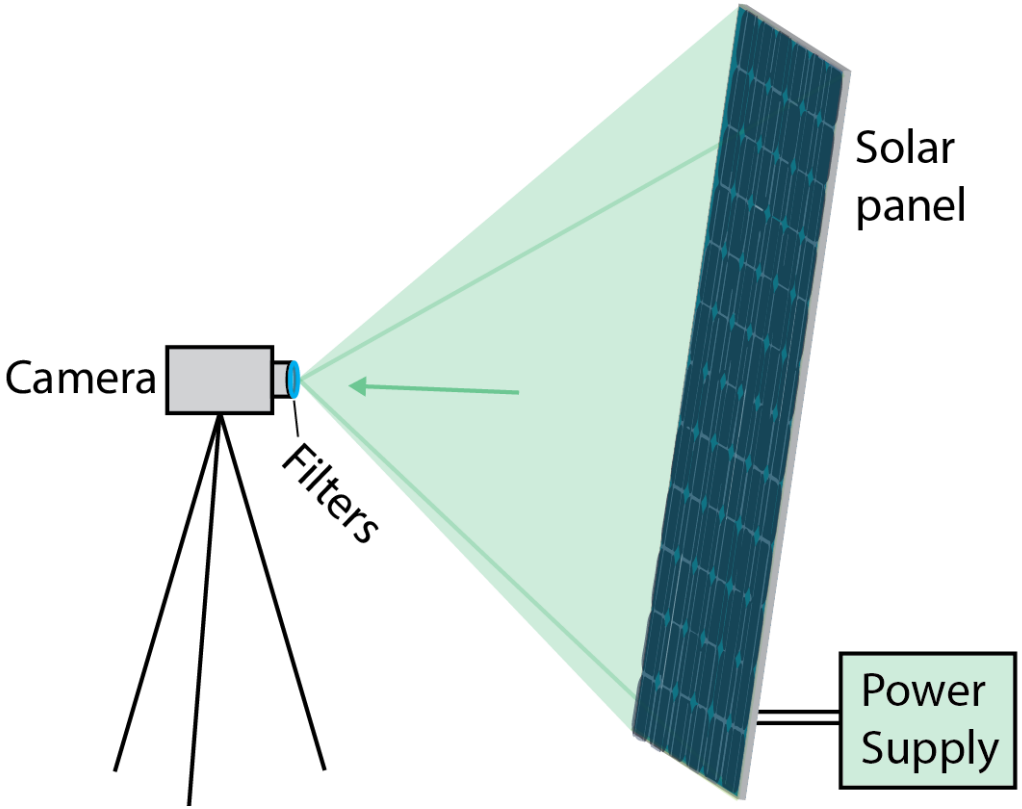
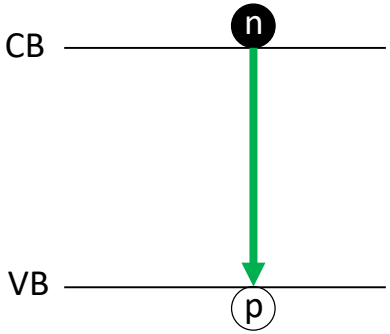
Block 4 – Imaging
Part 2: Electroluminescence Imaging

34553: Applied Photovoltaics

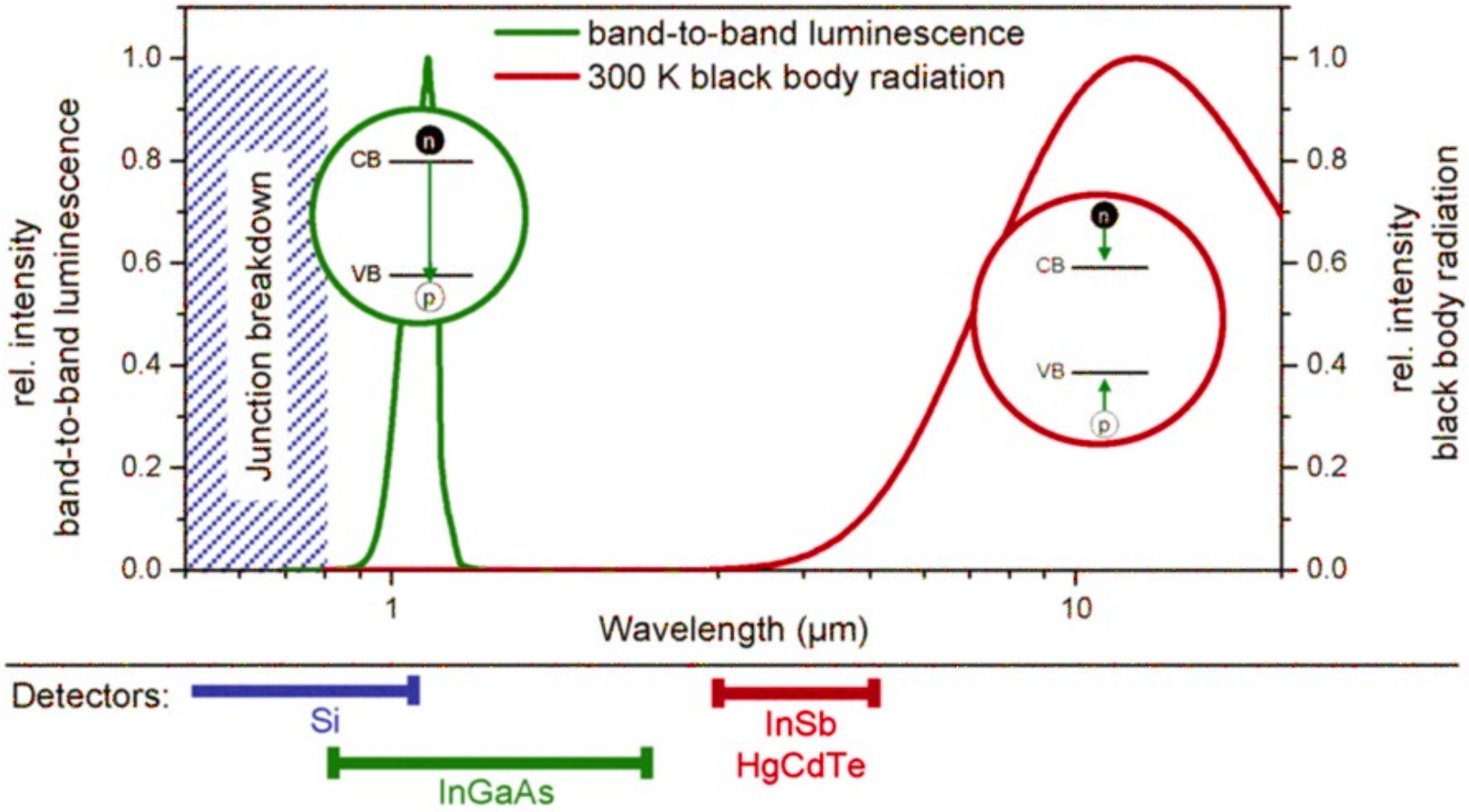
Electroluminescence (EL)

- **Technical Specification:** IEC TS 60904-13 “Photovoltaic Devices - Part 13: Electroluminescence of Photovoltaic



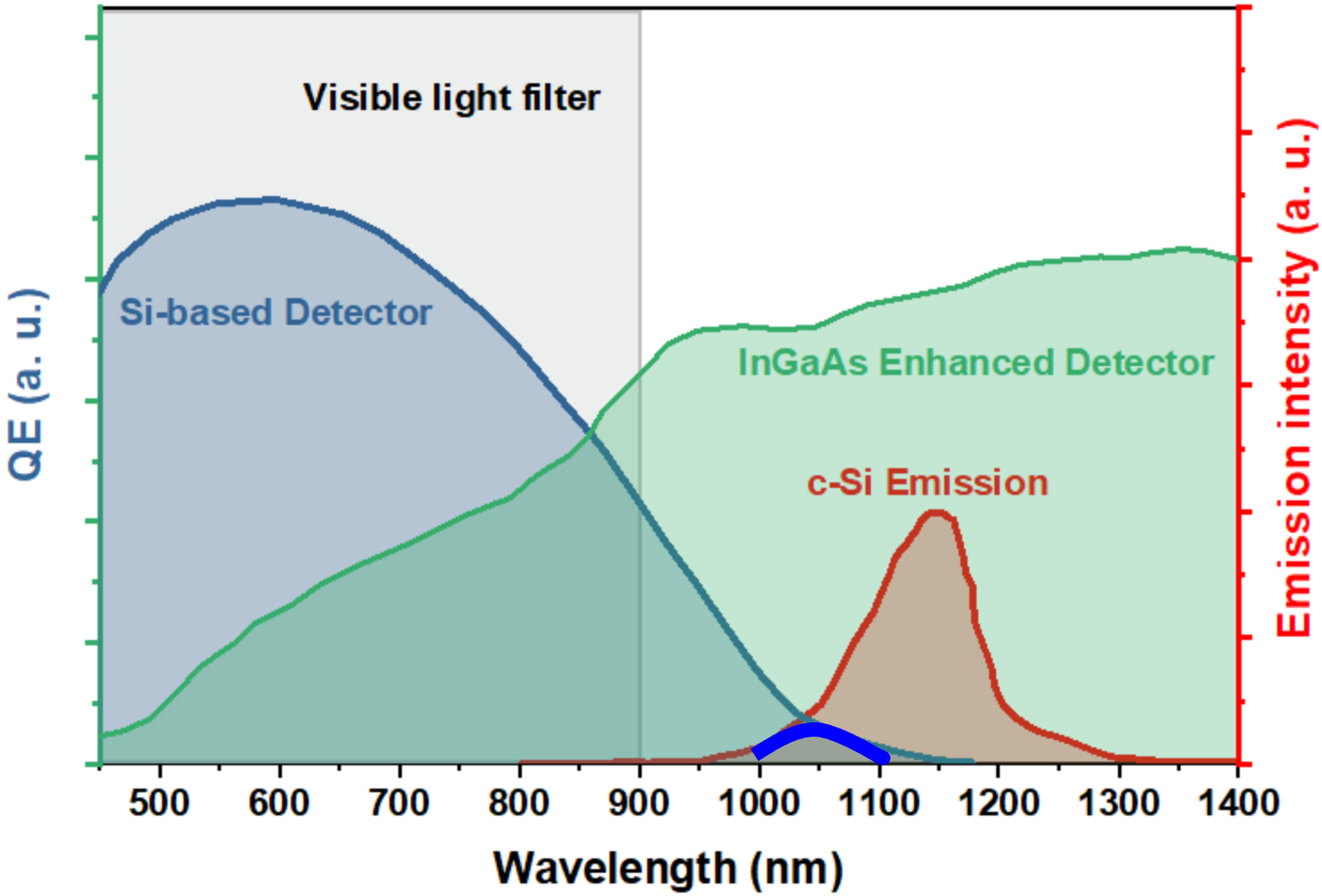


Spectral range of Si photon emission - Detectors



Modified from: Kasemann, M., Kwapil, W., Schubert, M.C., et al. 33rd IEEE Photovolt. Spec. Conf., 2008, 1–7

Detectors


Visible light filter
Si-based Detector
InGaAs Enhanced Detector
c-Si Emission
QE (a. u.)
Emission intensity (a. u.)
500
600
700
800
900
1000
1100
1200
1300
1400
Wavelength (nm)

Cameras

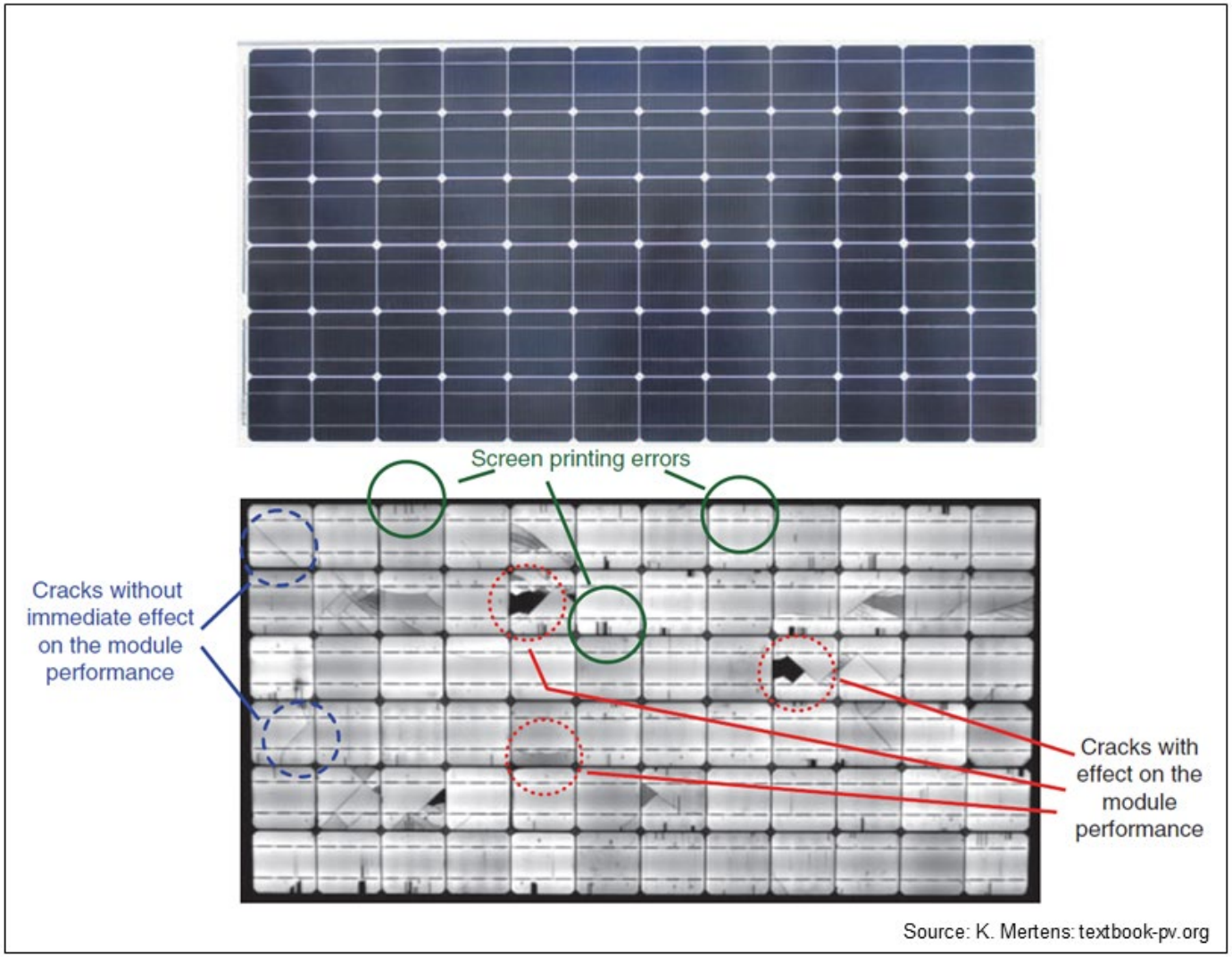
- CMOS modified Camera (Si-based)

- Raptor OWL640 (InGaAs-based)

InGaAs Camera – Raptor OWL640

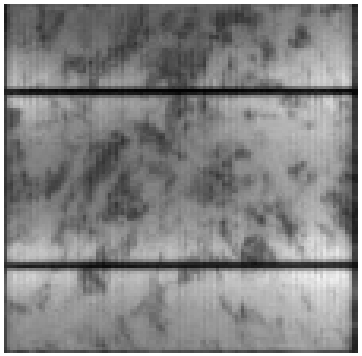
FPA Specification	
Sensor	SCD
Sensor Type	InGaAs PIN-Photodiode
Active Pixel	640 x 512
Pixel Pitch	15µm x 15µm
Active Area	9.6mm x 7.68mm
Spectral response	0.4µm to 1.7µm
Readout Noise (RMS)	LG: 174 electrons (typical), HG: 36 electrons (typical)
Quantum Efficiency	>80% @ 1.55µm
Full Well Capacity	Low Gain: 650Ke-, High Gain: 10Ke-
Pixel Operability	>99.5%
Camera Specification	
Digital Output Format	14 bit Camera Link (Base Configuration)
Exposure time	10µs to 26.8
Shutter mode	Global shutter
Frame Rate	Up to 120Hz
Optical Interface	C mount or M42
Dynamic Range	Low Gain: 71dB, High Gain: 49dB
Trigger interface	Trigger IN and OUT - TTL compatible
Power supply	12V DC ±0.5V
TE Cooling	Active
Image Correction	3 point NUC (Offset, Gain & Dark Current) + Pixel Correction
Functions controlled by serial communication	Exposure, Intelligent AGC, Non Uniformity Correction, Gamma, Pk/Av, TEC, ROI
Camera Power Consumption	<3.5W with TEC OFF, NUC ON
Operating Case Temperature	-20°C to +55°C
Storage Temperature	-30°C to +60°C
Dimensions & Weight	90.93mm x 50.00mm x 50.00mm | 282g

Diagnosis

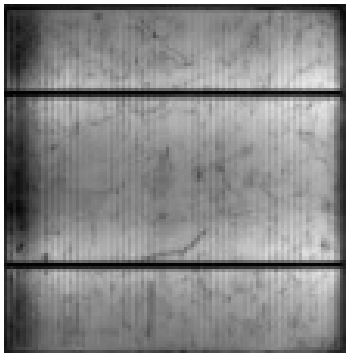


View and EL photo of a solar module that was improperly transported

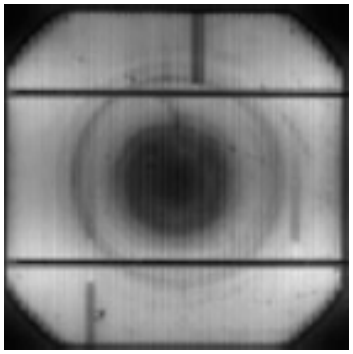
Diagnosis – Cell Level



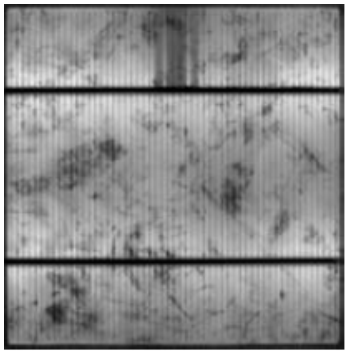
Defect: Healthy cell (Multi-Si)



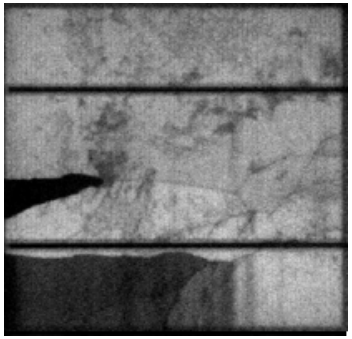
Defect: Edged Cell



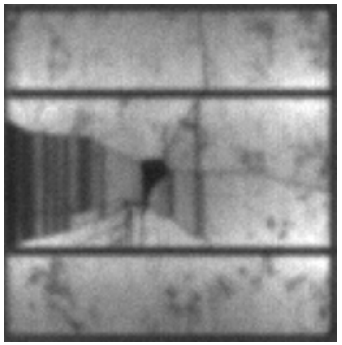
Defect: Striation rings



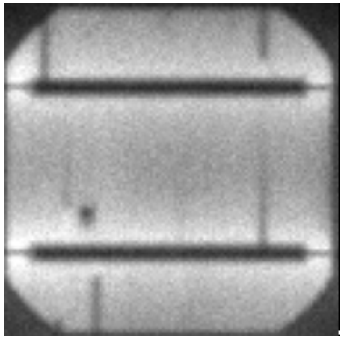
Failure: Finger interruptions



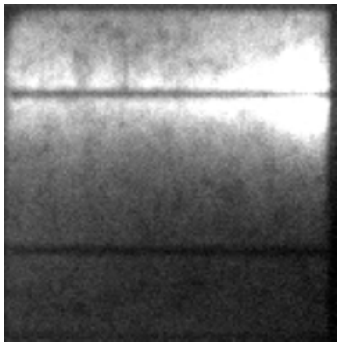
Failure: C-Crack + (B and A-Crack)



Failure: Finger interruptions along cell cracks

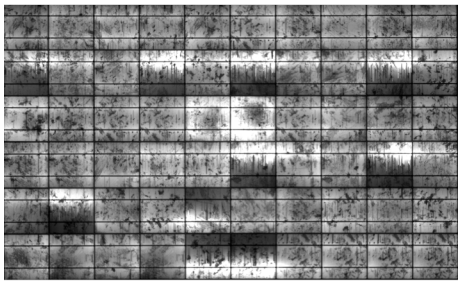


Failure: Shunt fault

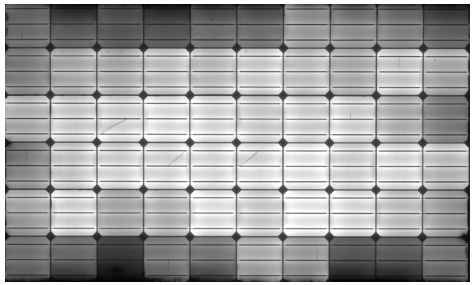


Failure: Disconnected cell interconnect

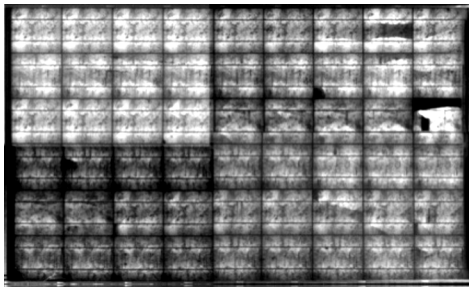
Diagnosis – Module Level



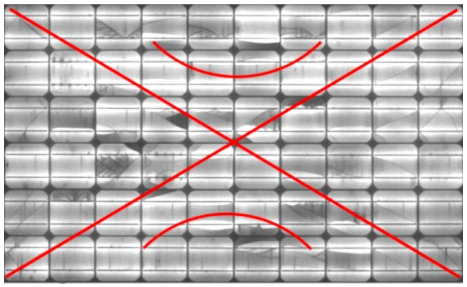
Ribbon damage



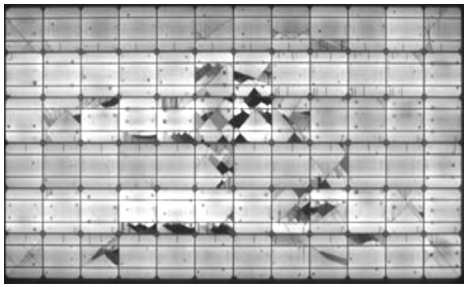
PID



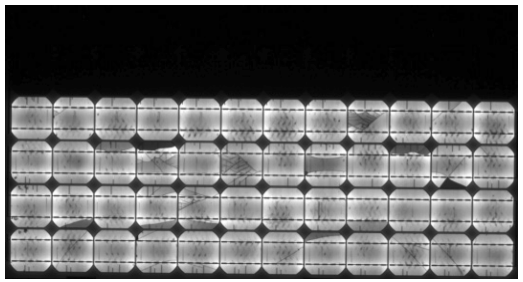
Production cracks



Homogeneous Mechanical Load Cracks



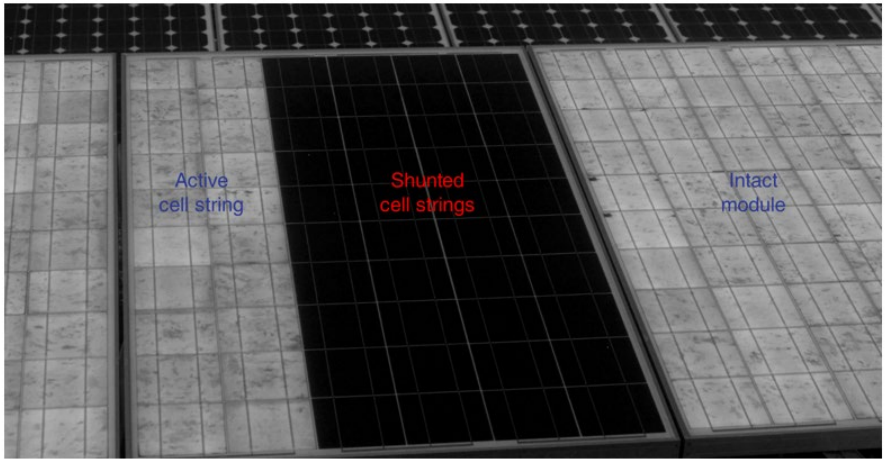
Tilt cracks



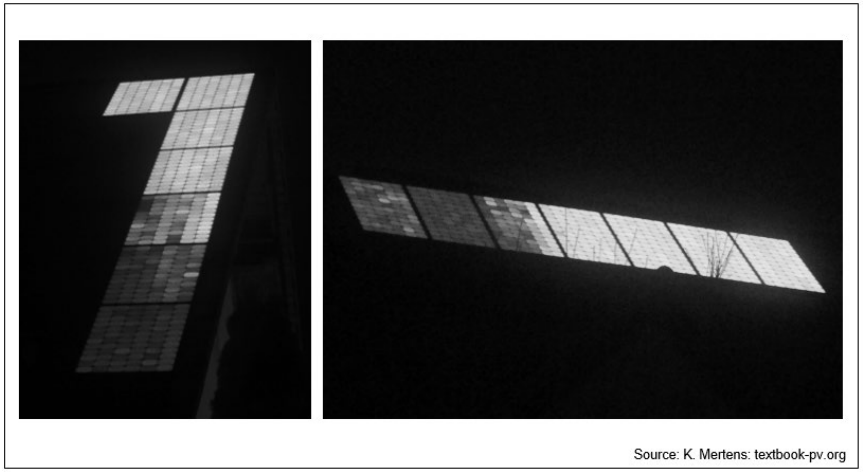
Current flow interruption (Shunted bypass diode)

Complete list at:
"IEA-PVPS - Review of Failures of Photovoltaic Modules" in Table 5.4.1, pages 42-46.

Outdoors EL – Night-time



Detection of defective bypass diodes: In the central module two cell strings remain dark as they are shunted by defective bypass diodes. Photos: M. Diehl



EL exposures of two strings affected by PID: The modules on the positive side of the strings show no anomalies, while the modules with stronger negative potential have the typical PID pattern. Photos: M. Diehl

IR and EL Thresholds

Table I: Comparison of the thresholds for IR and EL

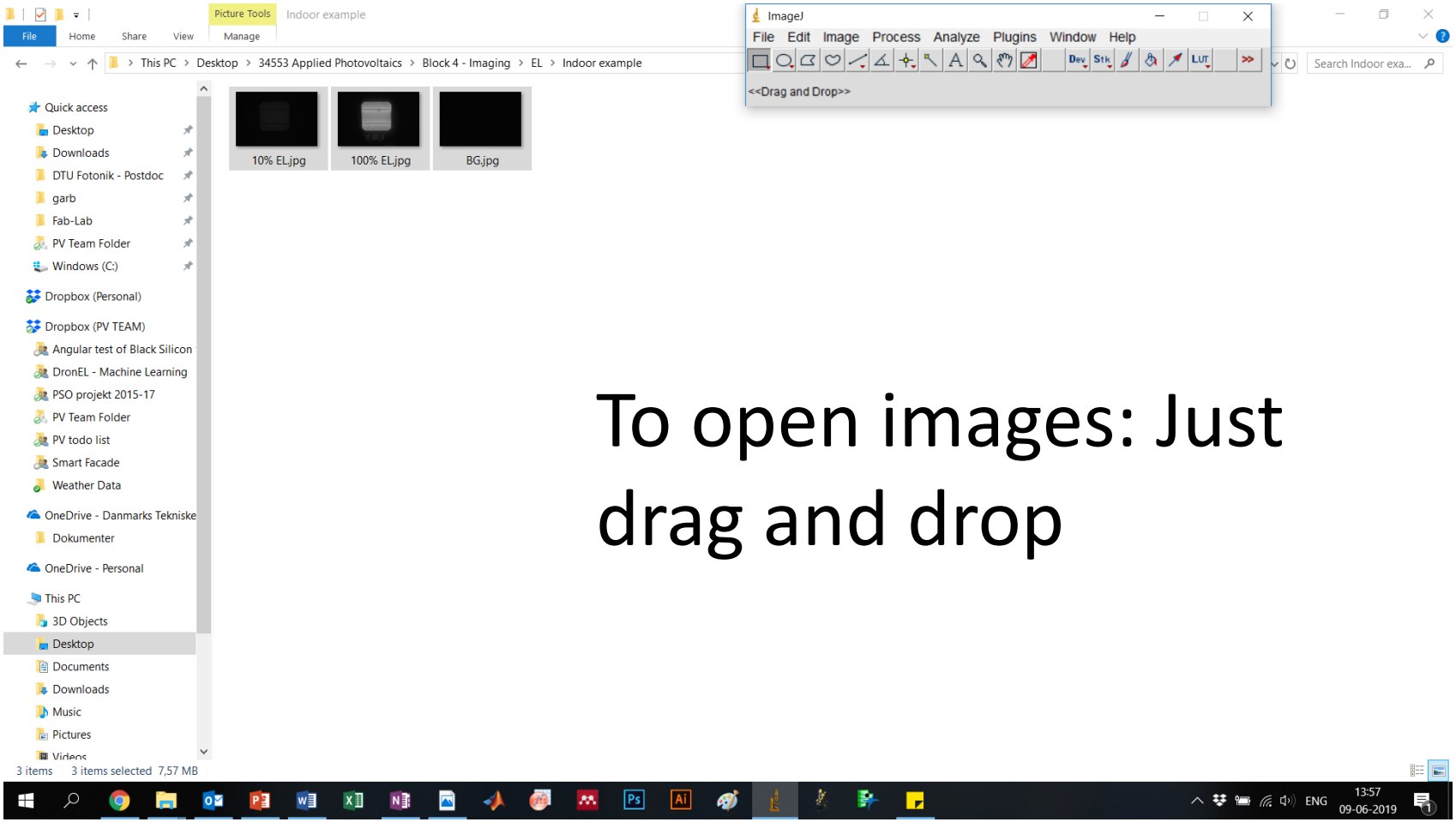
IR (IEC 6090 4-12 TS Ed.1)	**EL** (PI-Berlin experience)
Min. 600 W/m² (*influenced by the sun)*	Max 100 W/m² *(influenced by IR safety cameras and full moon)*
Max 4 Bft (*wind influences the module temperature distribution)*	Max 6 Bft
Max 2 okta (cloudiness)	-
Low soiling	Moderate soiling
No rain	No heavy rain
Angle of view not below 30° and not 90°	Angle of view not below 30°

S. Koch, T. Weber, T. Sobottka, A. Fladung, P. Clemens, and J. Berghold, in *32nd European Photovoltaic Solar Energy Conference and Exhibition*, 2016, pp. 1736–1740.

Image Processing

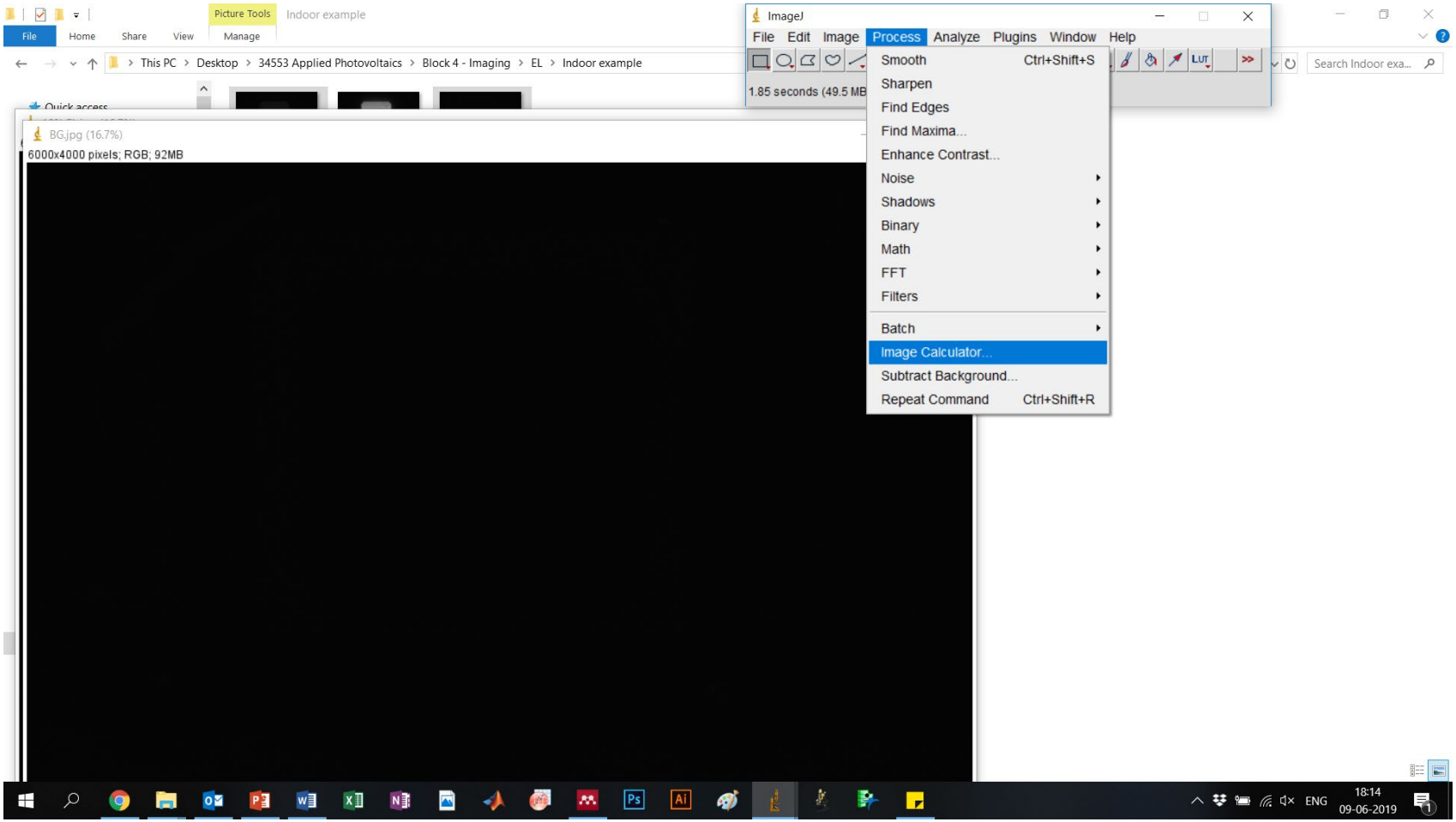
- Install ImageJ: Copy the folder from the flash drive.
- Image processing steps for Indoors EL:
  - In case of stray light or low signal
    - Subtract background
    - Convert to 8 bits
    - Enhance contrast
  - For power loss rough estimation (ELID):
    - Adjust Threshold
    - Measure area

ImageJ

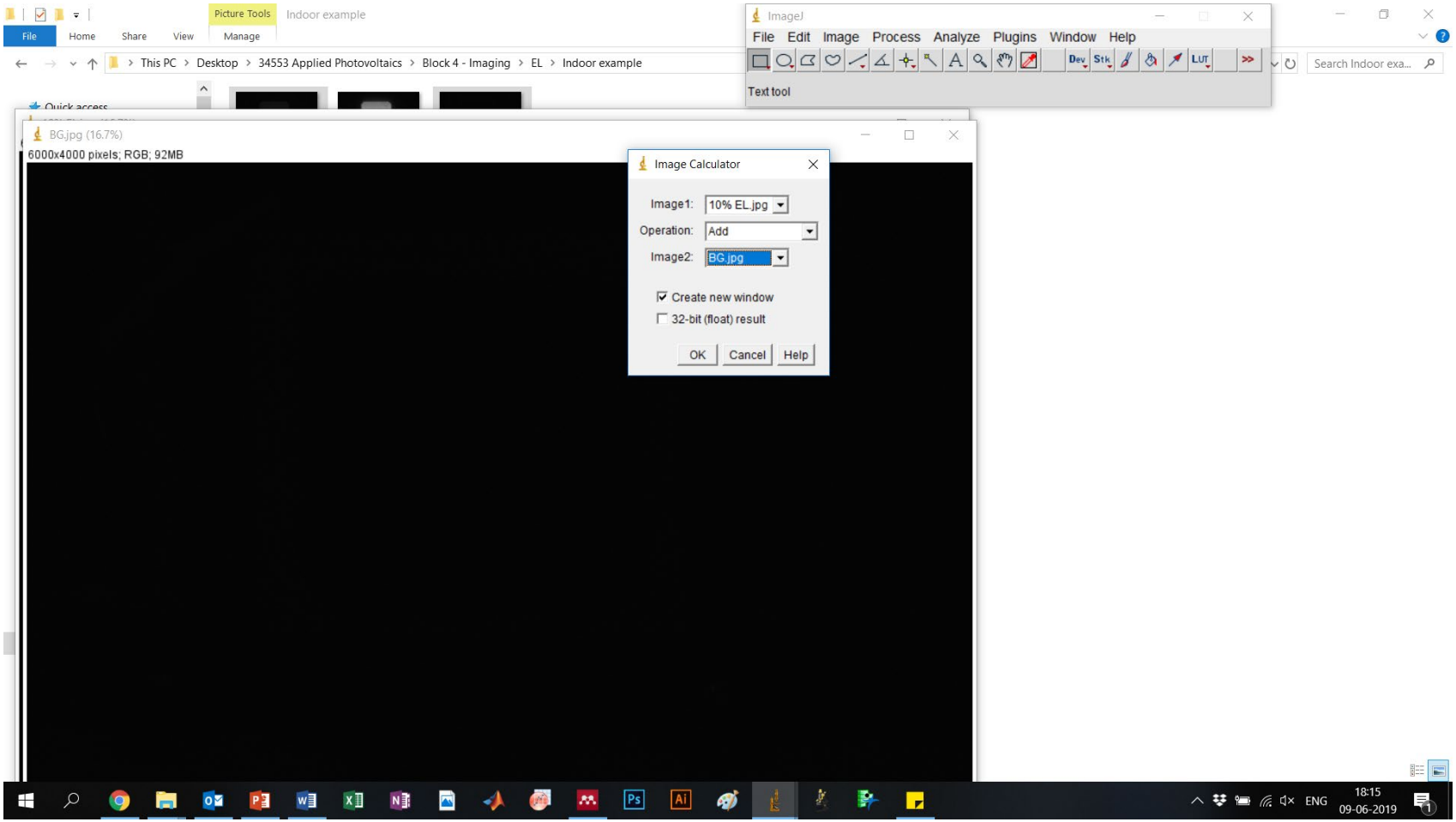


To open images: Just drag and drop

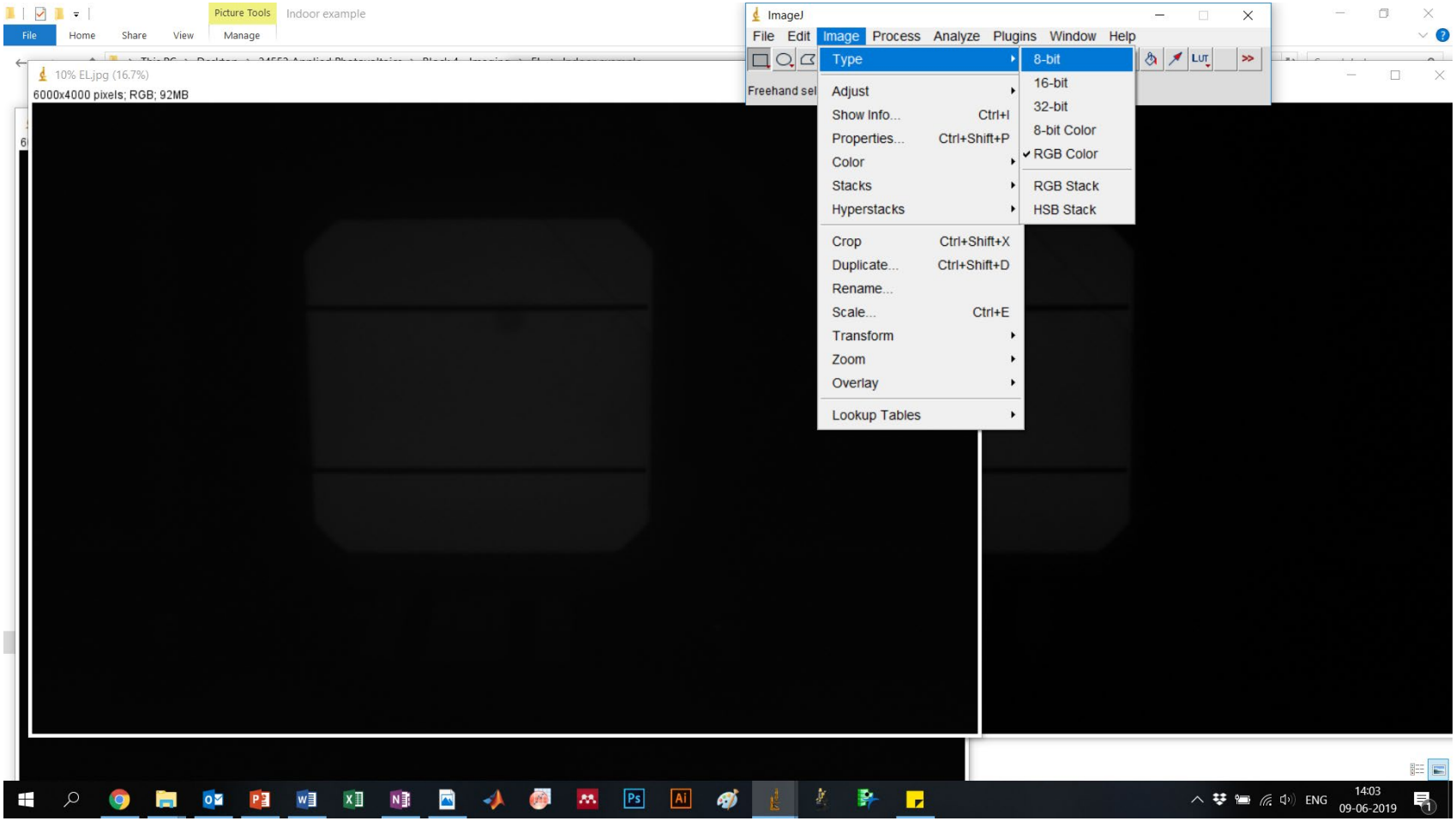
Subtract background



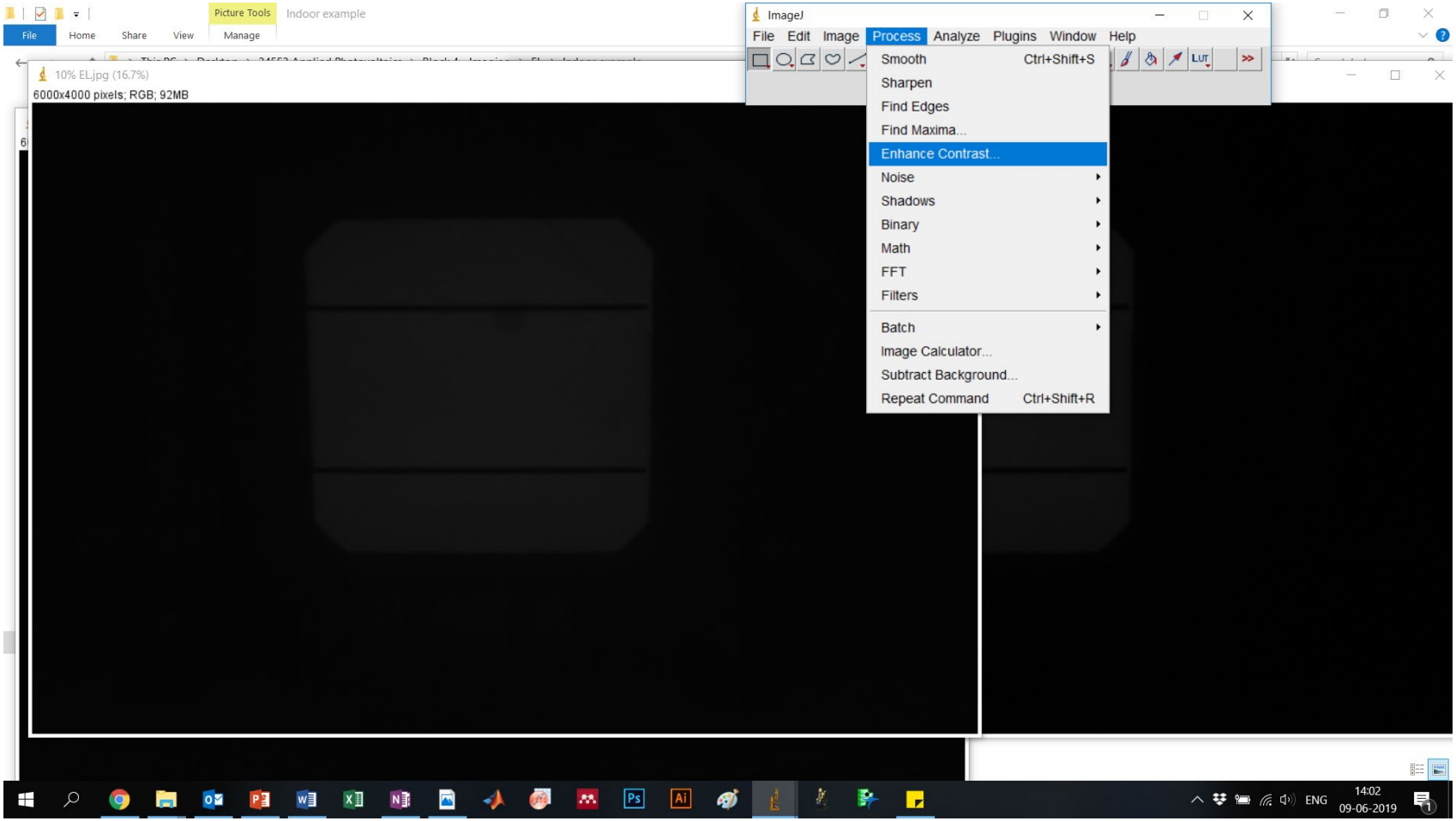
Subtract background



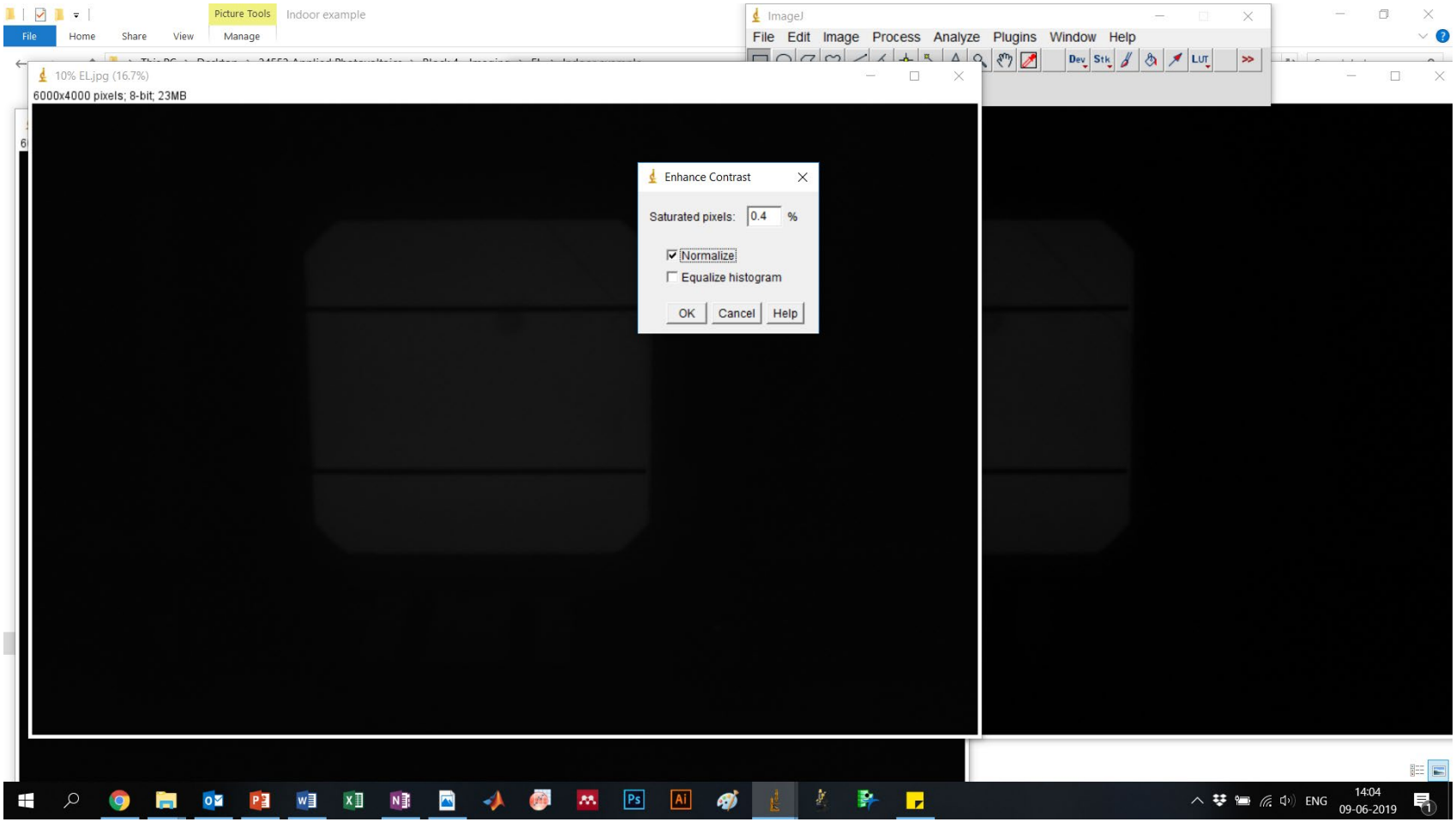
Convert to 8bits



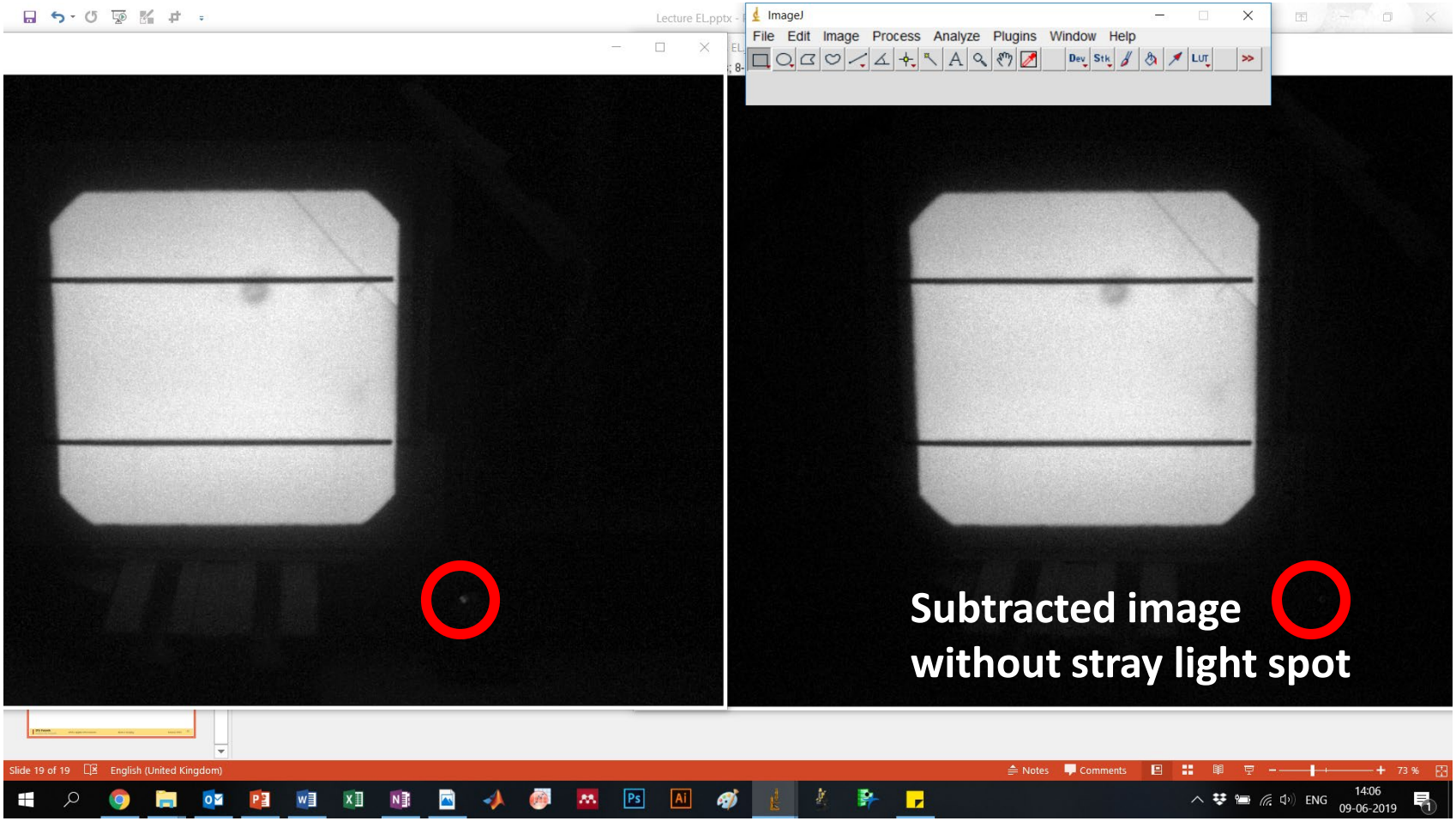
Enhance contrast



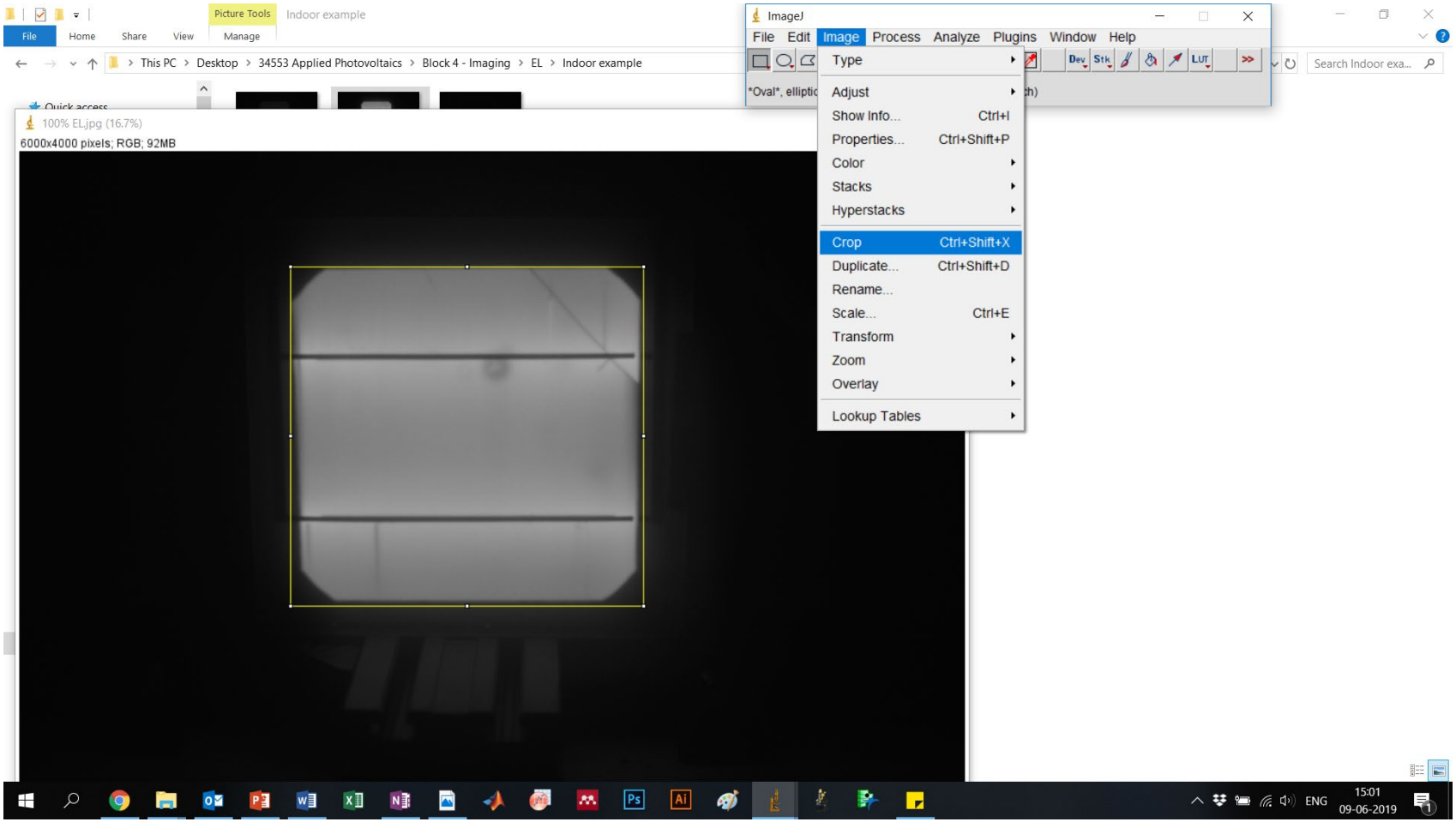
Enhance contrast



Subtracted background

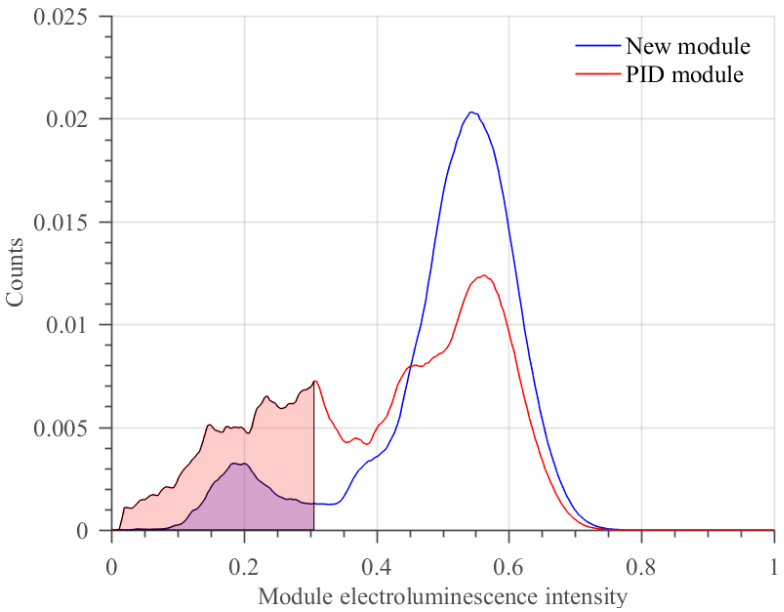


Crop

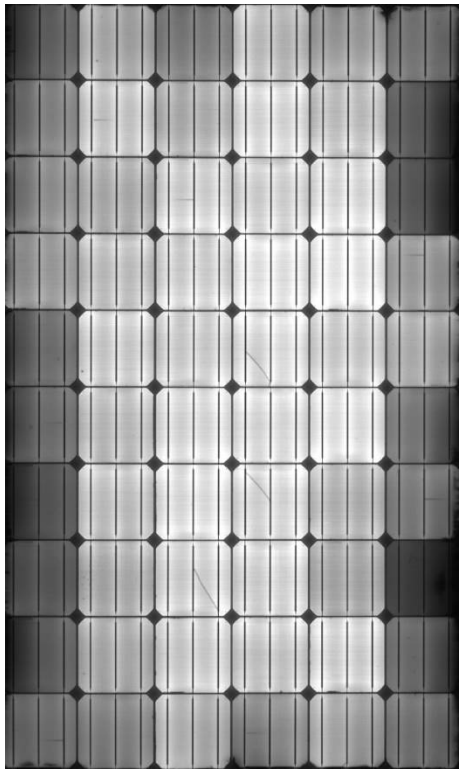

ImageJ
File Edit Image Process Analyze Plugins Window Help
Type
Adjust
Show Info... Ctrl+I
Properties... Ctrl+Shift+P
Color
Stacks
Hyperstacks
Crop Ctrl+Shift+X
Duplicate... Ctrl+Shift+D
Rename...
Scale... Ctrl+E
Transform
Zoom
Overlay
Lookup Tables
100% EL.jpg (16.7%)
6000x4000 pixels; RGB; 92MB
This PC > Desktop > 34553 Applied Photovoltaics > Block 4 - Imaging > EL > Indoor example
Picture Tools
Indoor example
File Home Share View Manage
ENG
15:01
09-06-2019

Power loss Rough Estimation
EL Intensity Distribution (ELID):

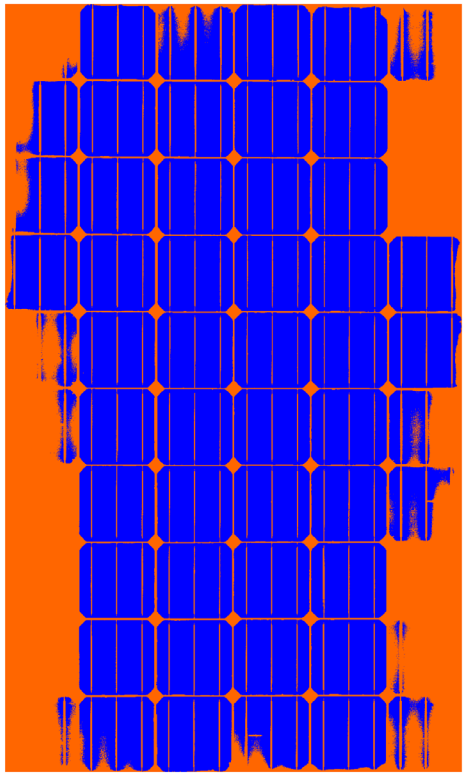
Histogram signature
PID Module



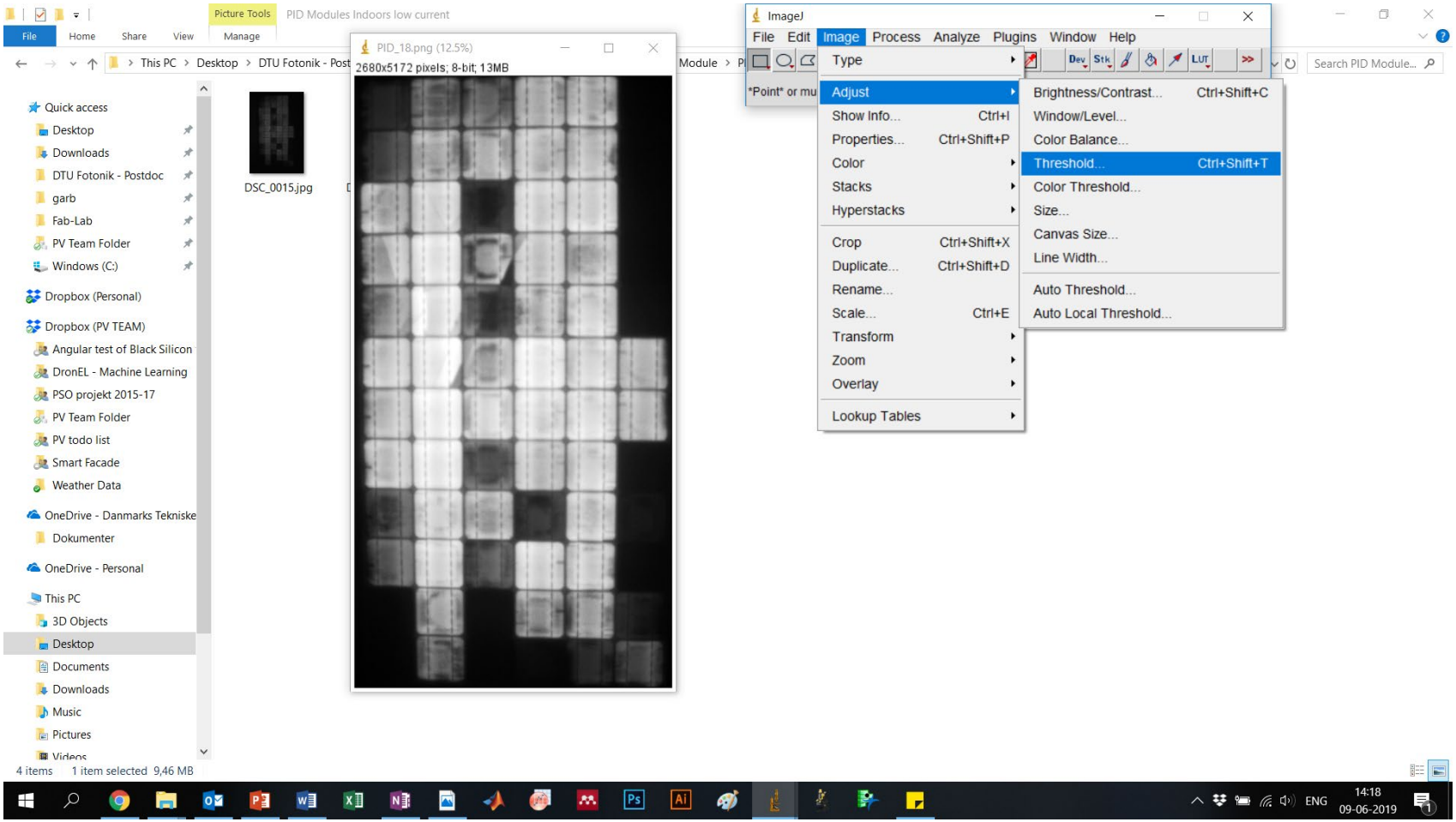
PID module



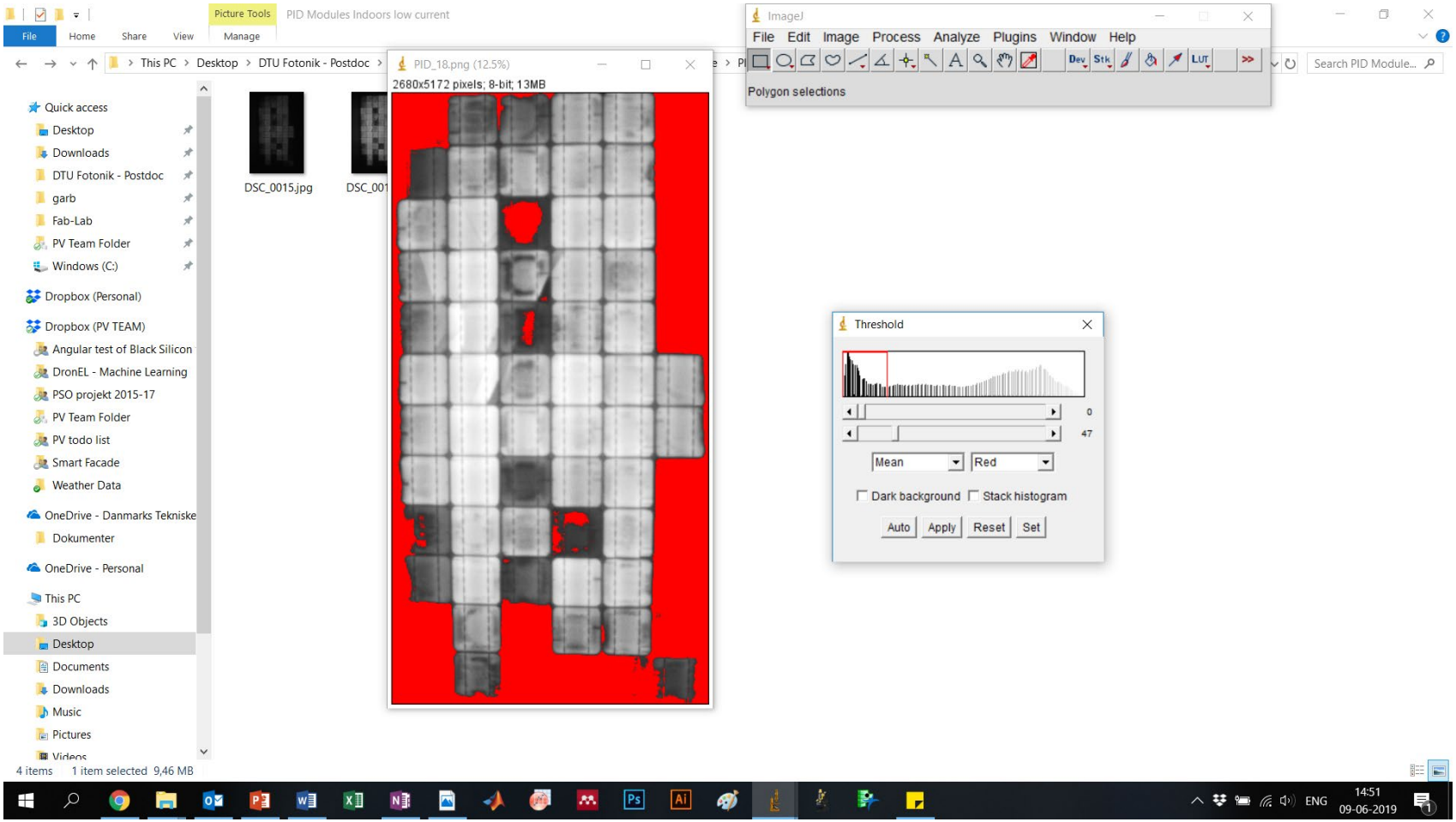
LID analysis



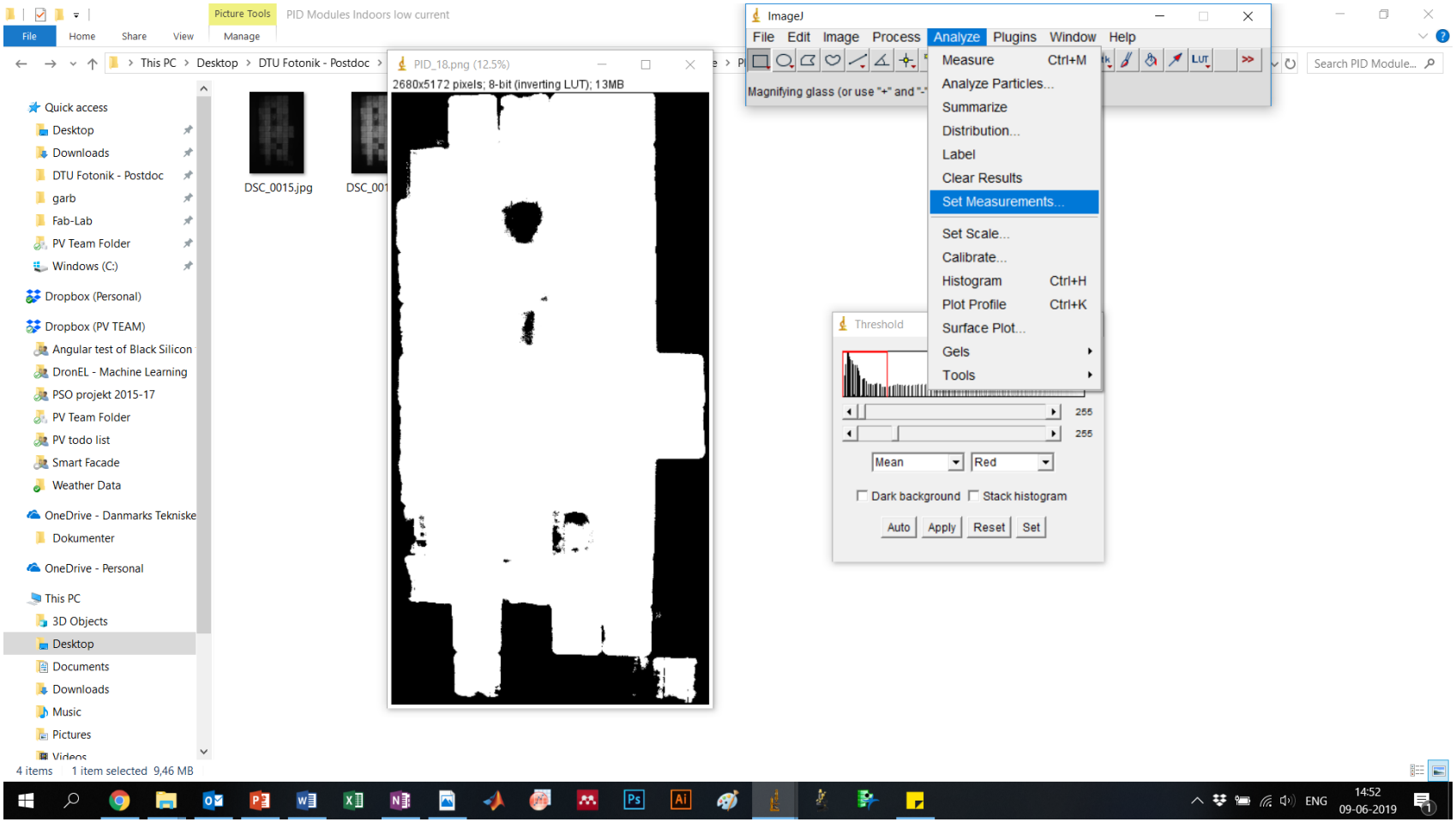
Adjust Threshold



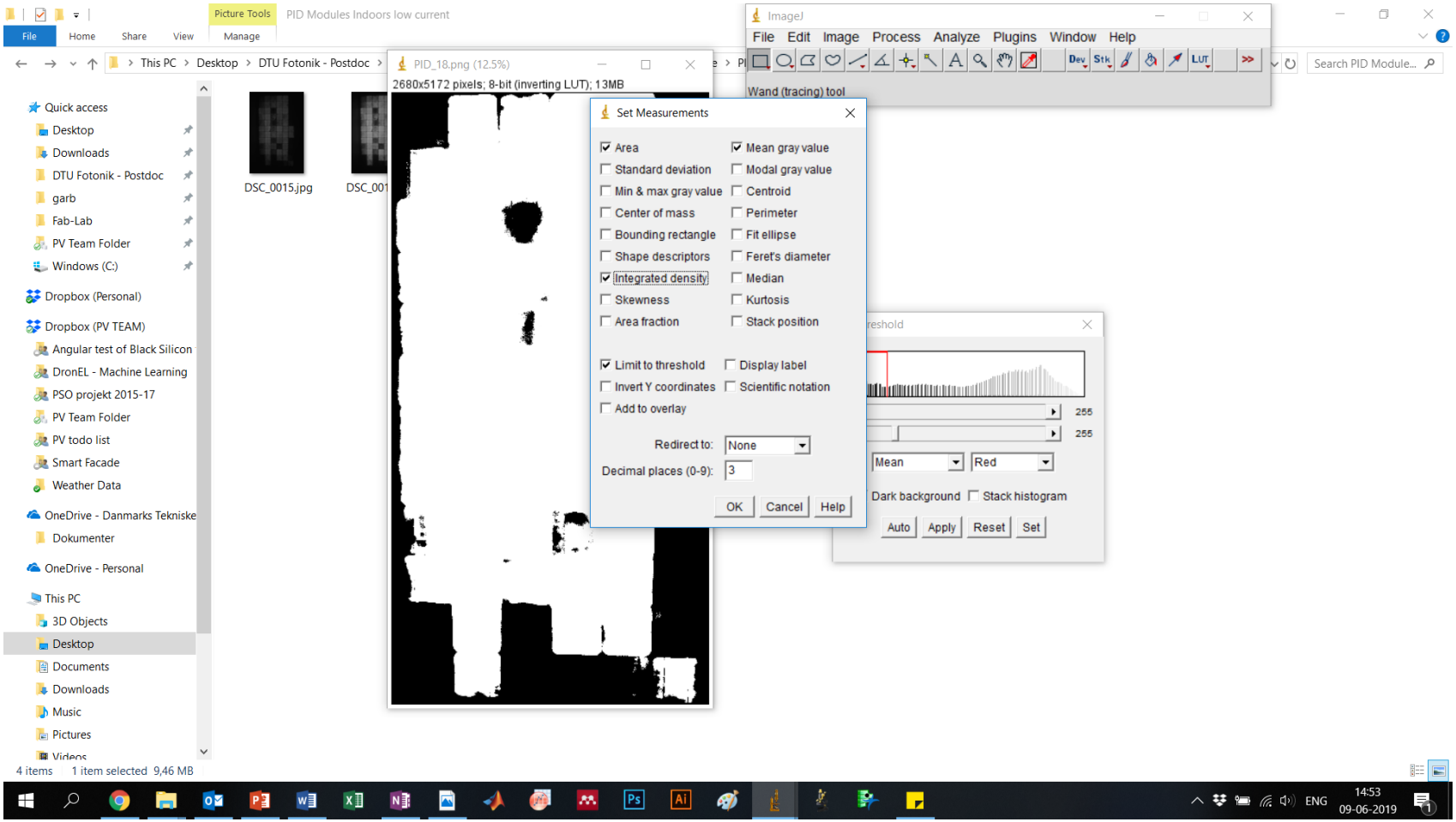
Adjust Threshold



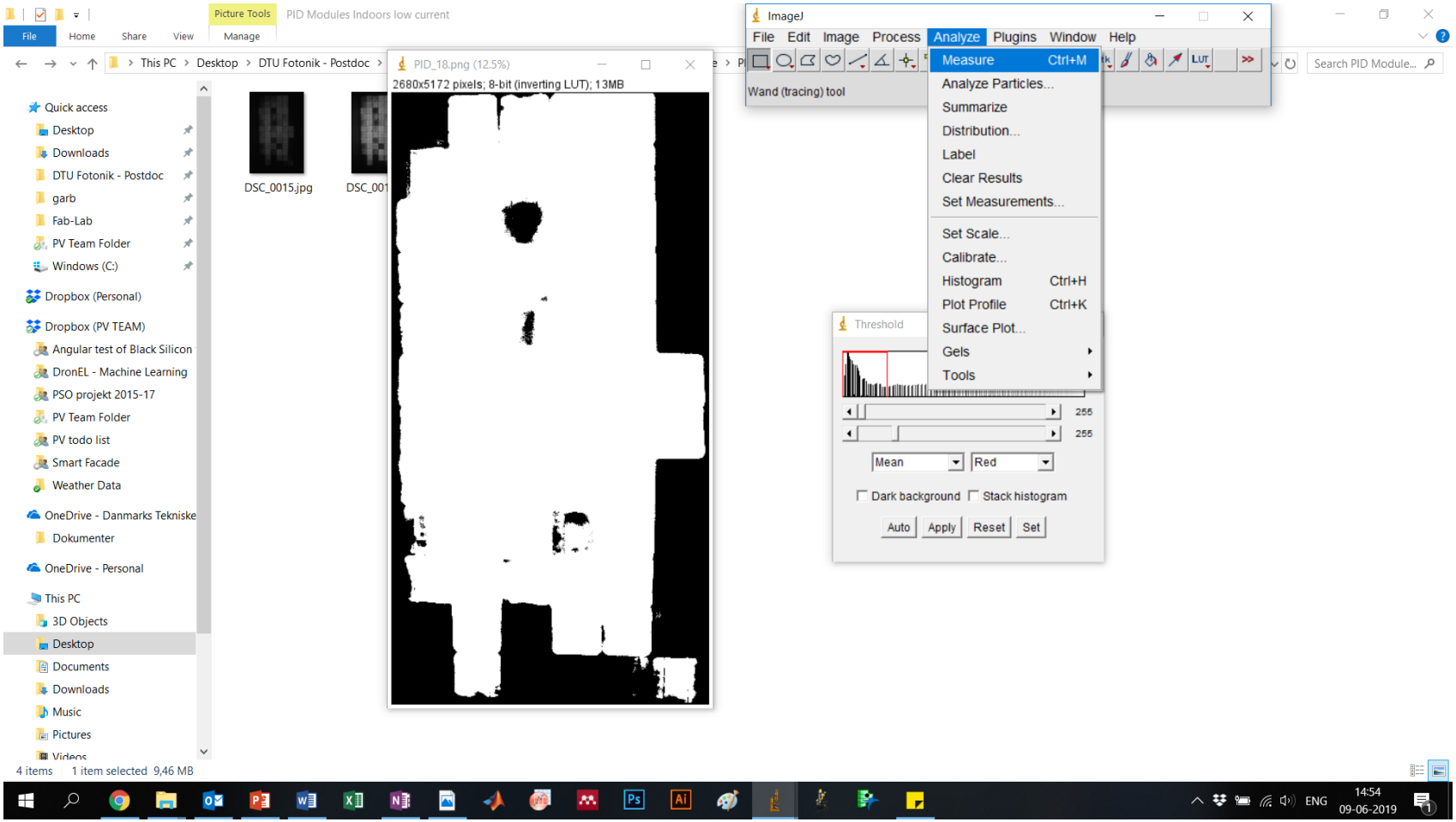
Set Measurements



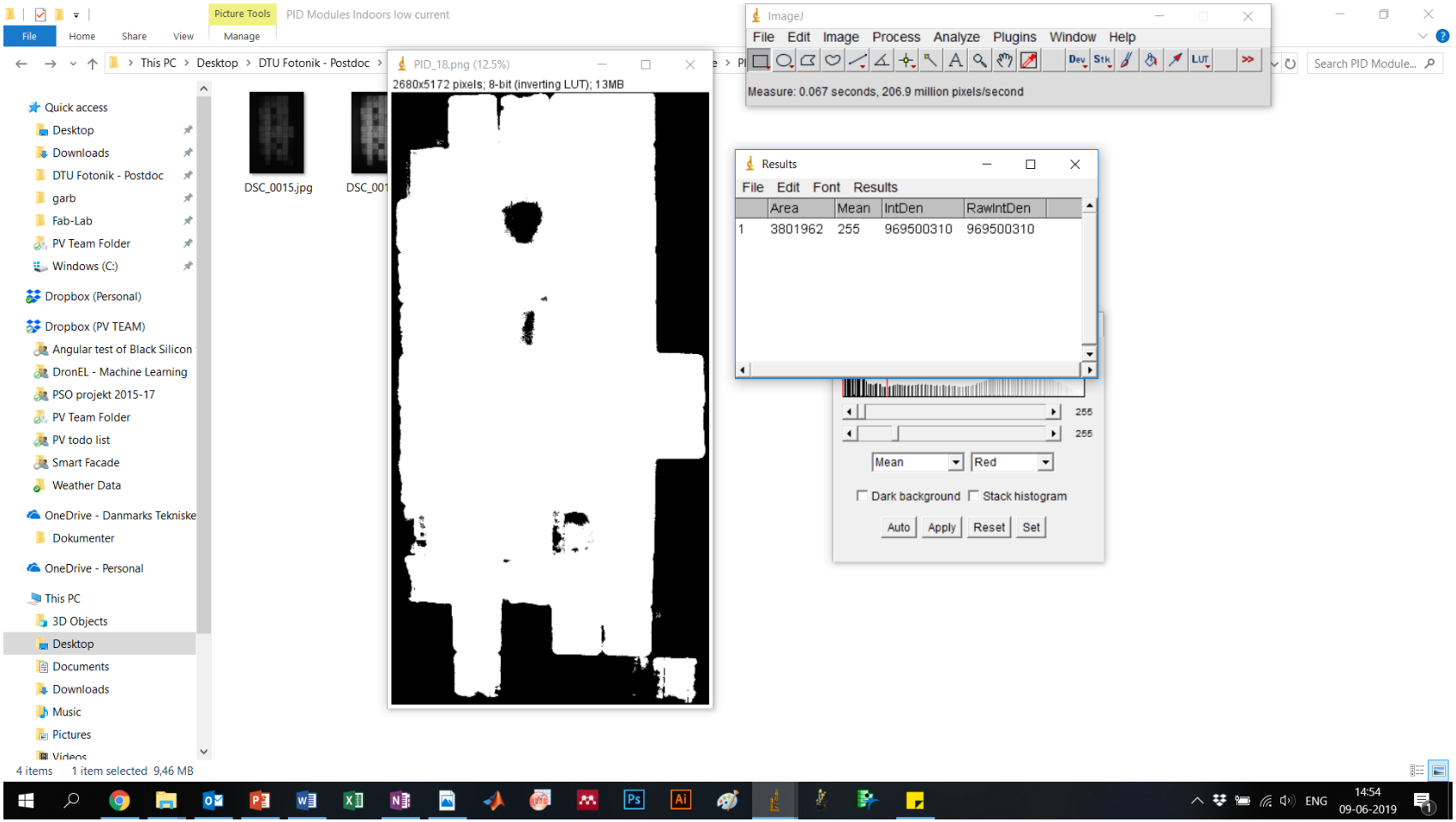
Set Measurements: Area



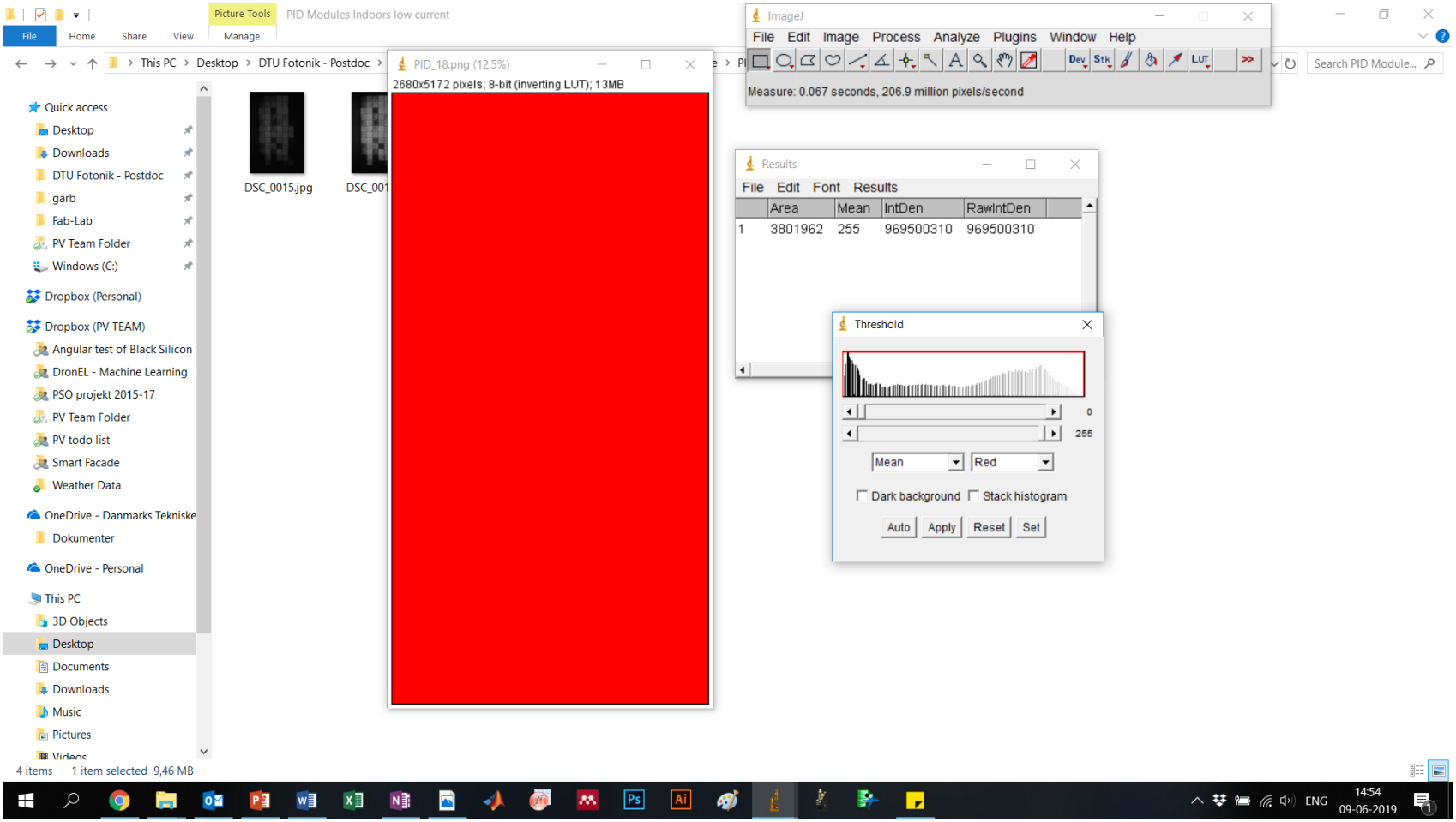
Measure


Picture Tools
PID Modules Indoors low current
File
Home
Share
View
Manage
This PC > Desktop > DTU Fotonik - Postdoc
Search PID Module...
Quick access
Desktop
Downloads
DTU Fotonik - Postdoc
garb
Fab-Lab
PV Team Folder
Windows (C:)
Dropbox (Personal)
Dropbox (PV TEAM)
Angular test of Black Silicon
DronEL - Machine Learning
PSO projekt 2015-17
PV Team Folder
PV todo list
Smart Facade
Weather Data
OneDrive - Danmarks Tekniske
Dokumenter
OneDrive - Personal
This PC
3D Objects
Desktop
Documents
Downloads
Music
Pictures
Videos
DSC_0015.jpg
4 items
1 item selected 9,46 MB
PID_18.png (12.5%)
2680x5172 pixels; 8-bit (inverting LUT); 13MB
ImageJ
File Edit Image Process Analyze Plugins Window Help
Wand (tracing) tool
Measure Ctrl+M
Analyze Particles...
Summarize
Distribution...
Label
Clear Results
Set Measurements...
Set Scale...
Calibrate...
Histogram Ctrl+H
Plot Profile Ctrl+K
Surface Plot...
Gels
Tools
Threshold
255
255
Mean
Red
Dark background
Stack histogram
Auto
Apply
Reset
Set
ENG
14:54
09-06-2019

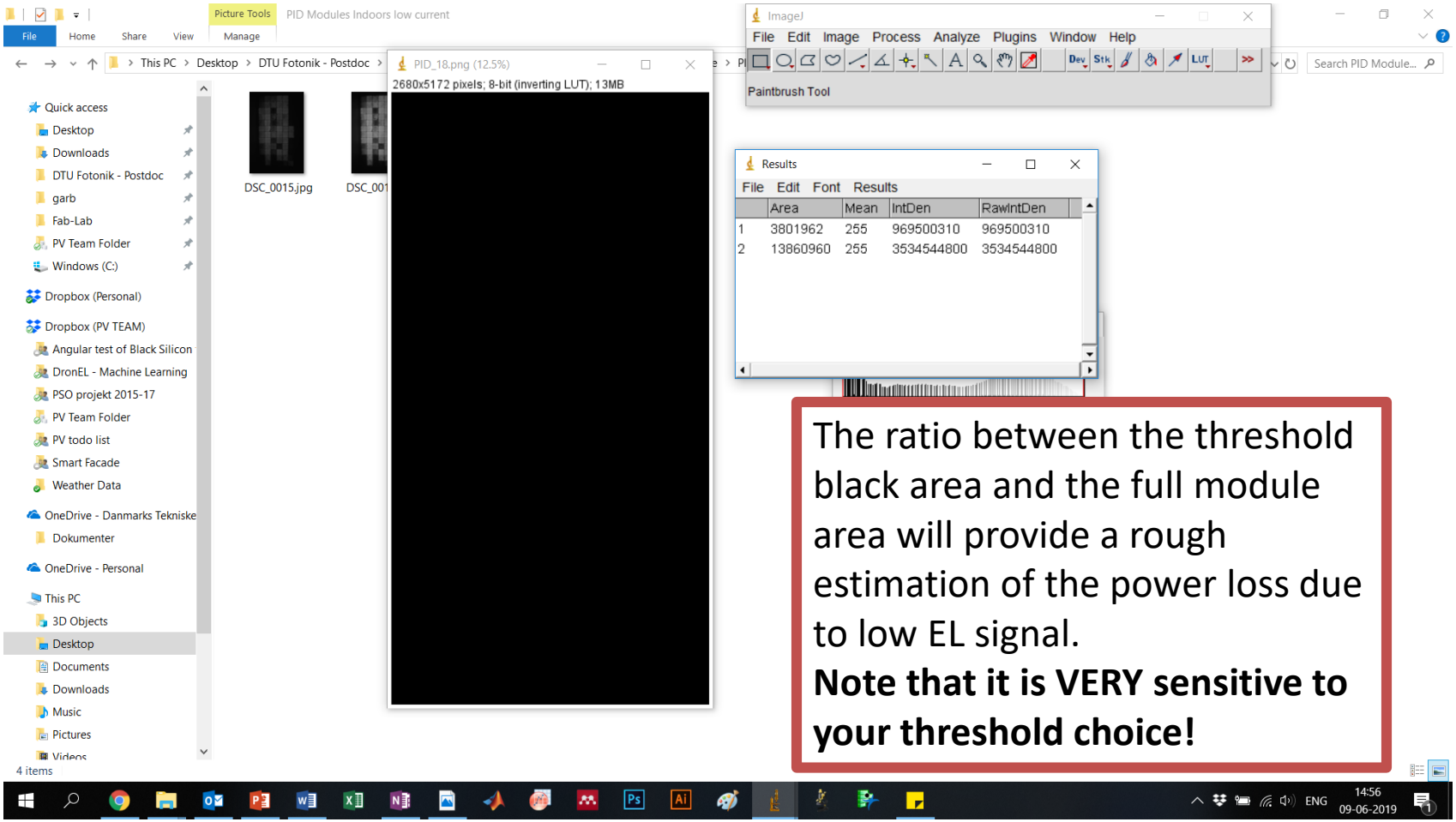
Measure


Picture Tools
PID Modules Indoors low current
File
Home
Share
View
Manage
This PC
Desktop
DTU Fotonik - Postdoc
Search PID Module...
Quick access
Desktop
Downloads
DTU Fotonik - Postdoc
garb
Fab-Lab
PV Team Folder
Windows (C:)
Dropbox (Personal)
Dropbox (PV TEAM)
Angular test of Black Silicon
DronEL - Machine Learning
PSO projekt 2015-17
PV Team Folder
PV todo list
Smart Facade
Weather Data
OneDrive - Danmarks Tekniske
Dokumenter
OneDrive - Personal
This PC
3D Objects
Desktop
Documents
Downloads
Music
Pictures
Videos
DSC_0015.jpg
4 items
1 item selected 9,46 MB
PID_18.png (12.5%)
2680x5172 pixels; 8-bit (inverting LUT); 13MB
ImageJ
File Edit Image Process Analyze Plugins Window Help
Measure: 0.067 seconds, 206.9 million pixels/second
Results
File Edit Font Results
Area Mean IntDen RawIntDen
1 3801962 255 969500310 969500310
255
255
Mean
Red
Dark background
Stack histogram
Auto
Apply
Reset
Set
ENG
14:54
09-06-2019

Threshold = Full module area



Measure again



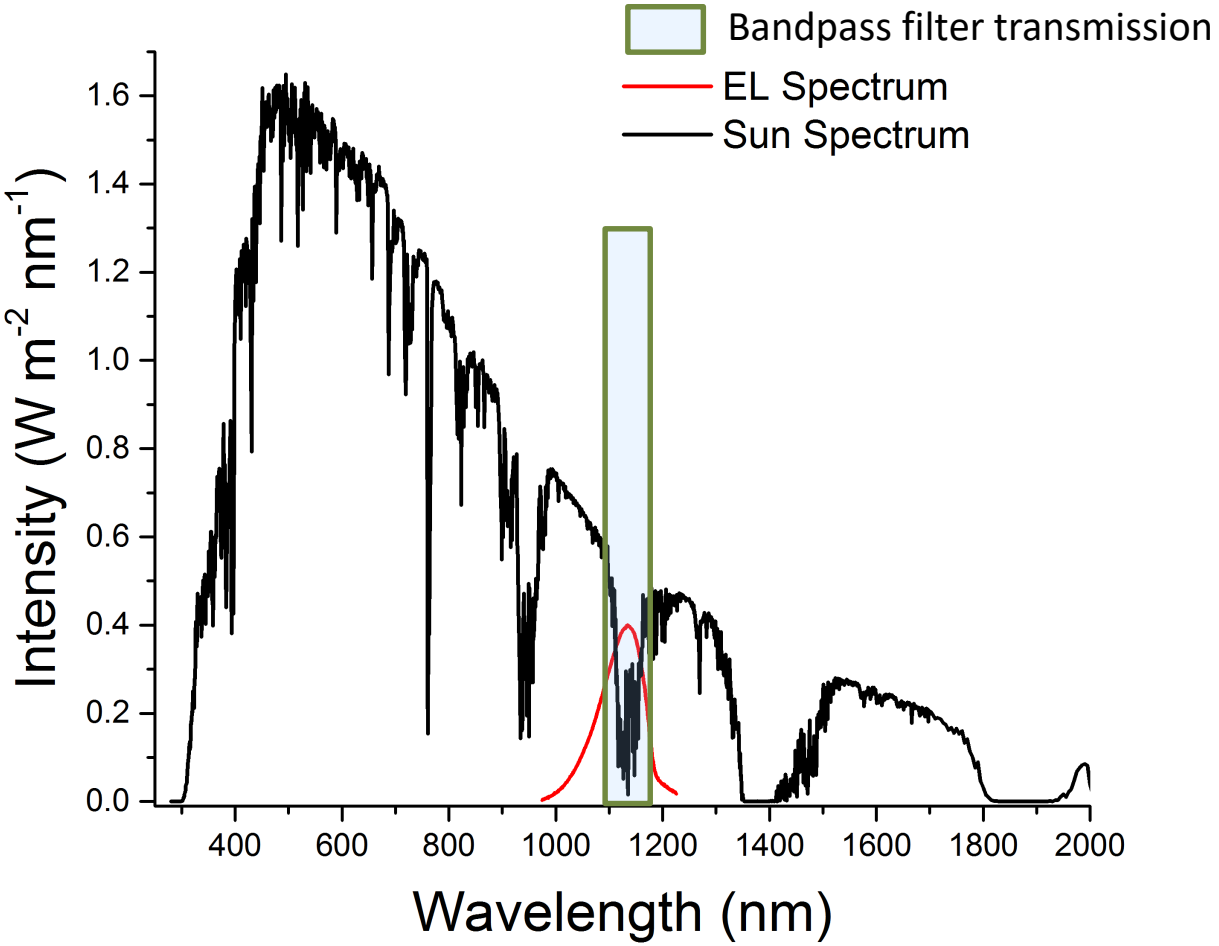
The ratio between the threshold black area and the full module area will provide a rough estimation of the power loss due to low EL signal.

Note that it is VERY sensitive to your threshold choice!

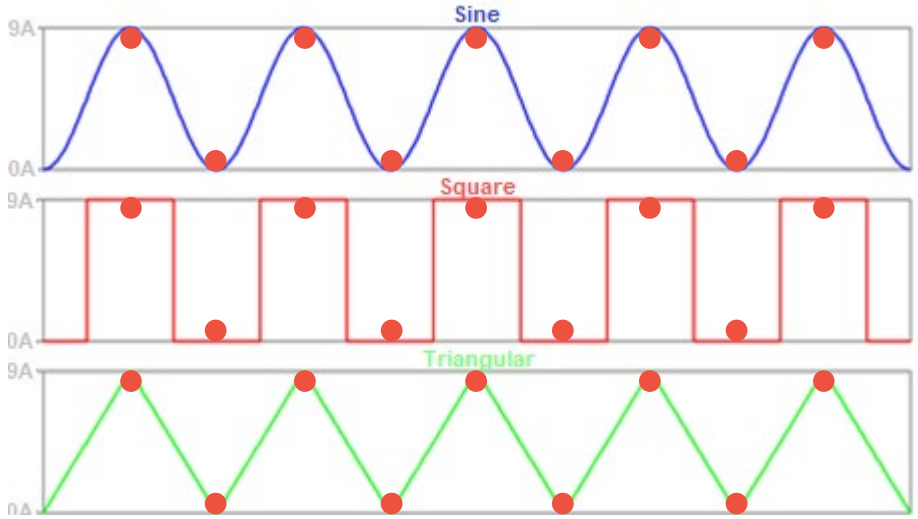
Daylight EL

Classroom Exercise

Daylight EL

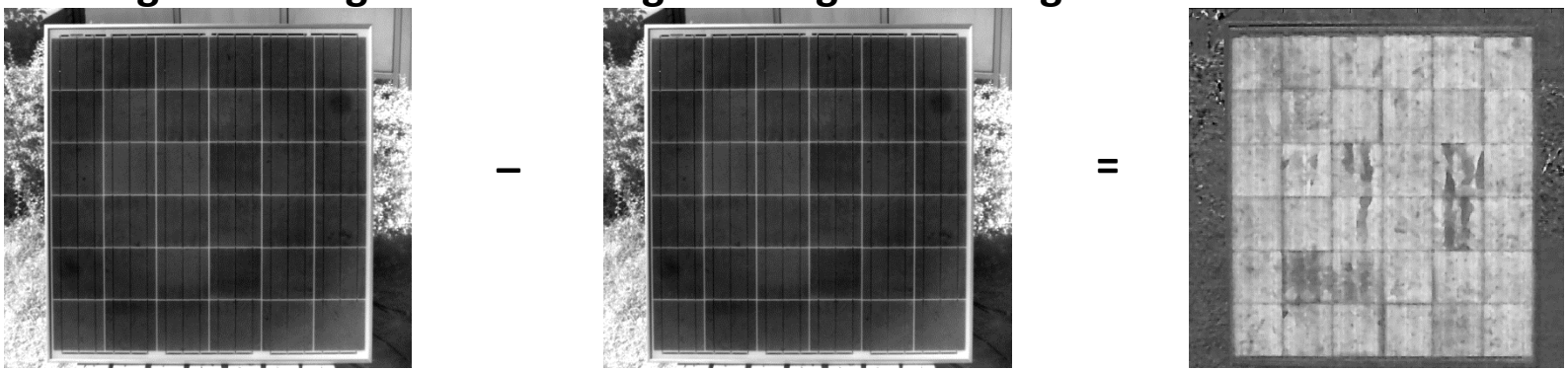

Bandpass filter transmission
EL Spectrum
Sun Spectrum
Intensity (W m-2 nm-1)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
400
600
800
1000
1200
1400
1600
1800
2000
Wavelength (nm)

Daylight EL



- Several EL and BG images have to be averaged to increase the signal-to-noise ratio.
- The images can also be taken in sequence instead of modulation signal, but the irradiation must be stable.

Averaged EL image **Averaged Background image**



Daylight EL

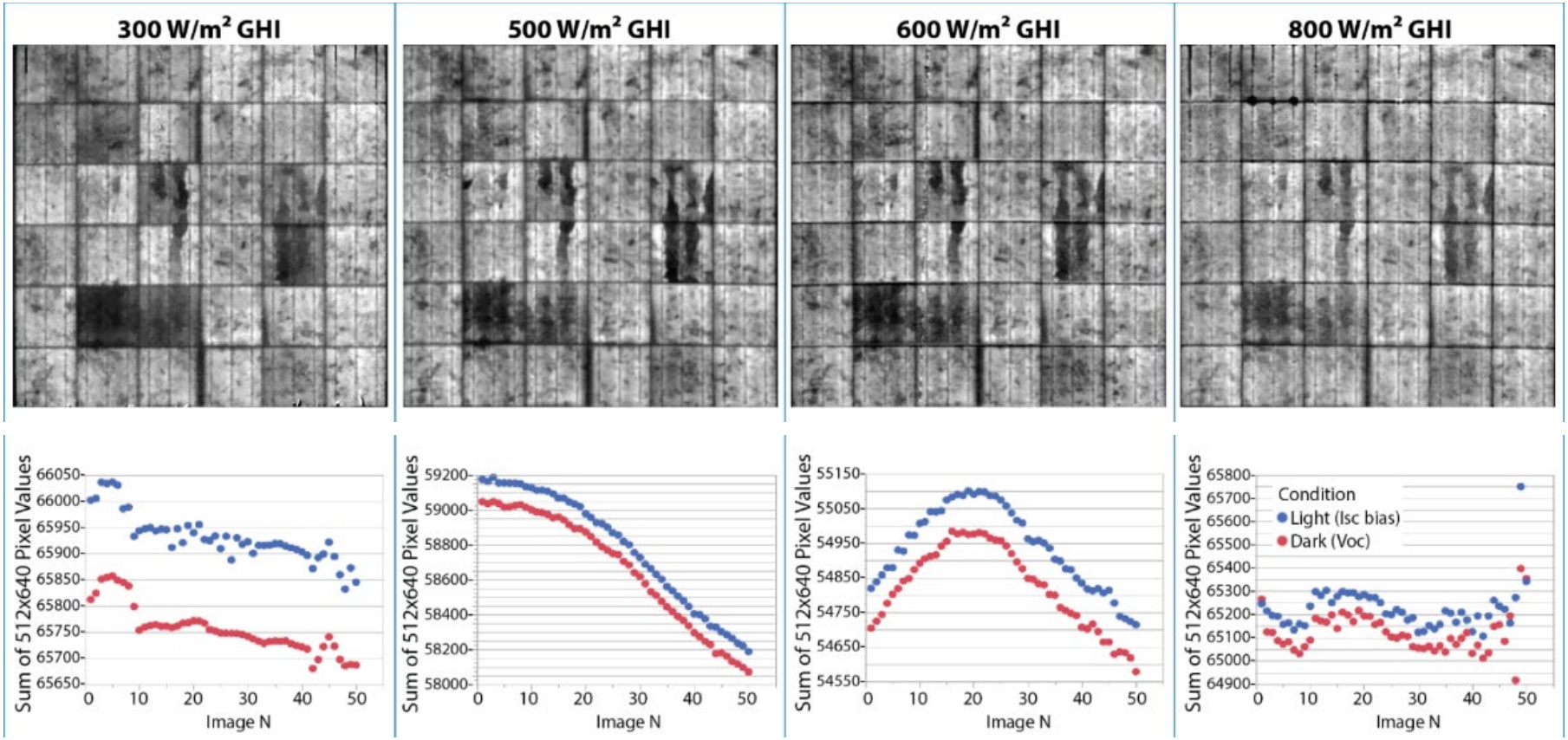
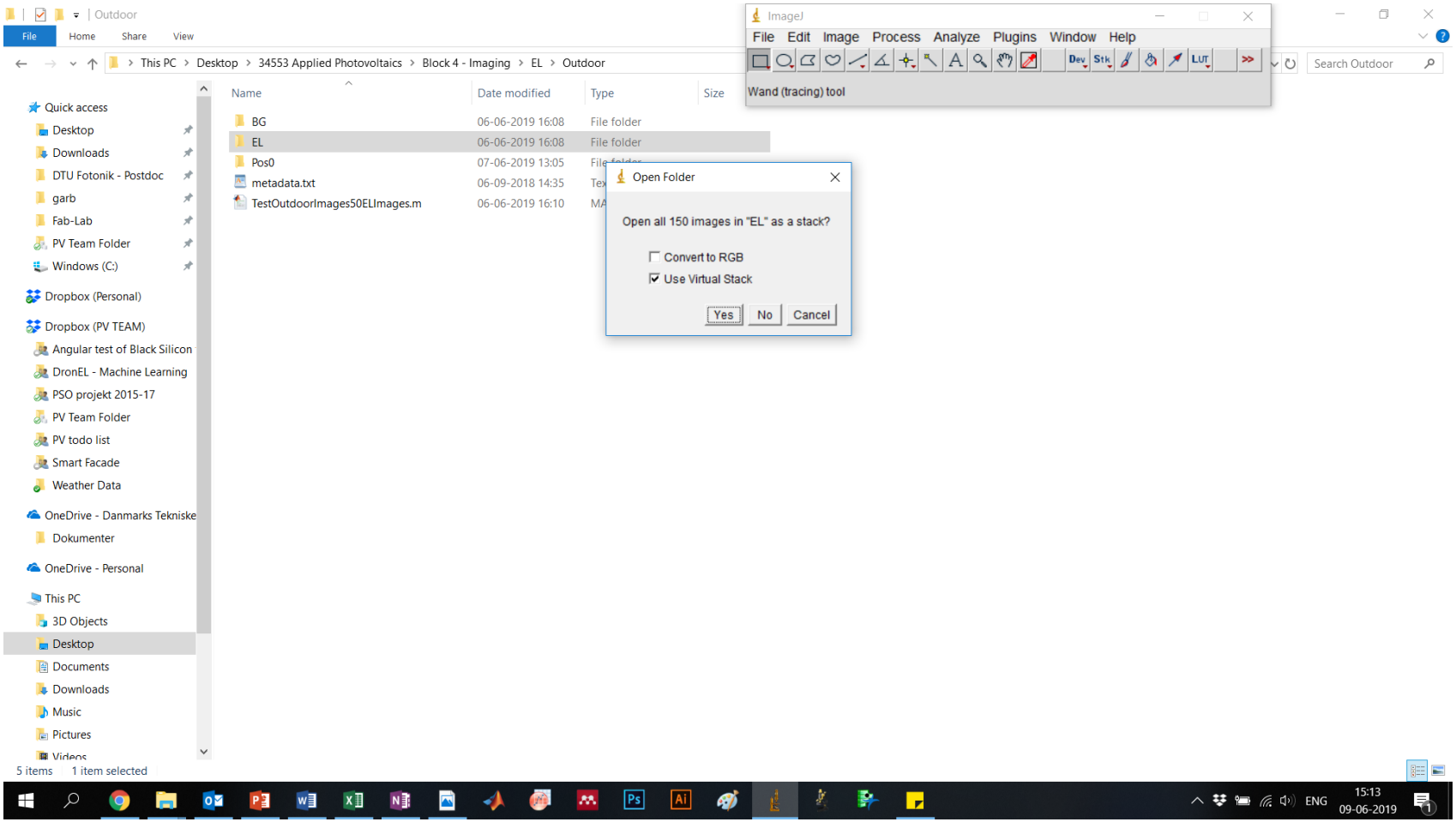

300 W/m² GHI
500 W/m² GHI
600 W/m² GHI
800 W/m² GHI
Sum of 512x640 Pixel Values
Image N
Condition
Light (Isc bias)
Dark (Voc)

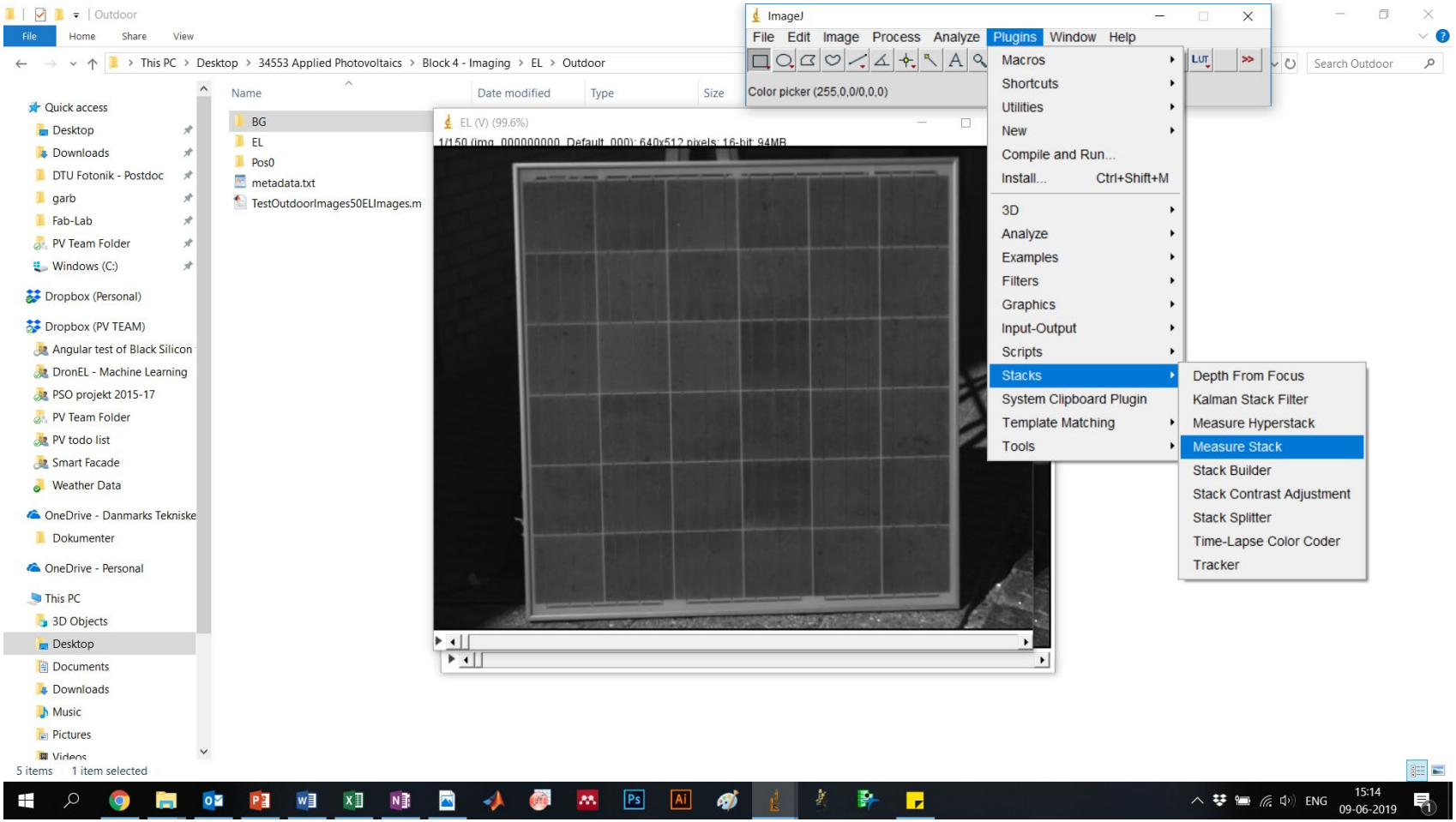
Image Processing

- Outdoors EL
  - Import the image sequences into ImageJ
  - Verify mean pixel numbers of the image sequence (stack)
  - Take an average image of the EL image sequence
  - Take an average image of the BG image sequence
  - Subtract the resulting averaged images

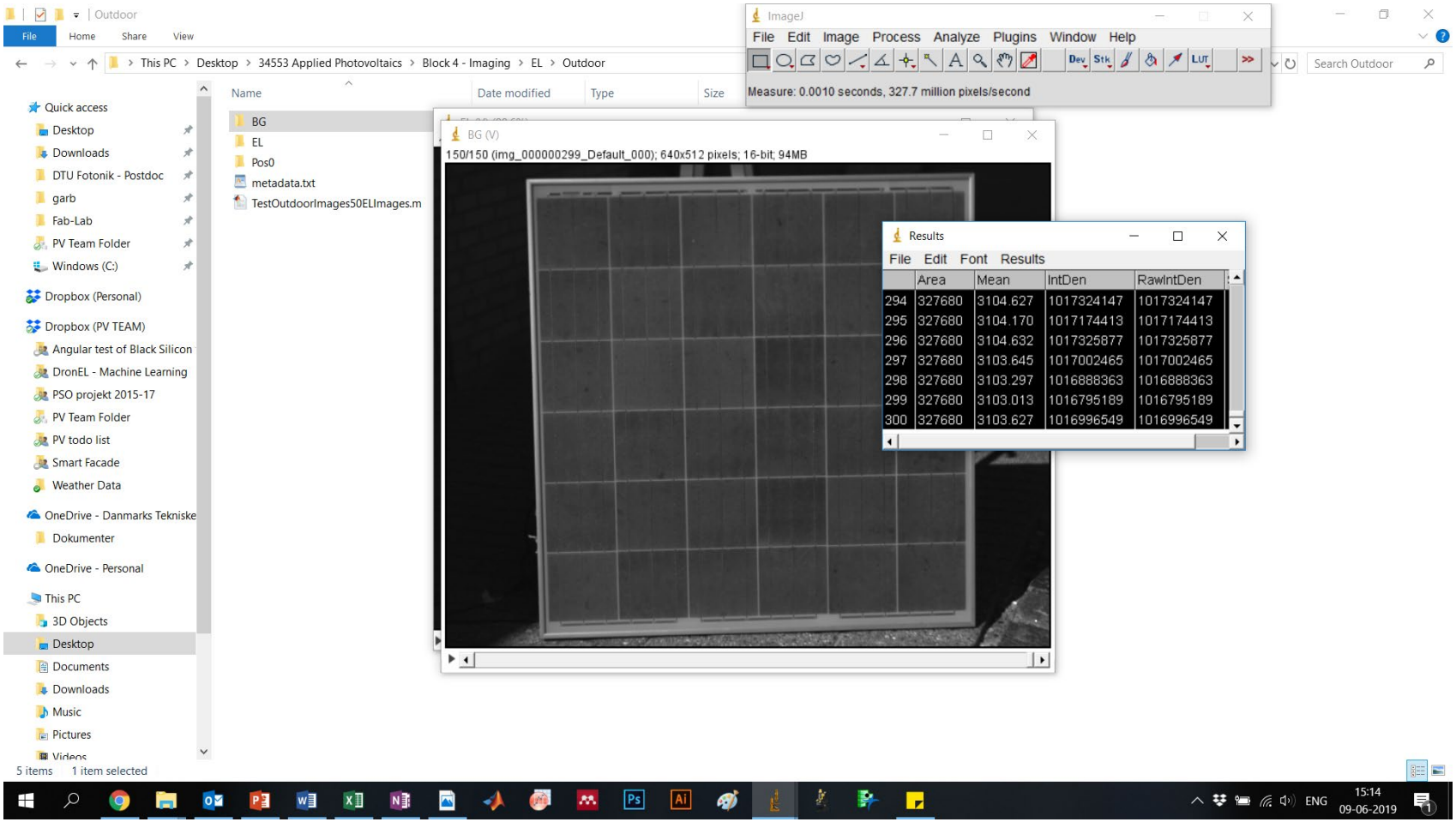
Drag and drop the full sequence folders



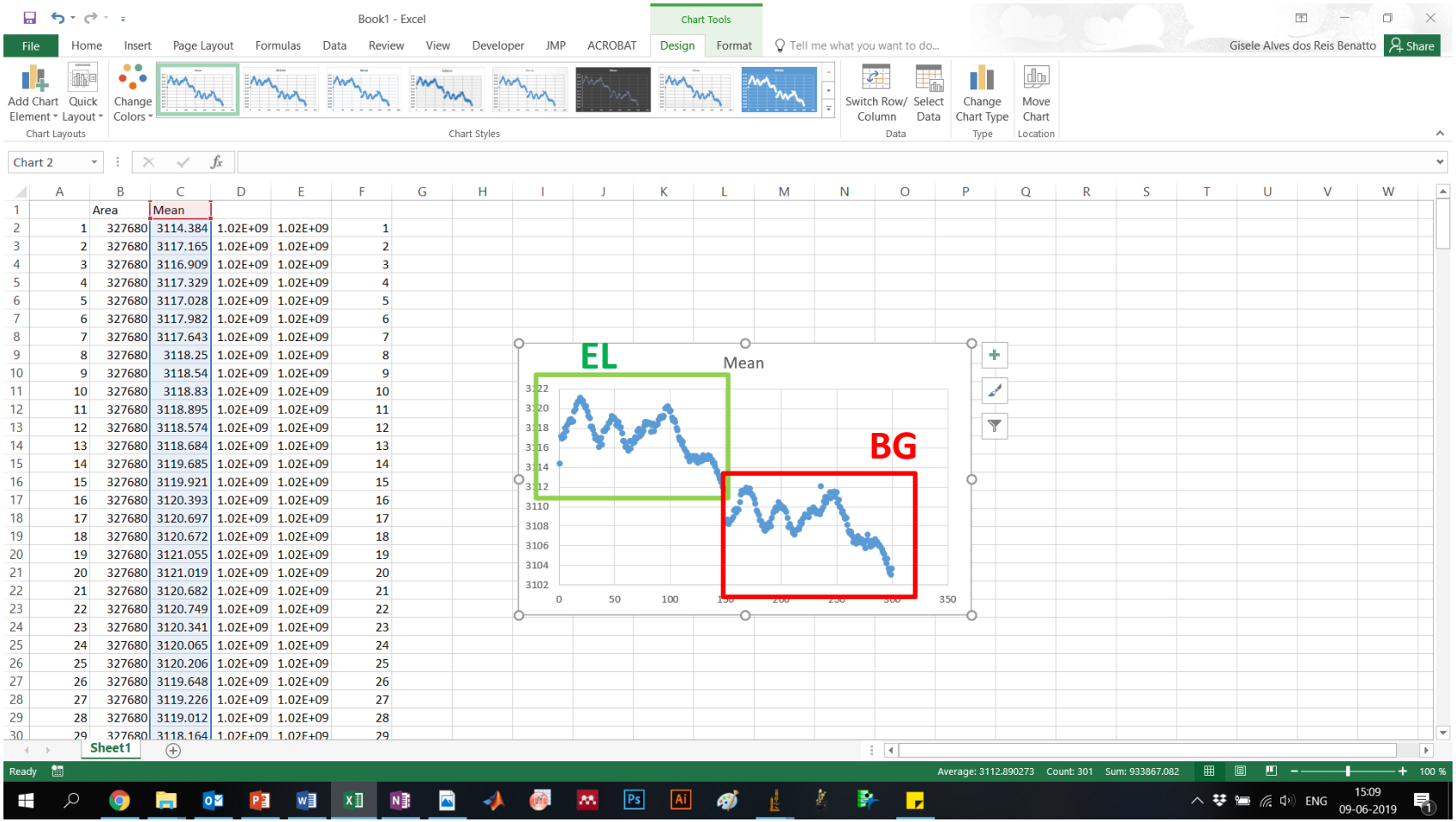
Measure both Stacks: EL and BG



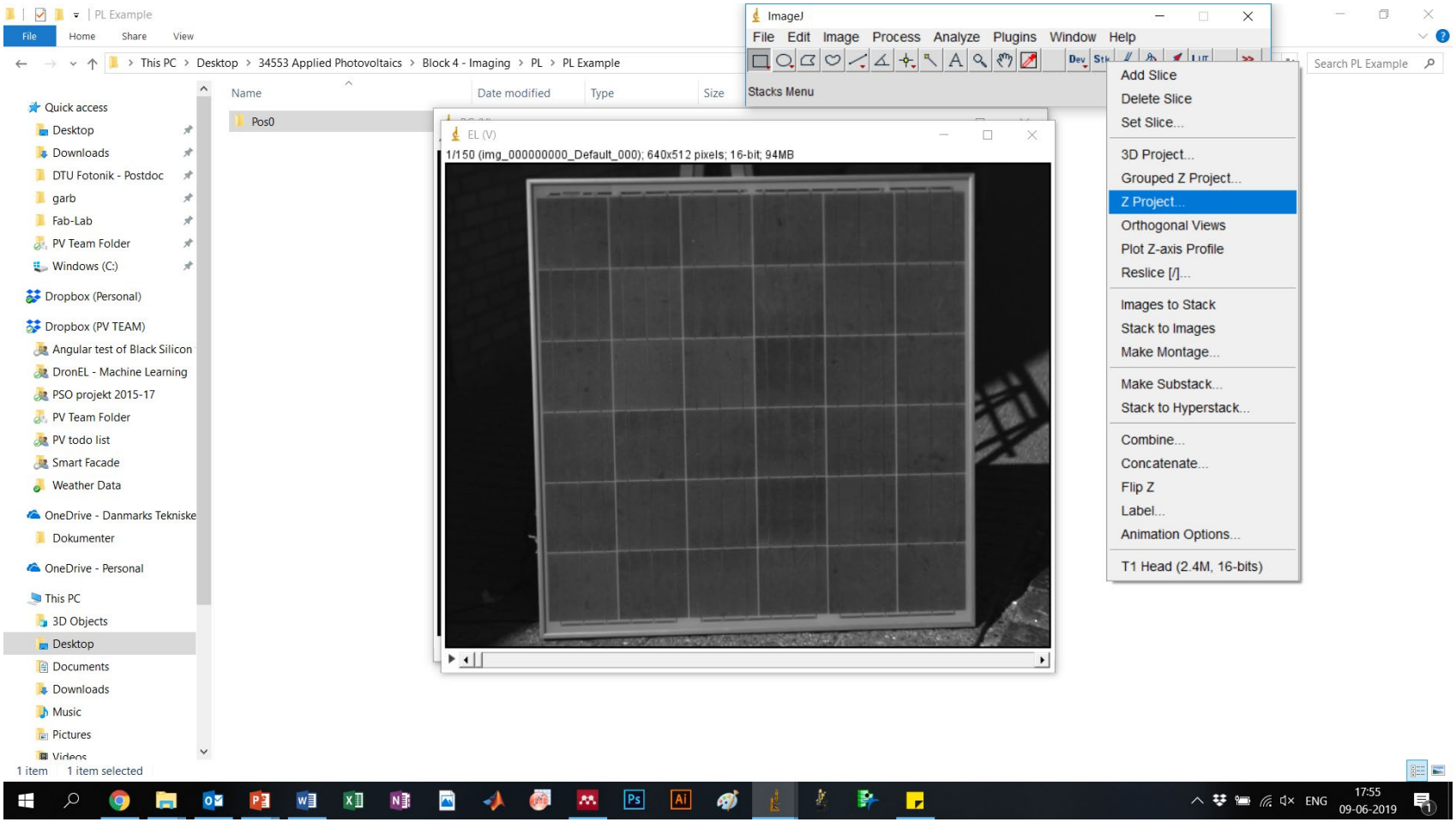
Plot the results in Excel



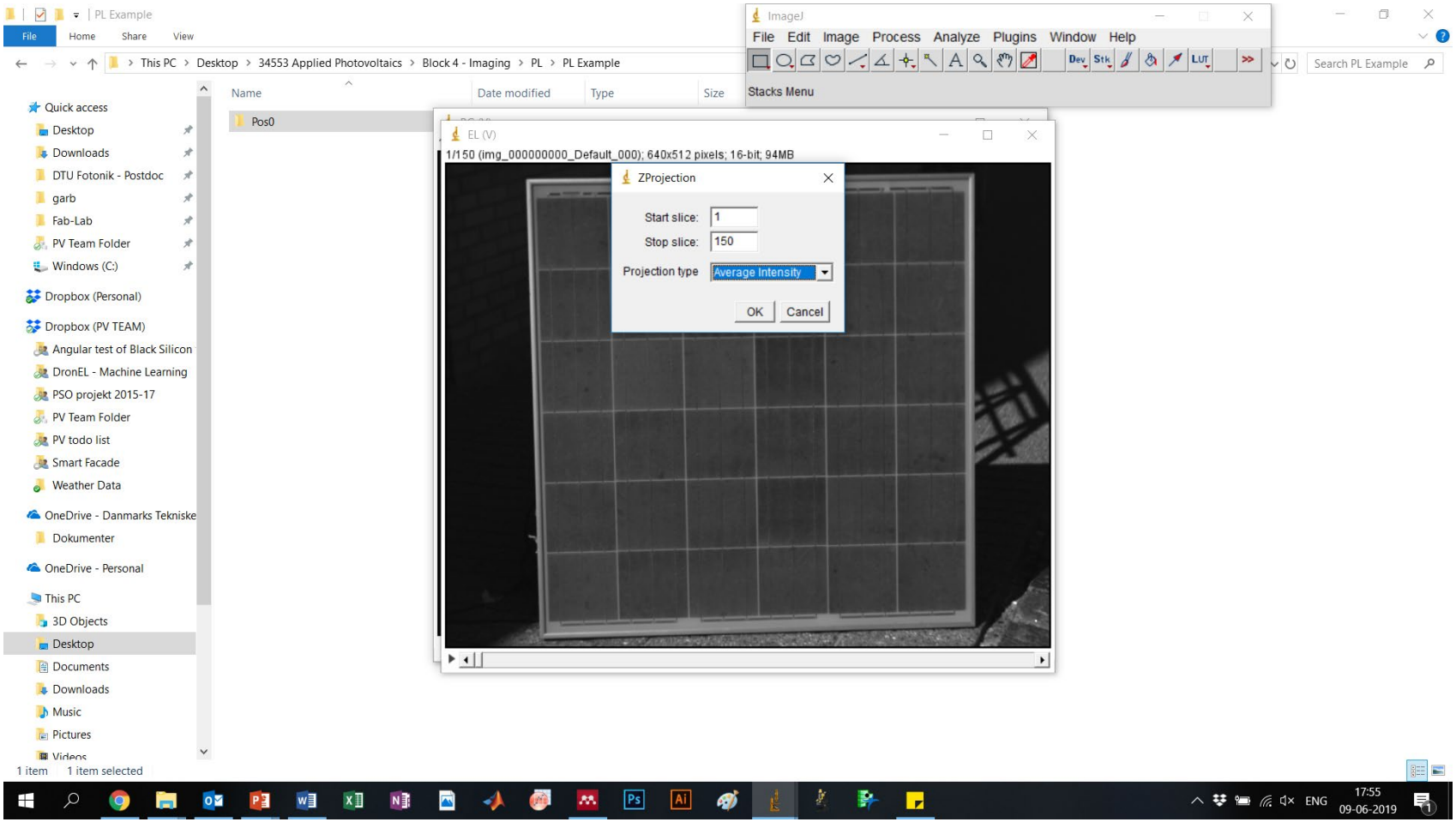
Verify statistical difference between EL and BG



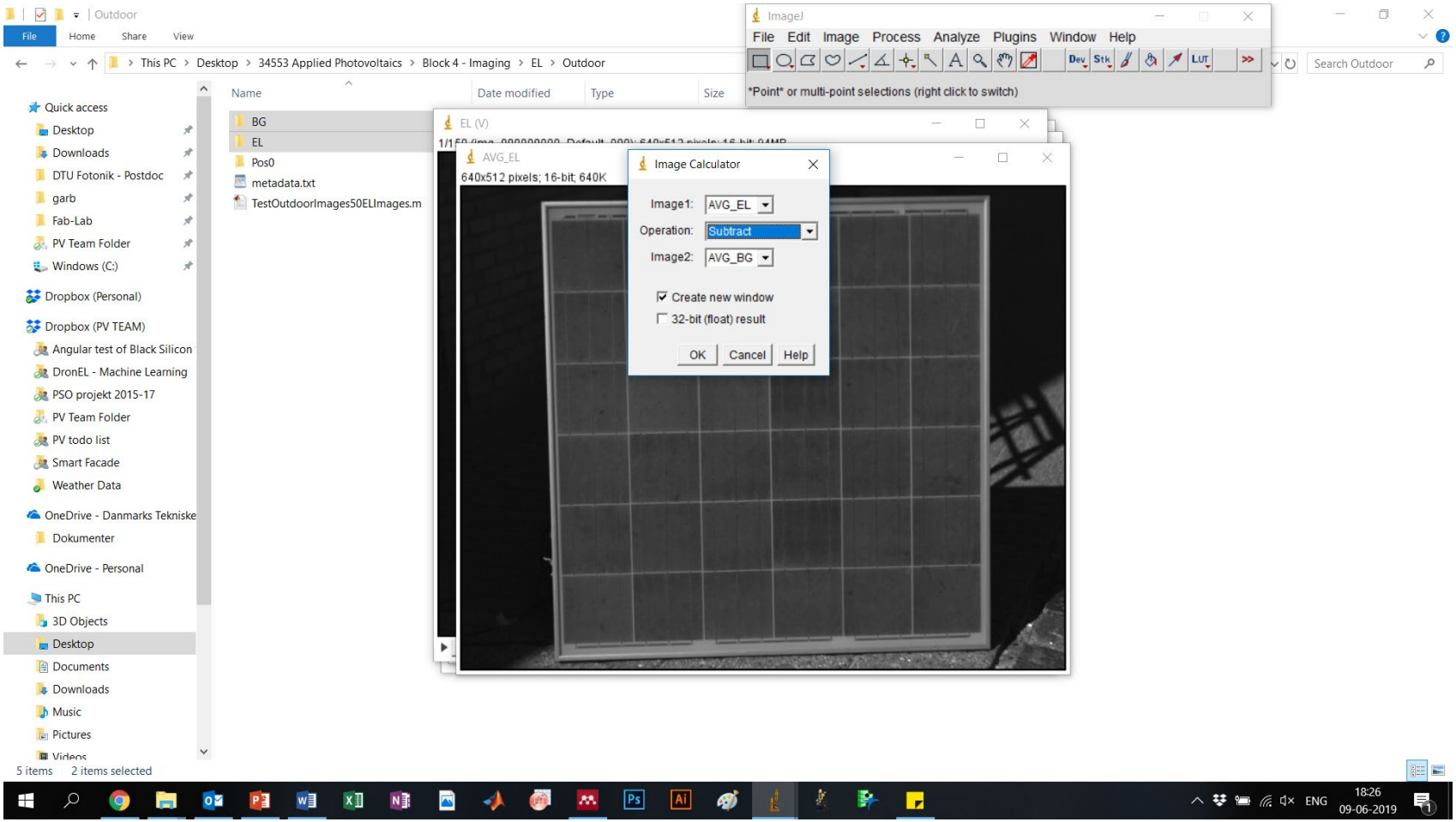
Average image from the stacks



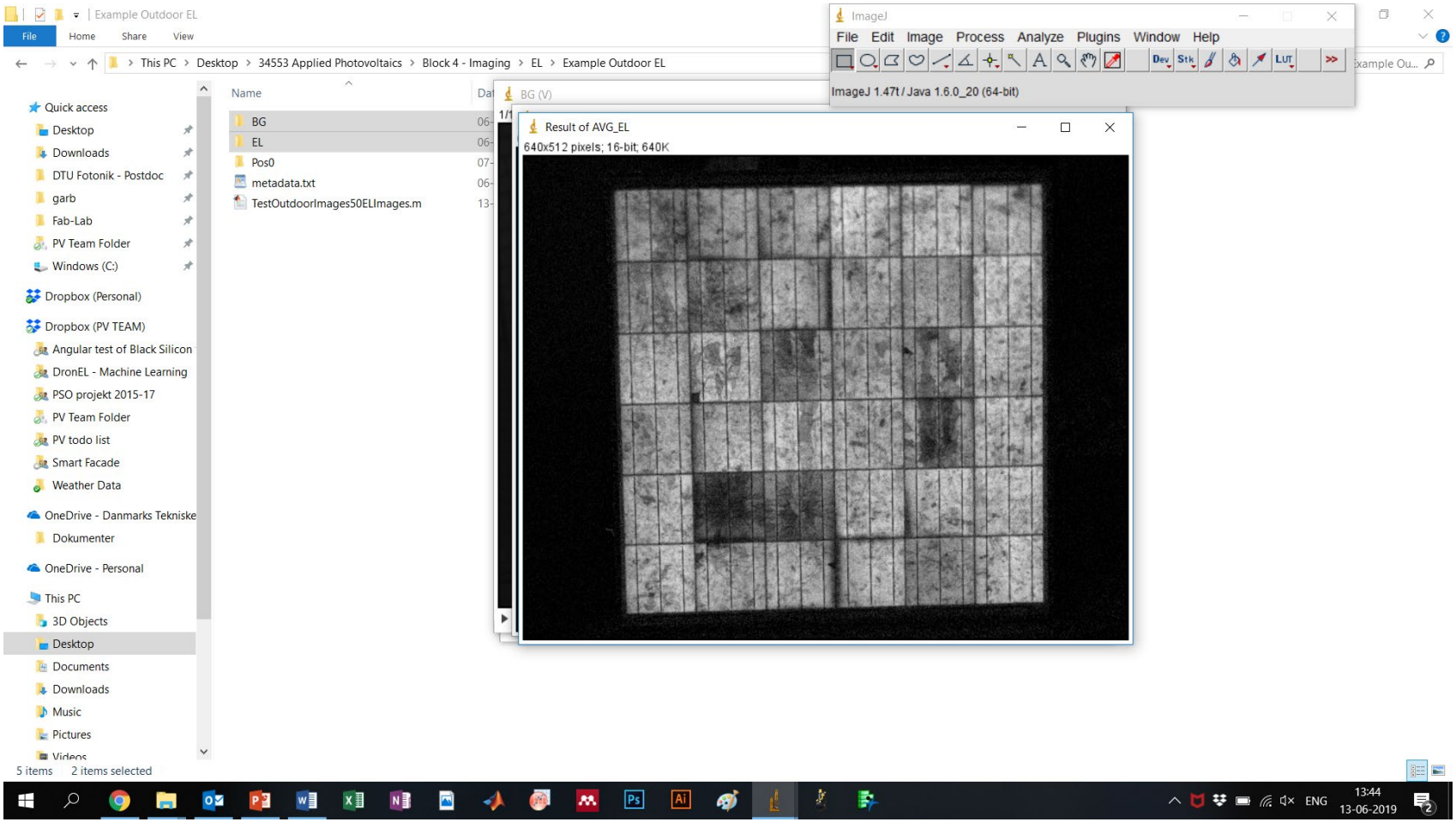
Average image from the stacks



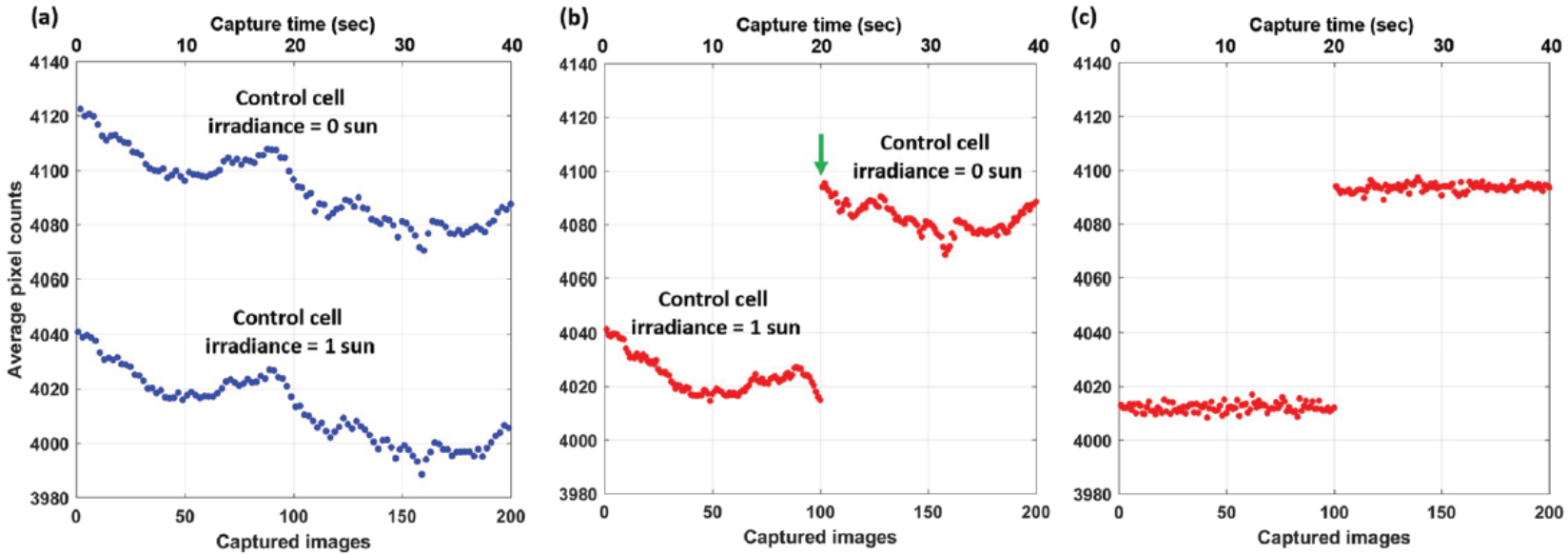
Subtract the averaged images



Resulting Outdoor EL image



Normalized Sunlight Variation



R. Bhoopathy, O. Kunz, M. Juhl, T. Trupke, and Z. Hameiri, *Prog. Photovoltaics Res. Appl.*, vol. 28, no. 3, pp. 217–228, 2020.