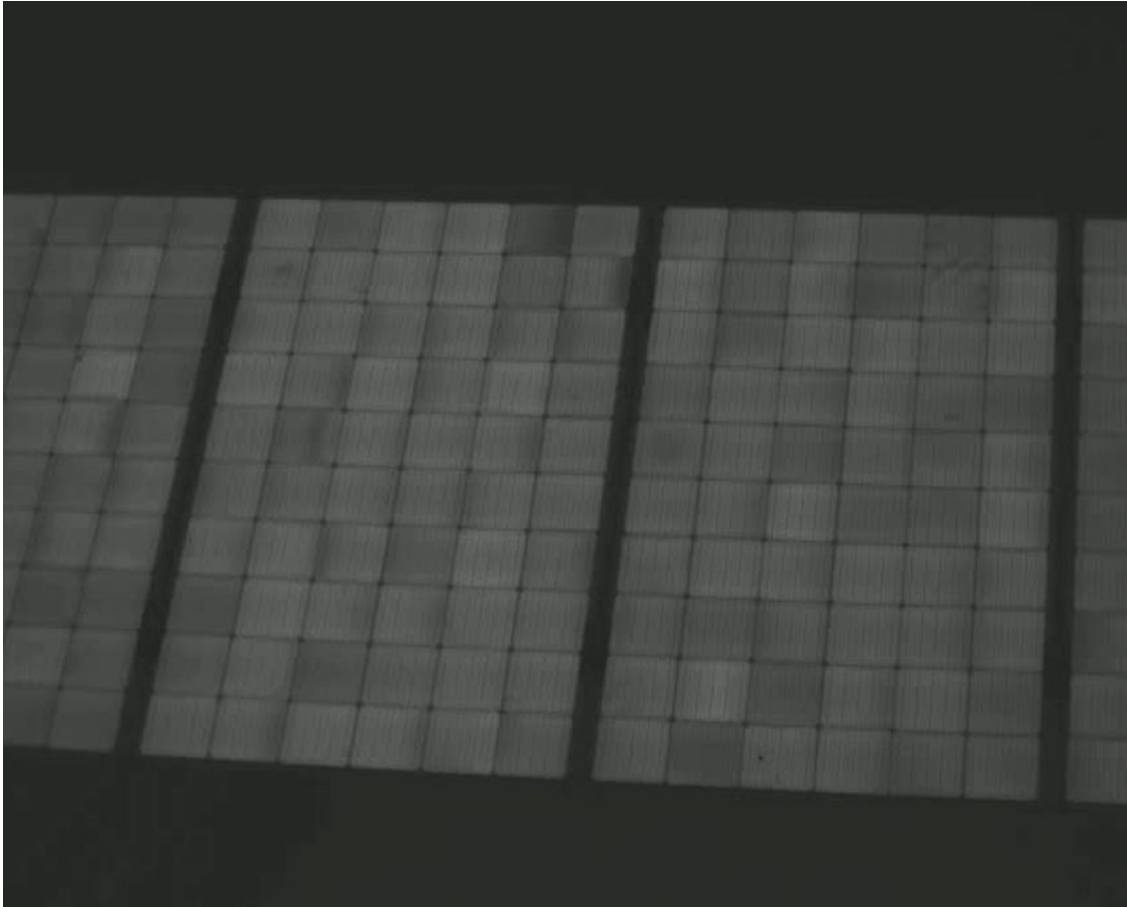
Electroluminescence (EL)

Si photon emission - Detectors

Adams, J., et. Al. *32nd European Photovoltaic Solar Energy Conference and Exhibition, 2016.*
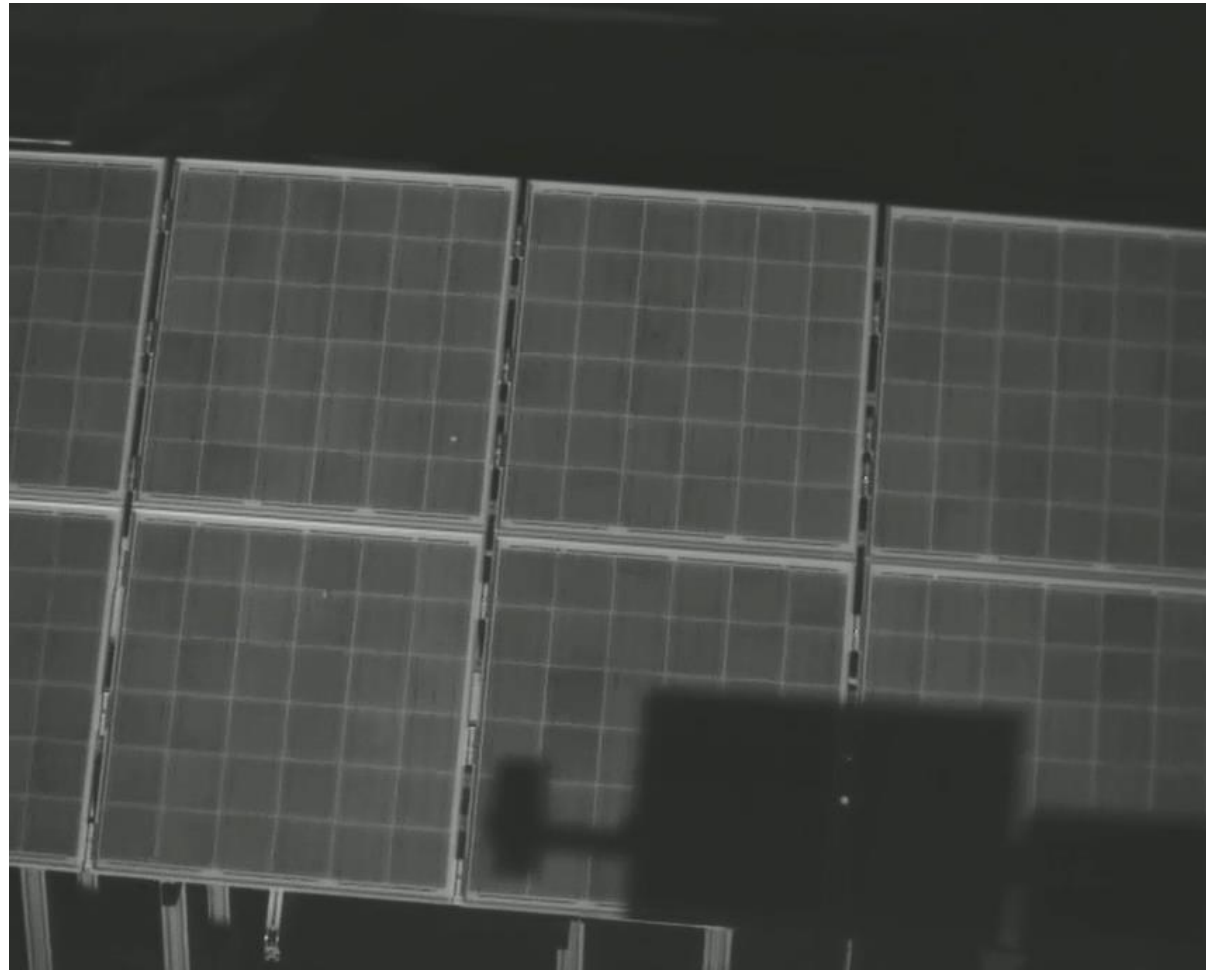
Drone-based EL – Nighttime & Dusk-Dawn

Night time
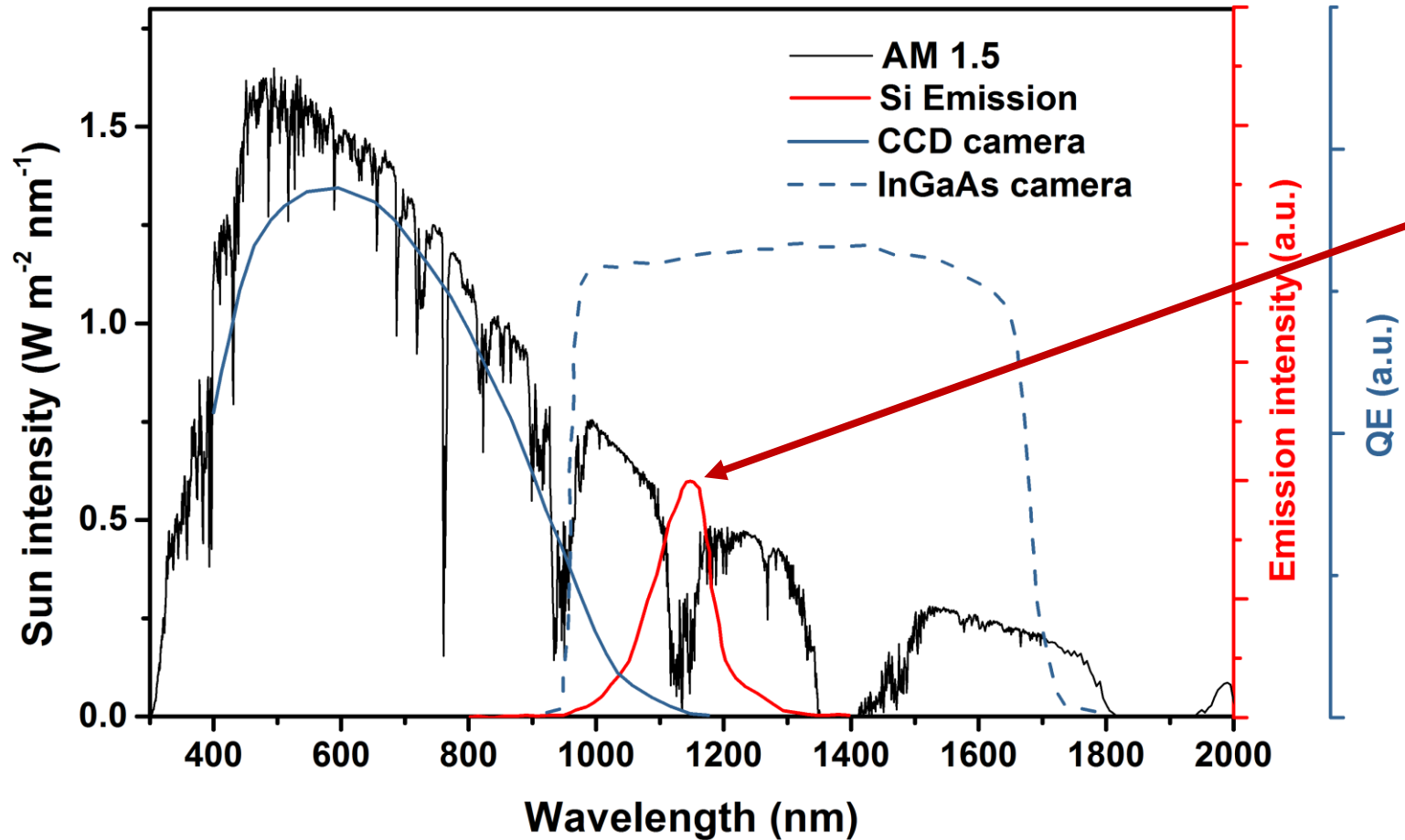

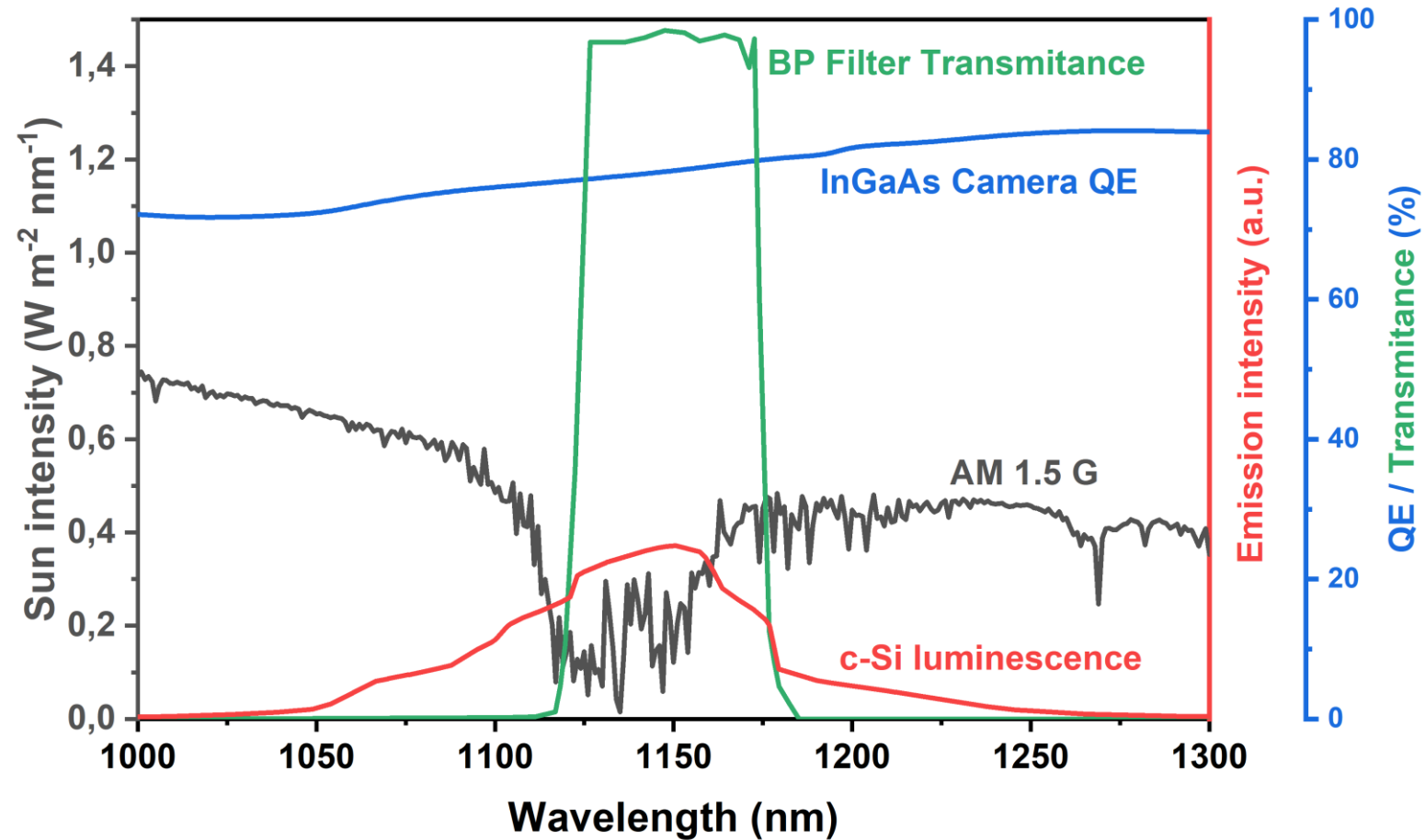Before sunrise

Drone-based EL – Daytime

Daytime

Daylight EL – Challenges

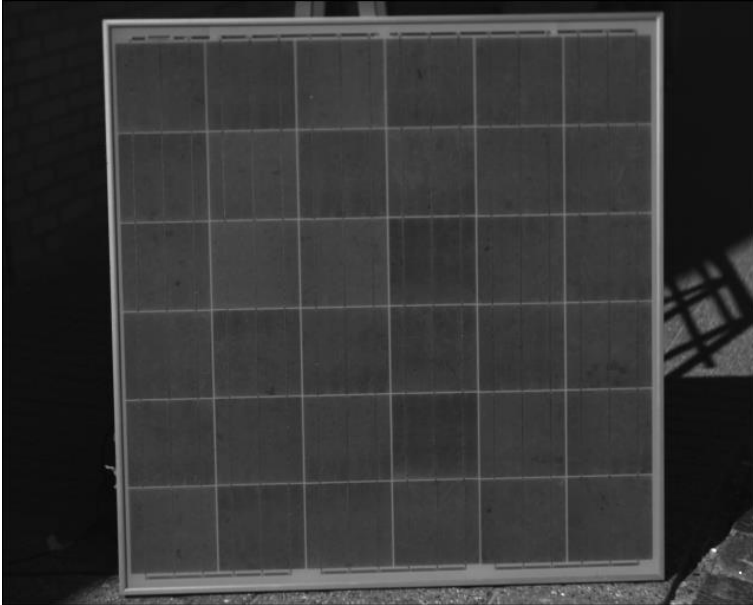4-5
Orders of
Magnitude
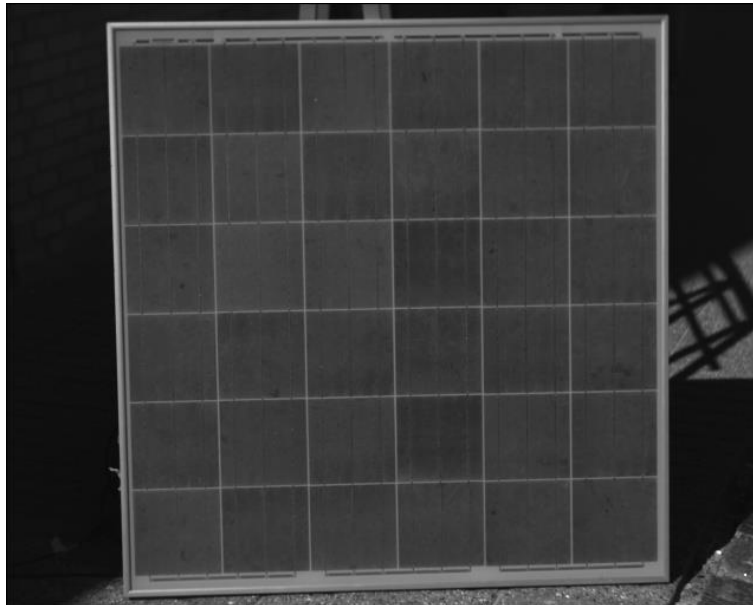less intense!

Daylight Filter

G. Alves dos Reis Benatto et al., IEEE J. Photovoltaics, vol. 10, no. 3, pp. 1–6, 2020.
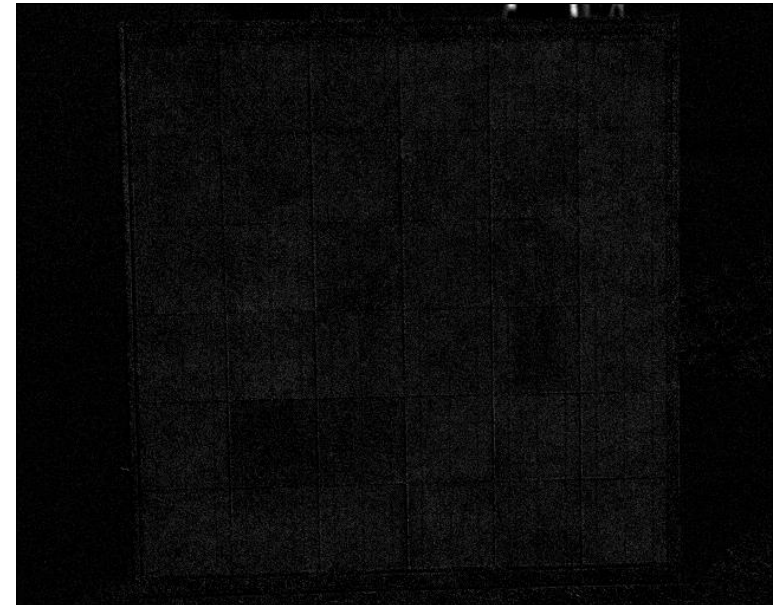
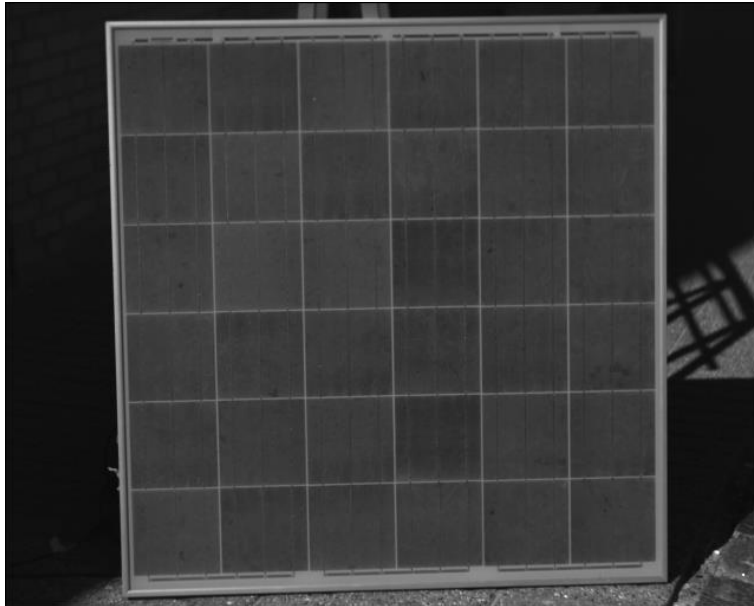# Background Subtraction

EL image

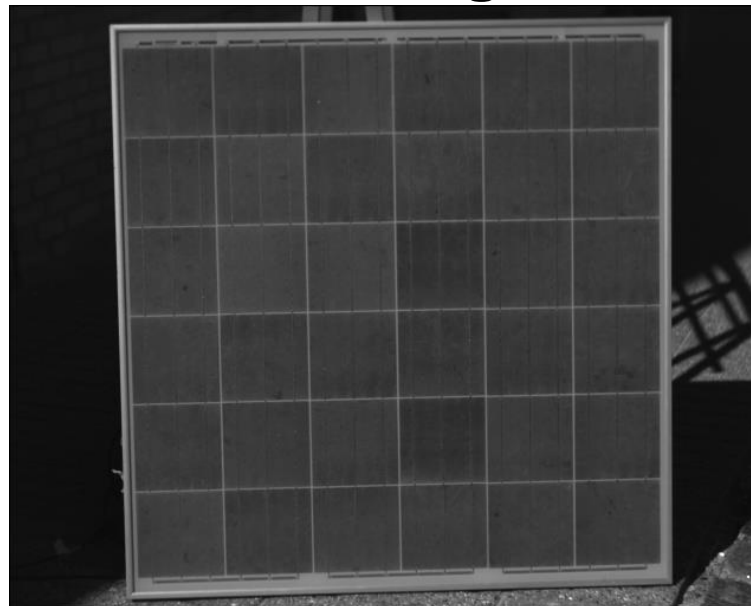**BG image**

\-

\=

G. Alves dos Reis Benatto, 2020.

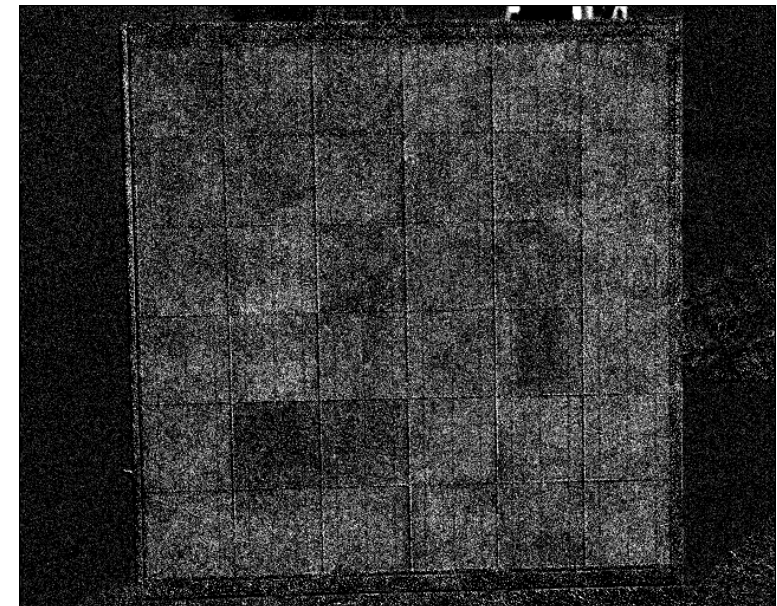# Background Subtraction

EL image

BG image

-

=

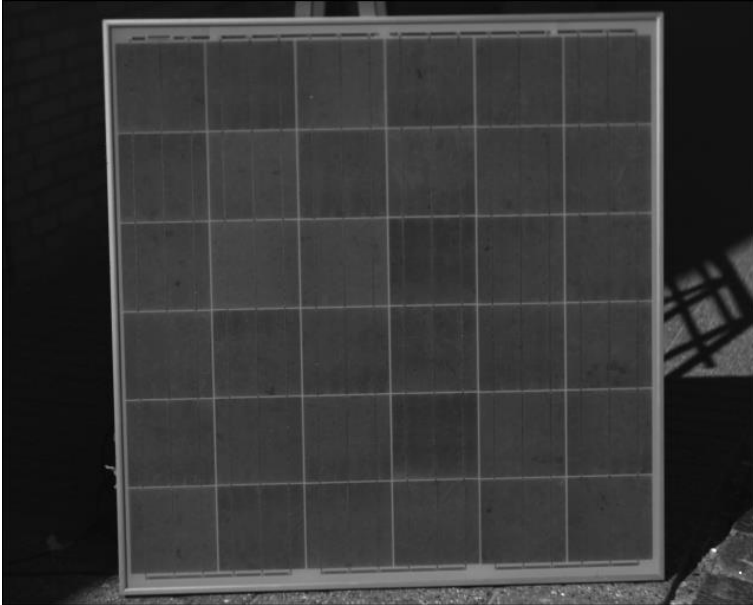

G. Alves dos Reis Benatto, 2020.

Averaging and Background Subtraction

Averaged EL images   **Averages BG images**   **Daylight EL**
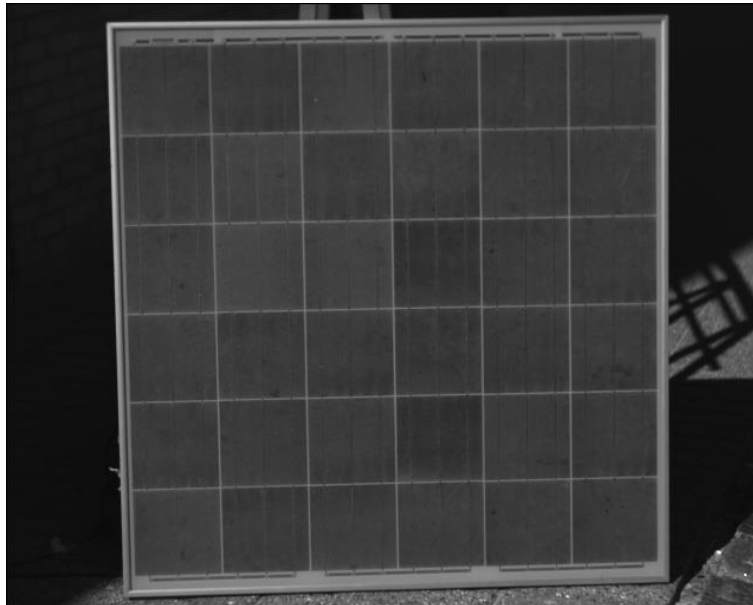
−   =

G. Alves dos Reis Benatto, 2020.

Modulated Image Acquisition

- **Sequence of EL and images following a waveform:**
  - Framerate = 2 x modulation frequency
  - Required to overcome irradiance variations

- **Statistical difference between EL and BG images**

G. A. dos Reis Benatto *et al.*, *44th IEEE Photovolt. Spec. Conf.*, 2017.

SNR Quality Criteria

- **Indoors EL =>** $SNR_{50} > 45$

- **Outdoors EL =>** $SNR_{50} > 5$

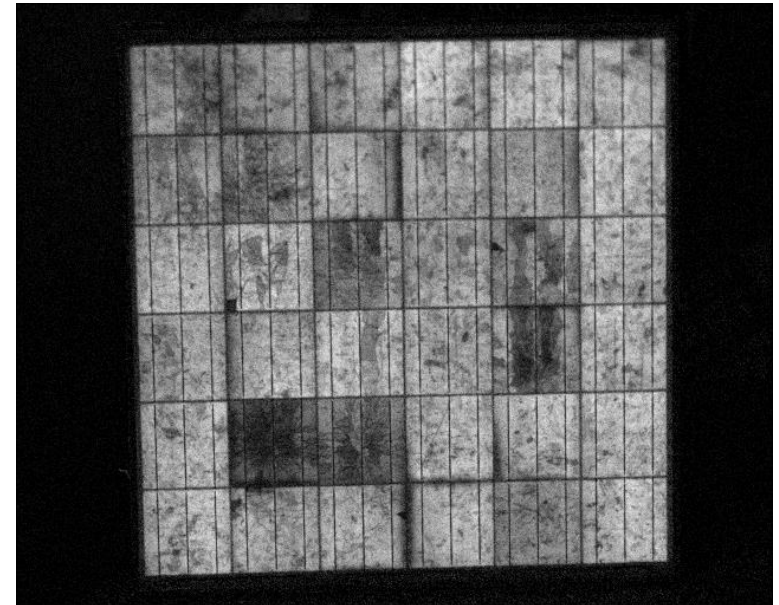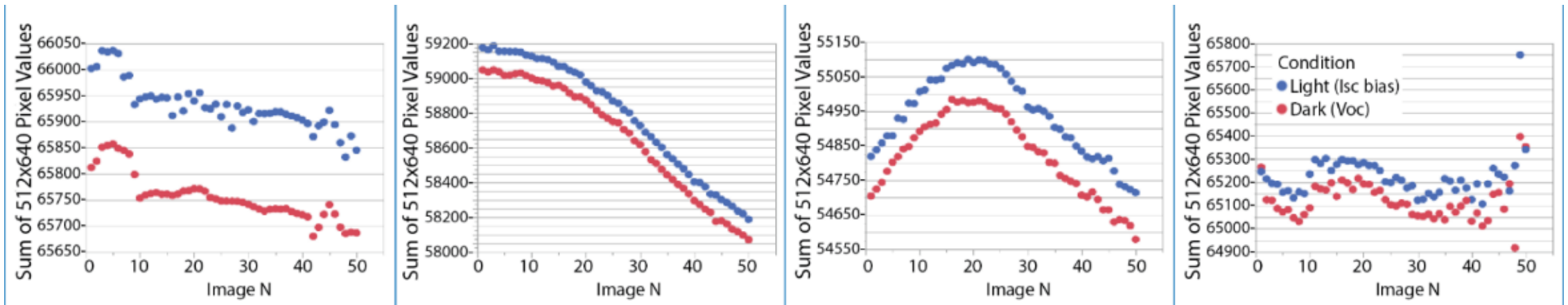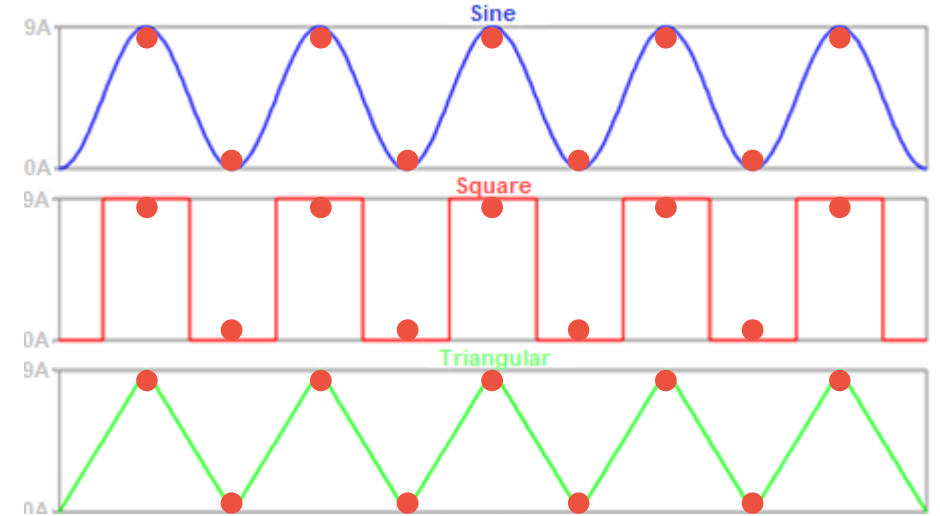$$SNR_{50} = \frac{\sum_k \left(0.5 \cdot \left(EL_1(k) + EL_2(k) \right) - BG(k) \right)}{\sum_k \left(|EL_1(k) - EL_2(k)| \cdot K \right)}$$

$$SNR_{AVG} = \frac{\sum_k \left(avg_{i \in N} \left(EL_i(k) - BG_i(k) \right) \right)}{\sum_k \left(\left| avg_{i \in N_1} \left(EL_i(k) \right) - avg_{j \in N_2} \left(EL_j(k) \right) \right| \cdot K \right)}$$

- **SNR_{50} for INDIVIDUAL images:**
  - EL_1 = 1 "Light" image
  - EL_2 = 1 "Light" image
  - BG = 1 "Dark" image

- **SNR_{AVG} for AVERAGED images:**
  - EL_i = Average of N_1 "Light" images
  - EL_j = Average of N_2 "Light" images
  - BG = Average of N "Dark" images

$$K = \sqrt{0.5} \cdot \left(\frac{2}{\pi} \right)^{-0.5}$$

IEC, "IEC TS 60904-13 Photovoltaic Devices - Part 13: Electroluminescence of Photovoltaic Modules," http://www.iec.ch/

C. Mantel et al., 7th World Conference on Photovoltaic Energy Conversion (WCPEC) 2018, pp. 3285–3289.

SNR Quality Criteria
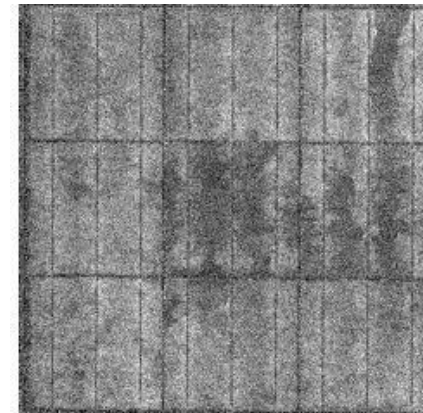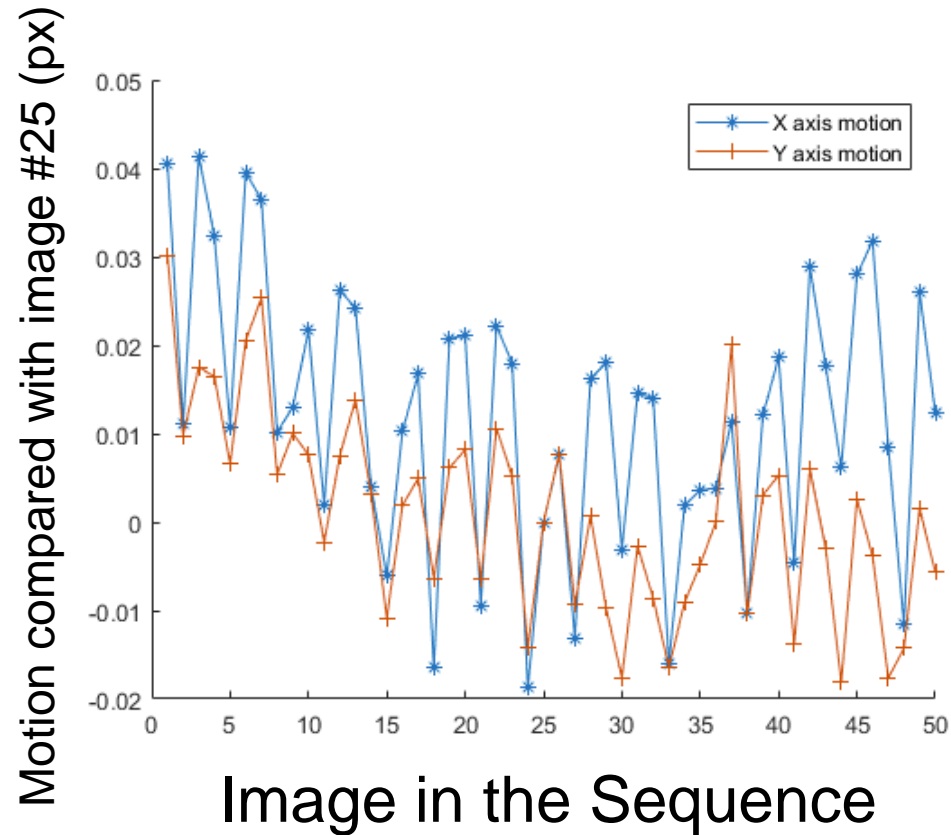
- **Daylight EL – Stationary**

  - G_{POA} = 891 W m^{-2}
  - Image sequences acquired one after the other
  - Same modulation frequencies

- **Good quality images, but SNR$_{AVG}$ not always adds up in quality**
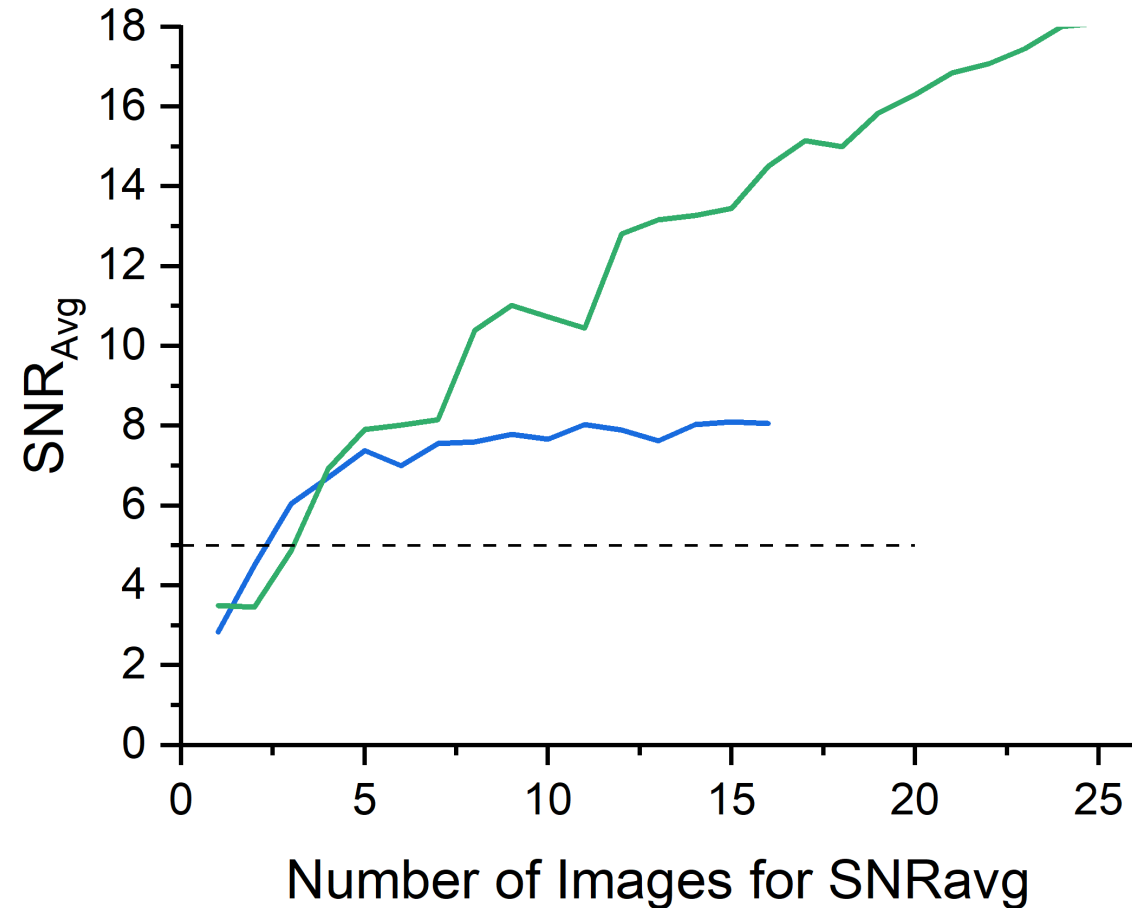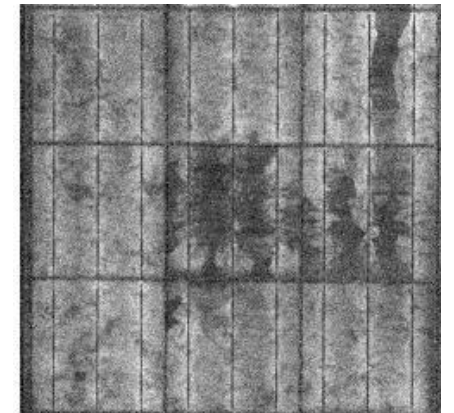

G. Alves dos Reis Benatto, 2020.

Motion between frames

- Main factor that prevents image quality enhancement

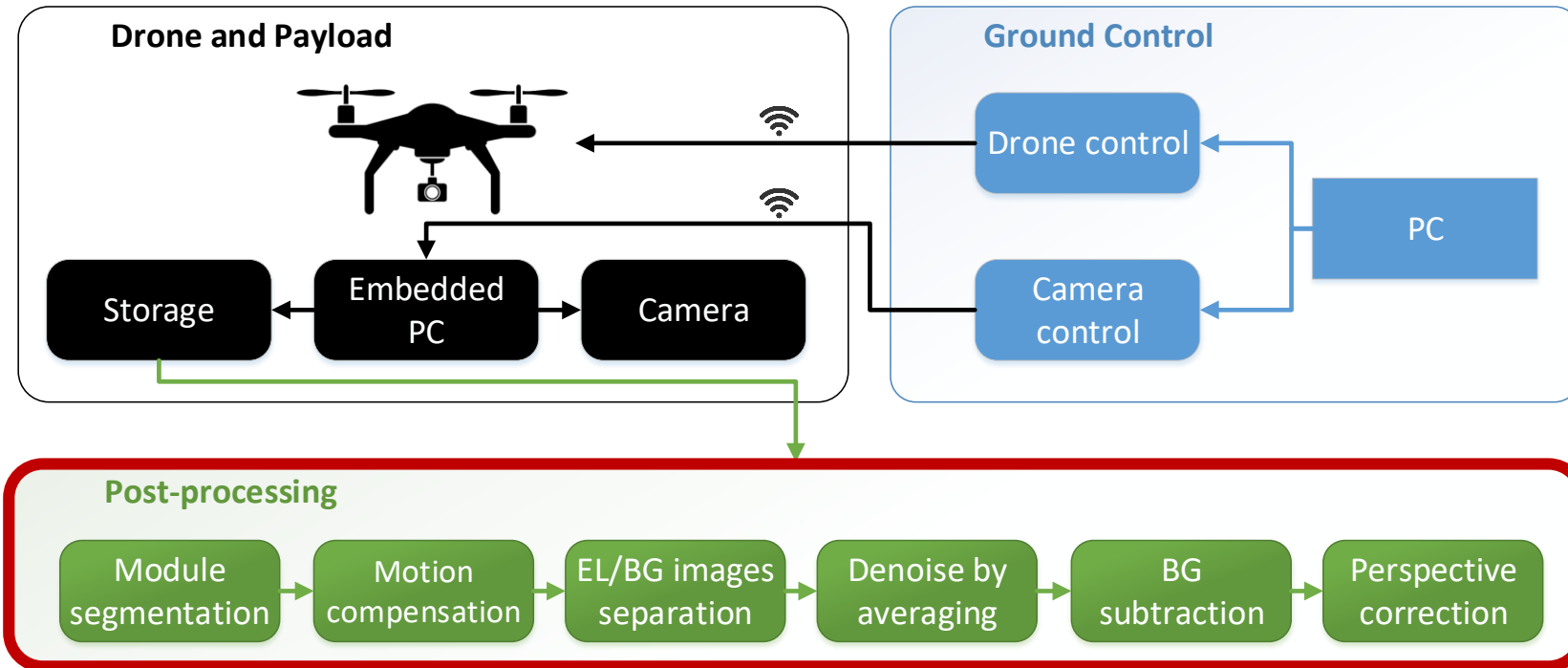Motion compared with image #25 (px)

Image in the Sequence

Without shake selection

With shake selection

C. Mantel et al., 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion, WCPEC 2018, pp. 3285–3289.
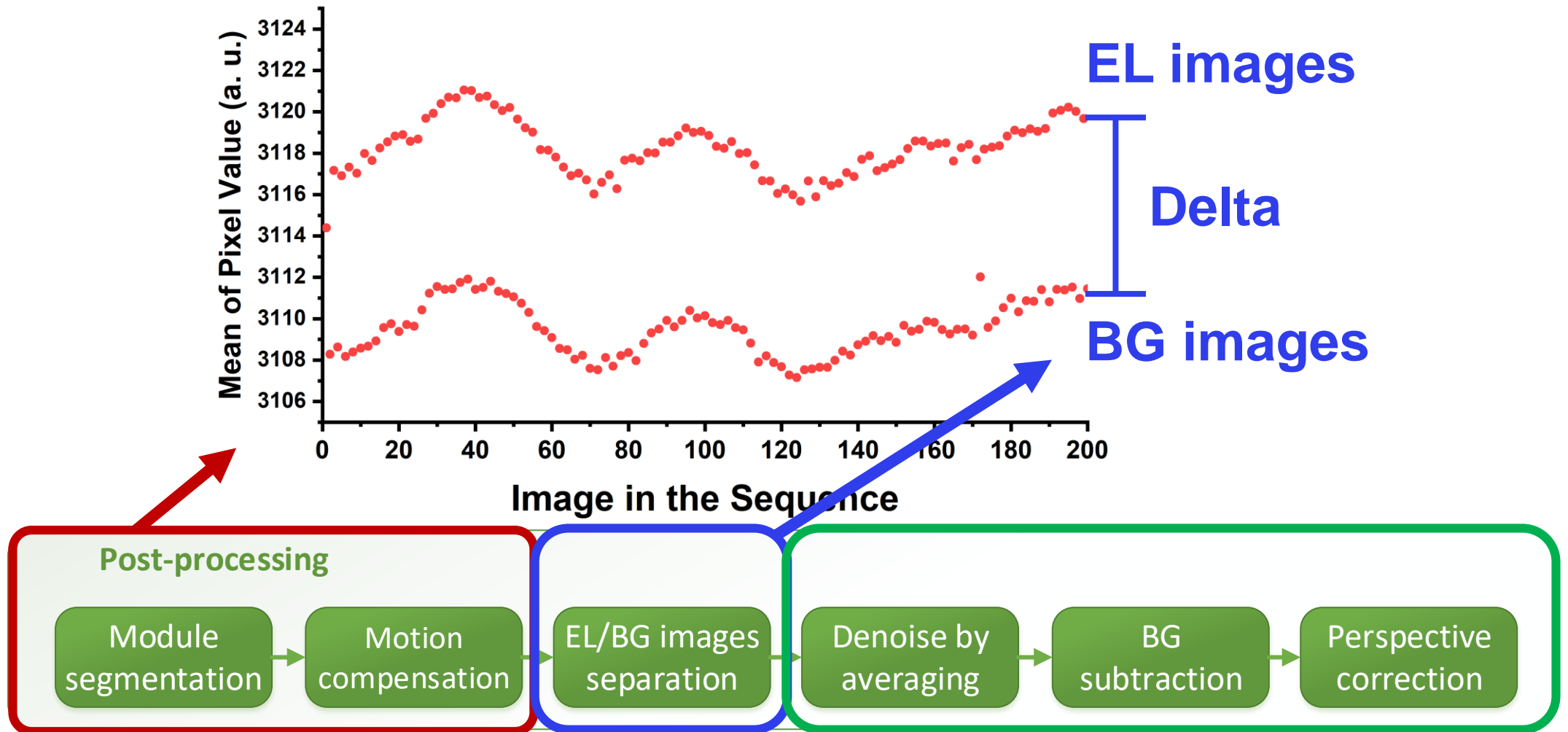
Image Acquisition System

Drone and Payload

- Storage ↔ Embedded PC ↔ Camera

Ground Control

- Drone control
- Camera control
- PC

Post-processing

Module segmentation → Motion compensation → EL/BG images separation → Denoise by averaging → BG subtraction → Perspective correction

G. Alves dos Reis Benatto et al., IEEE J. Photovoltaics, vol. 10, no. 3, pp. 1–6, 2020.

Image Processing

EL images

Delta

BG images

Post-processing

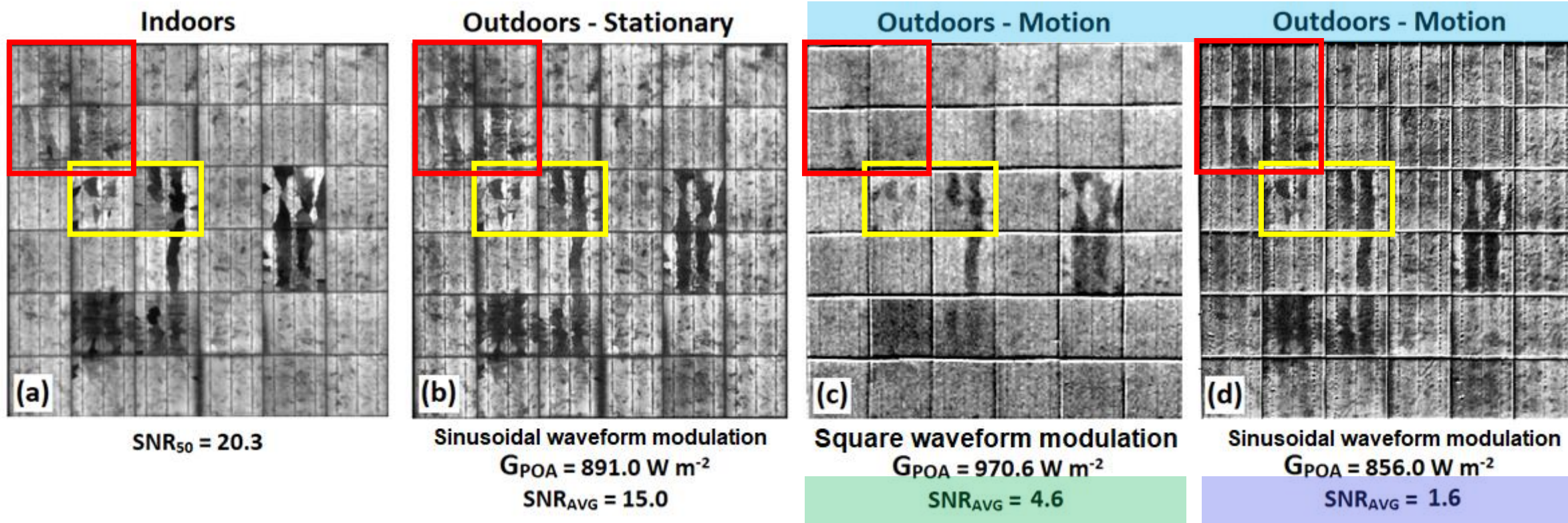Module segmentation → Motion compensation → EL/BG images separation → Denoise by averaging → BG subtraction → Perspective correction

G. Alves dos Reis Benatto et al., IEEE J. Photovoltaics, vol. 10, no. 3, pp. 1–6, 2020.

Resulting EL images

| Indoors	Outdoors - Stationary	Outdoors - Motion	Outdoors - Motion
(a)	(b)	(c)	(d)
$SNR_{50} = 20.3$	Sinusoidal waveform modulation $G_{POA} = 891.0$ W m^{-2} $SNR_{AVG} = 15.0$	Square waveform modulation $G_{POA} = 970.6$ W m^{-2} $SNR_{AVG} = 4.6$	Sinusoidal waveform modulation $G_{POA} = 856.0$ W m^{-2} $SNR_{AVG} = 1.6$

G. Alves dos Reis Benatto et al., IEEE J. Photovoltaics, vol. 10, no. 3, pp. 1–6, 2020.

Conclusions and Outlook

- **Image quality criteria:** Needs revision for Daylight EL Scenario

- **Many improvements are required for Upscaling Drone-based EL:**

  – Efficient module and signal detection

  – Robust motion compensation

  – Automatic fault detection and severity evaluation
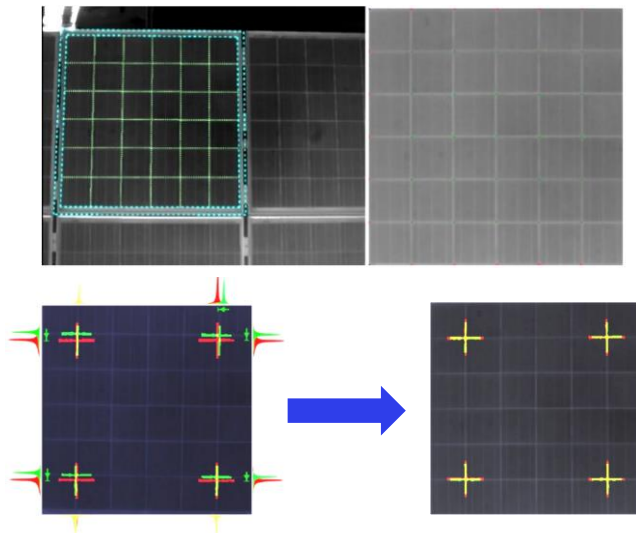
Thøger Kari Hass, Spataru, S., Santamaria Lancia, A. A., Parikh, H., Poulsen, P. B., & dos Reis Benatto, G. A. *37th European Photovoltaic Solar Energy Conference and Exhibition*, 1573–1579, 2020.
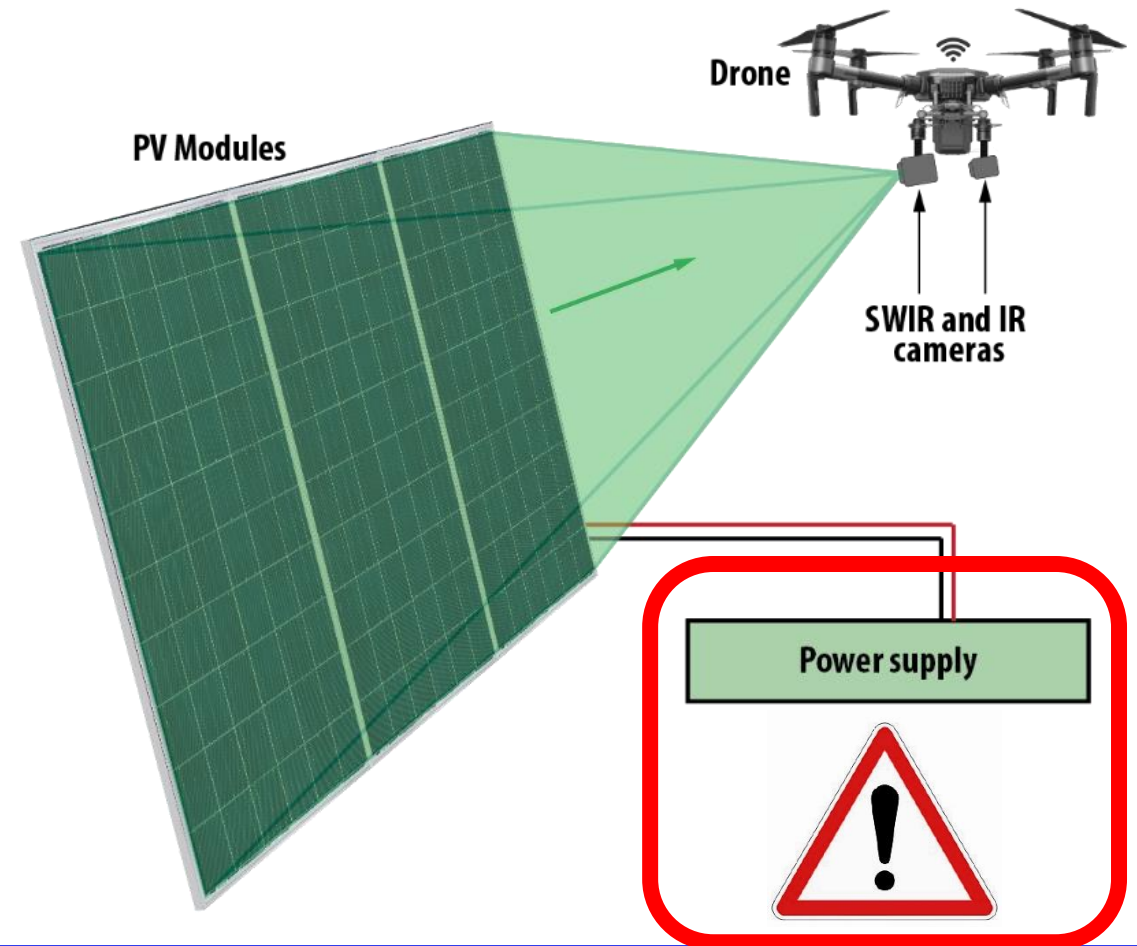
Parikh, H. R., Buratti, Y., Spataru, S., Villebro, F., Reis Benatto, G. A. Dos, Poulsen, P. B., Wendlandt, S., Kerekes, T., Sera, D., & Hameiri, Z. *Applied Sciences*, *10*(24), 8834, 2020.
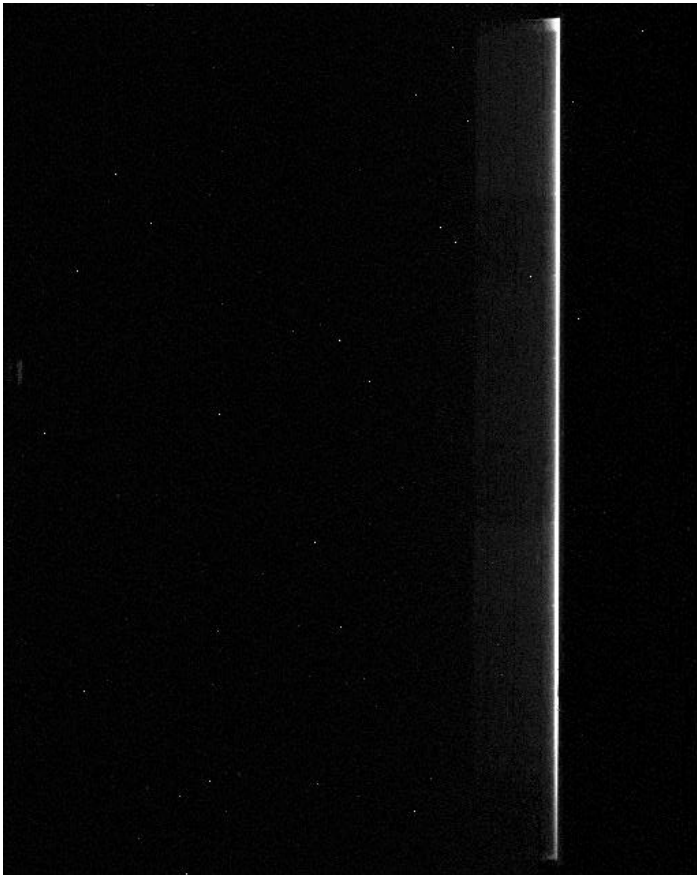
Outlook

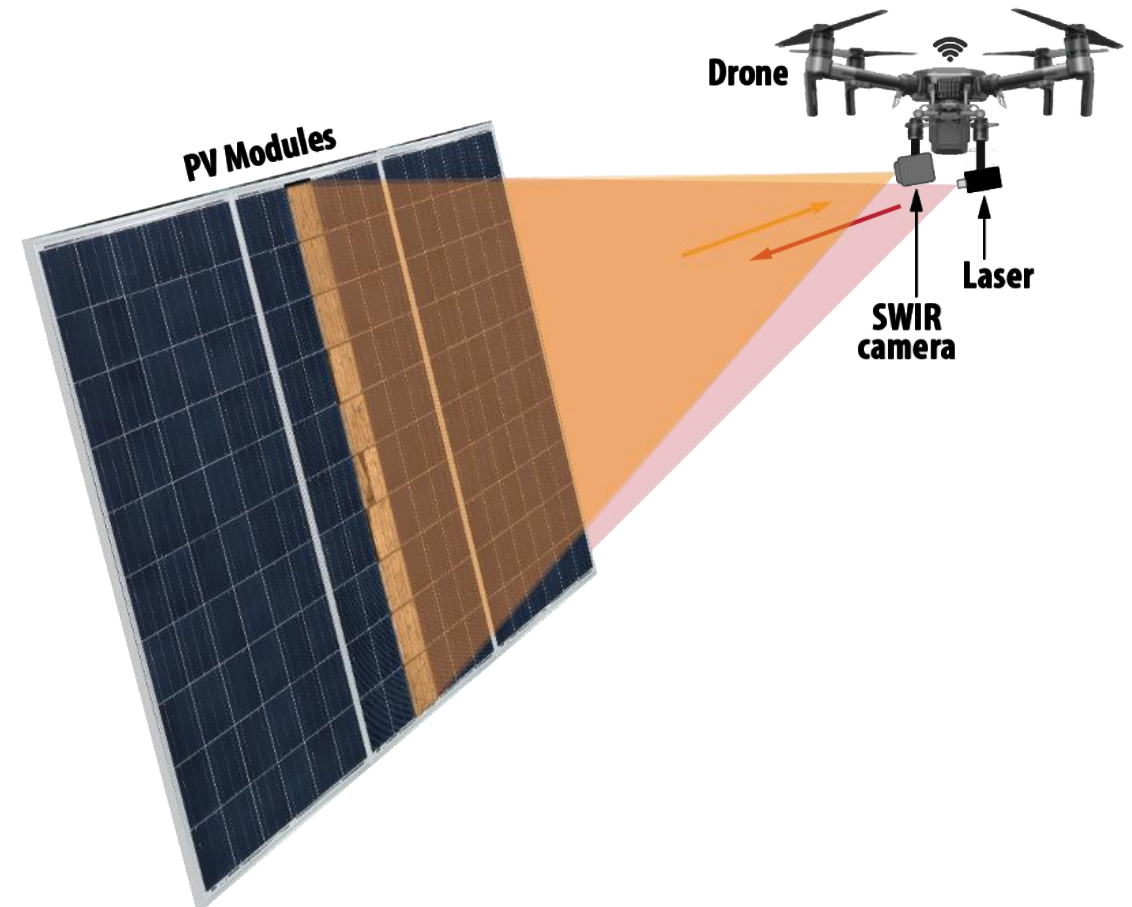- 80% of EL inspection time is due to electrical connections!

Outlook

- Laser Induced Luminescence (LIL)

LIL scan

PV Modules

Drone

Laser

SWIR camera

Thank you for your attention!

Questions?