

Crosstalk Characterization of a Digital SiPM in 150 nm CMOS Imaging Technology

DESY Summer School Program project, hosted by the DESY ATLAS group

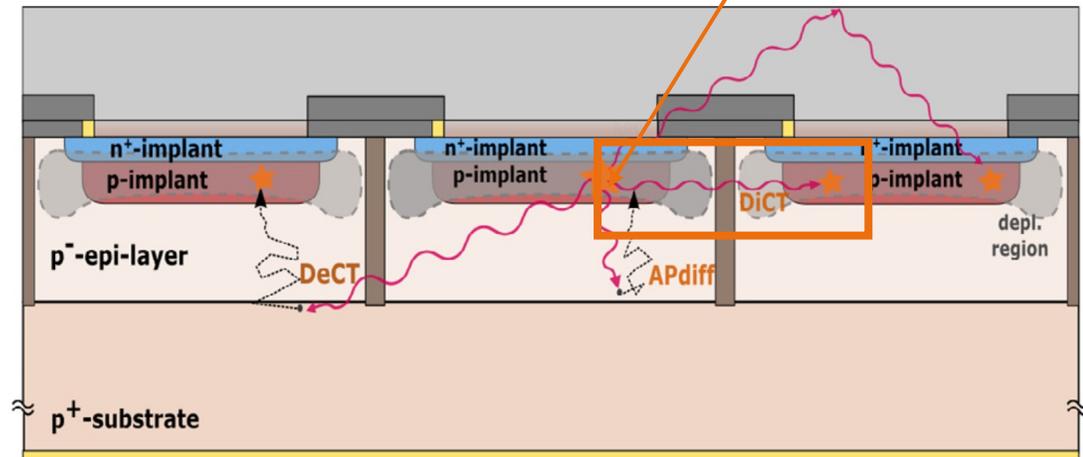
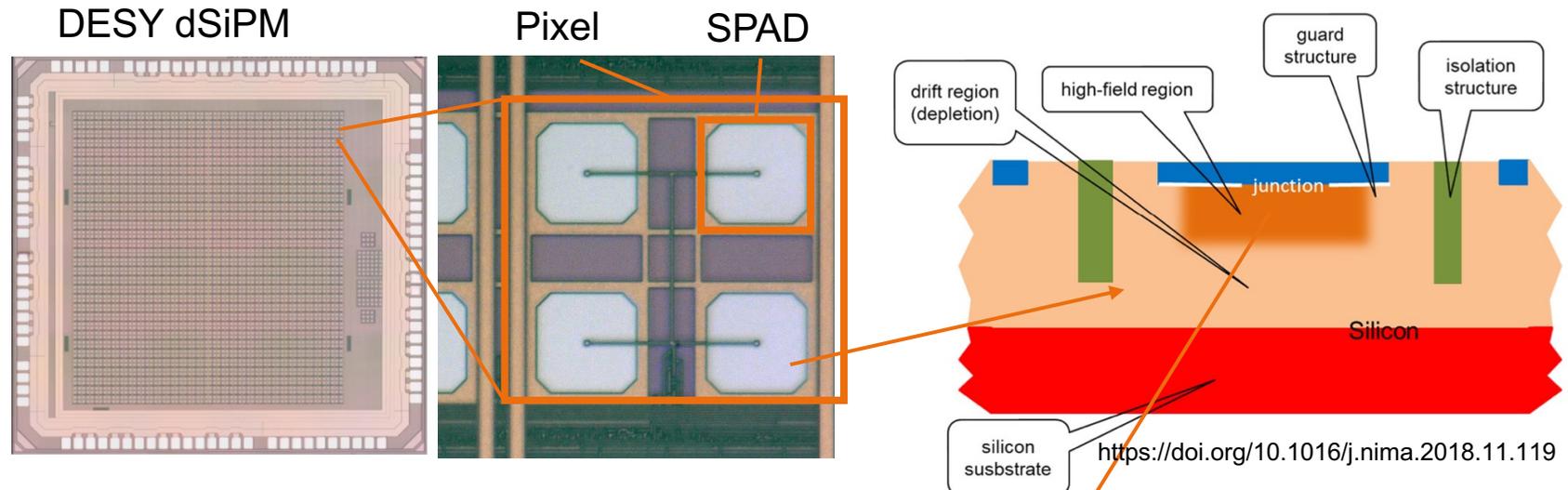
Ono Feyens

Supervised by Finn King and Gianpiero Vignola

Introduction

dSiPMs and optical crosstalk

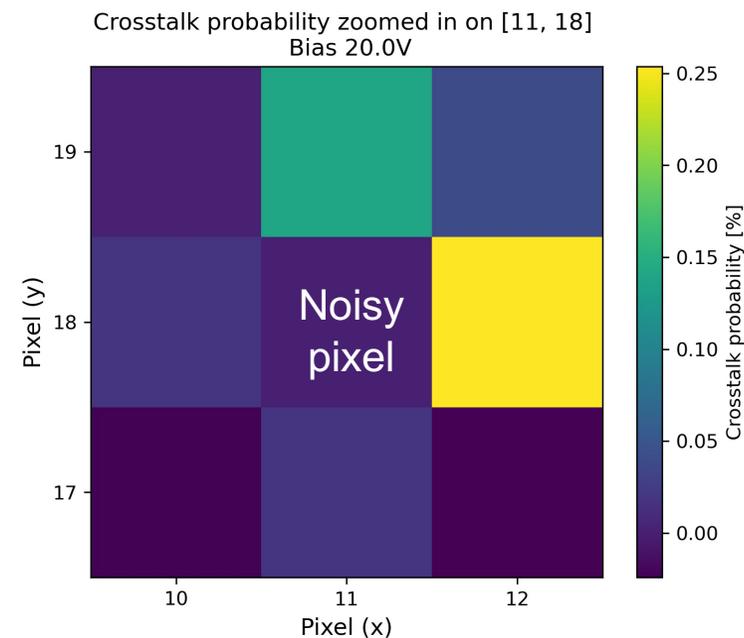
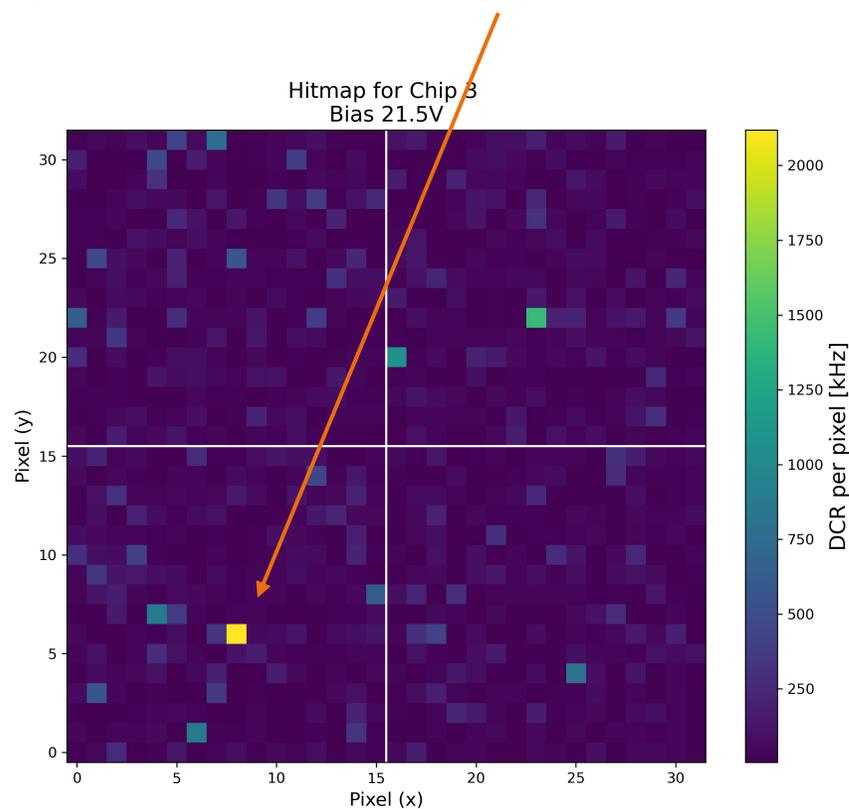
- **SiPM** (silicon photomultiplier): solid-state PMT
 - Single-photon sensitivity
 - Timing resolution, compact, insensitive to magnetic field
 - Digital \rightarrow spatial information
- **Future HEP** experiments (readout scintillating fibers, 4D tracker)
 - Pixel \rightarrow 4 SPADs (single photon avalanche diodes), operated in Geiger-mode \rightarrow **avalanche multiplication**
 - **Secondary photons** created in avalanche process \rightarrow **optical crosstalk (CT)**



Sensor data

Detection of noisy pixels and determination of the crosstalk probability

- Sensor data: in which pixel was a photon detected
- Hitmap in dark conditions → dark count rate (DCR) → detection of **noisy pixels**
- Determination of the **crosstalk probability**
 1. Unmask only single pixel
 2. Unmask central pixel and 1 neighbor
 3. Additional dark count due to crosstalk



Camera data

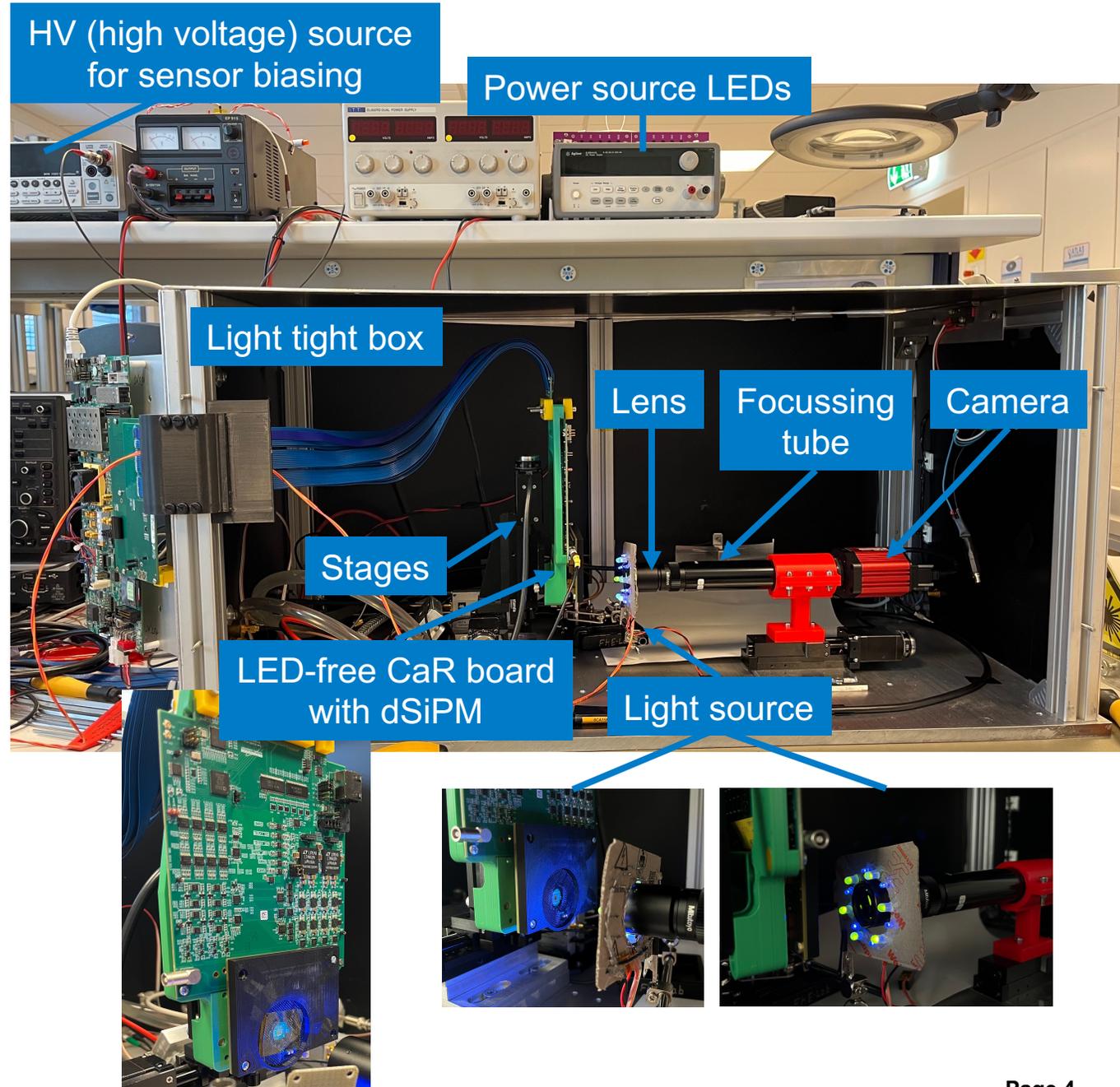
Brightness and location of secondary photons

- **NIR** (near infrared) CMOS camera from Thorlabs → longer wavelengths → look deeper



<https://www.thorlabs.com/thorproduct.cfm?partnumber=CS135MUN>

- What we are looking for:
 - Location source of secondary photons (identify noisy SPAD)
 - Identify defect in SPAD
- Experimental setup

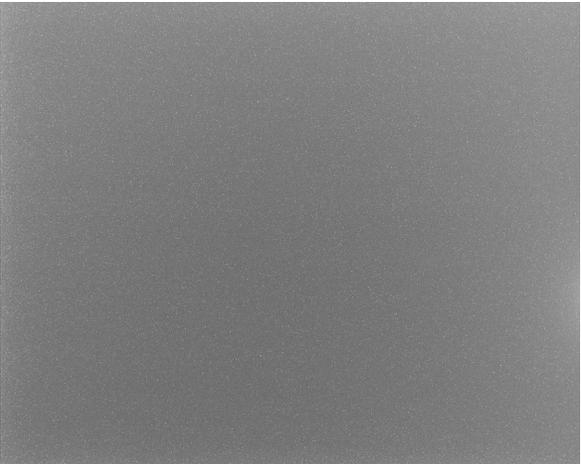


Camera data

Data taking and processing

x repetitions, wait 5s in between

REF	DARK	LIGHT	REF
LEDs on, 1500 ms, HV off	LEDs off, 17500 ms, HV off	LEDs off, 17500 ms, HV on	LEDs on, 1500 ms, HV off
To determine location of the emission	Thermal and electronic noise of the camere	Secondary photons	Check for stable setup



→ Automatized: LabVIEW

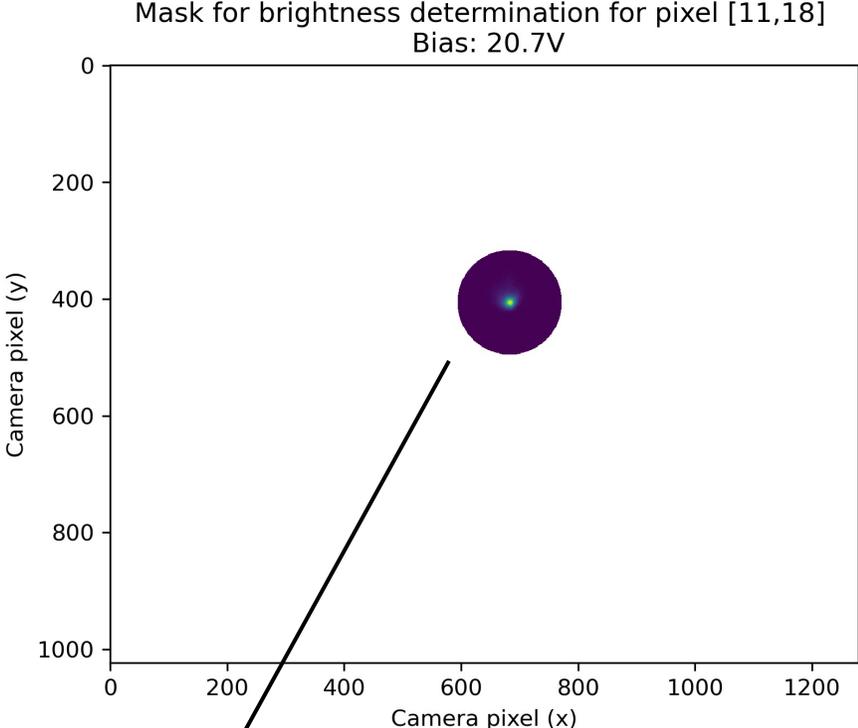
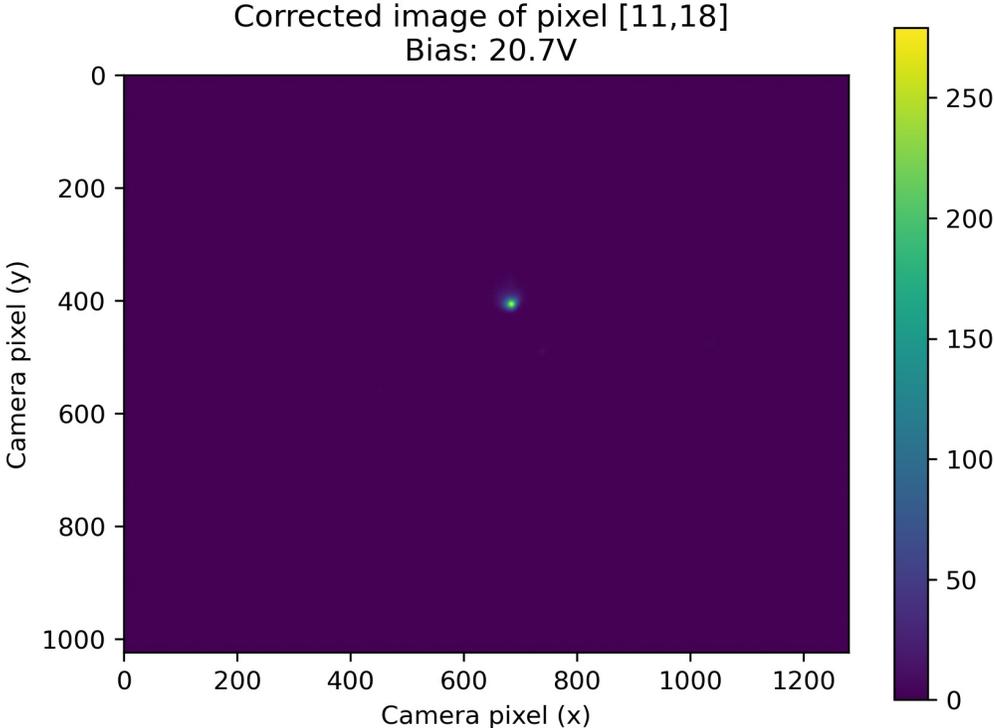
→ Remotely controlable: TeamViewer

Camera data

Data taking and processing

Corrected image = mean(lights) – mean(darks)

Brightness

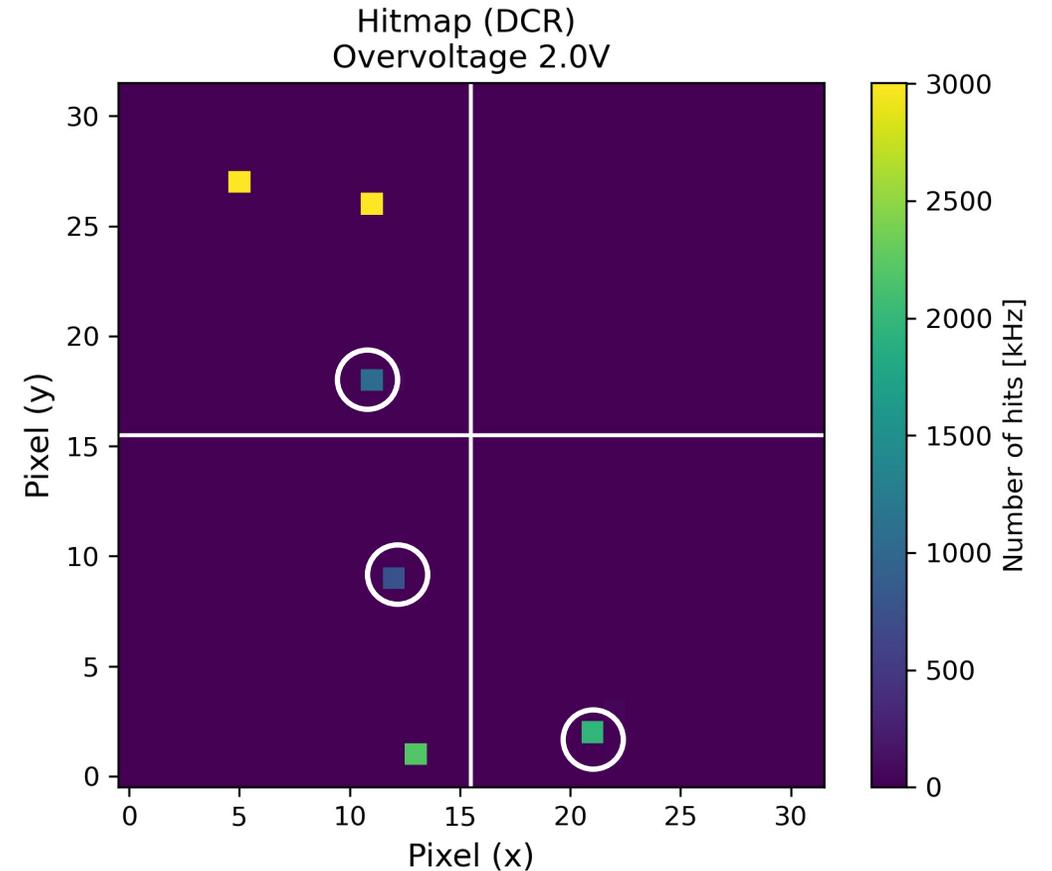


Integrate values in this area
→ brightness value

Results

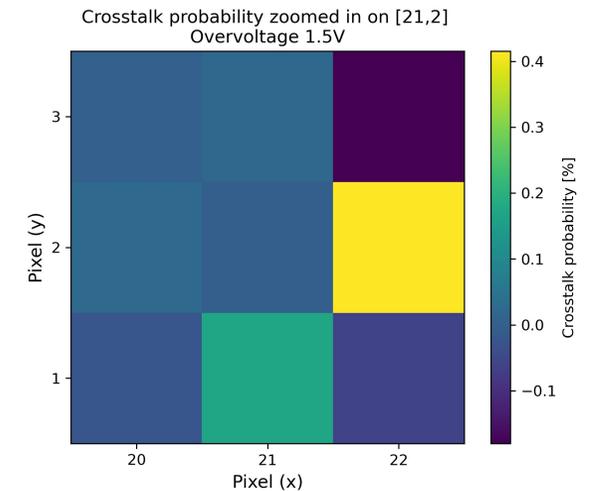
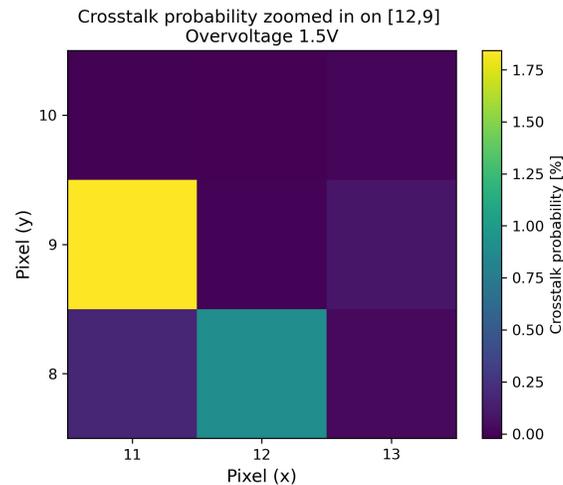
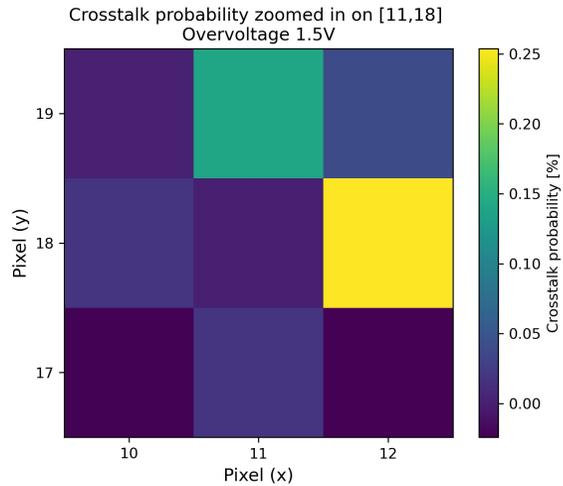
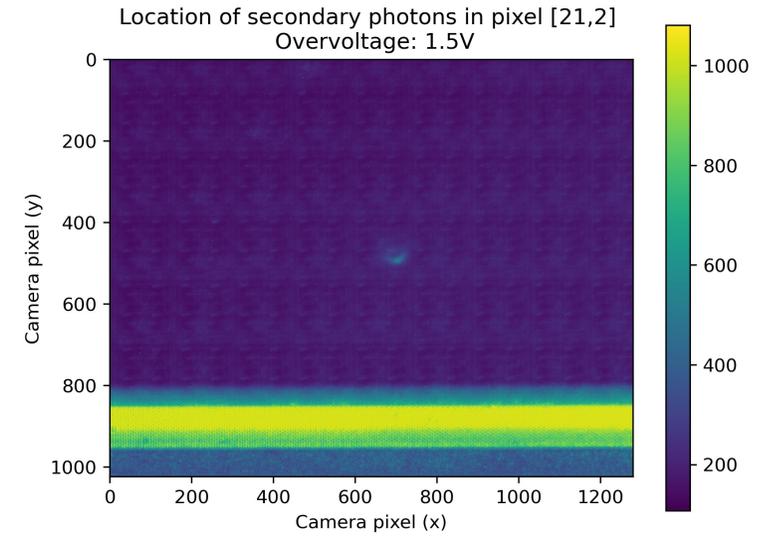
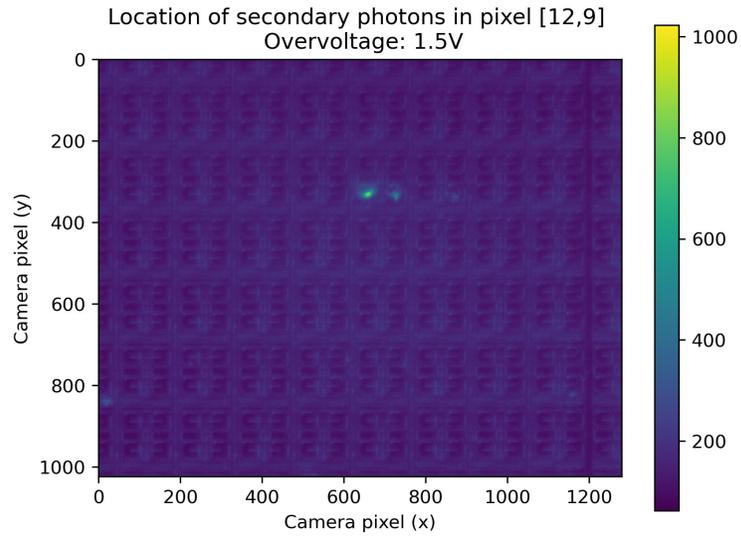
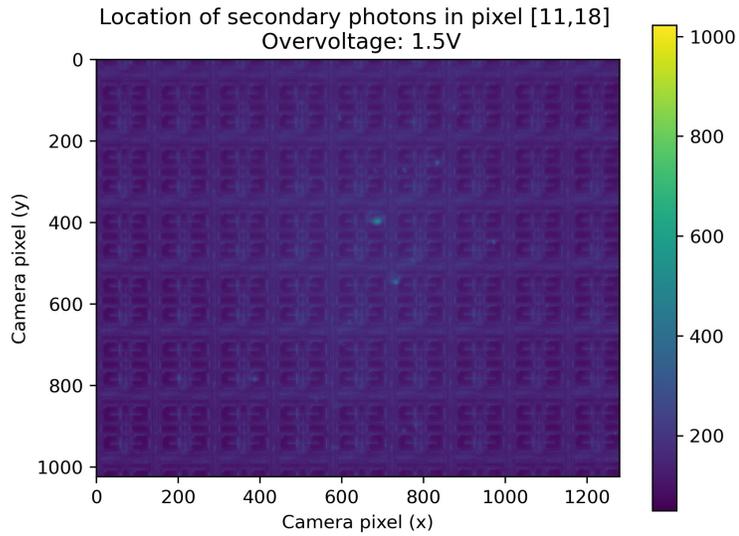
The DUT

- Chip 1: 6 noisy pixels
→ looked at 3 [11,18], [12,9], [21,2]
- Camera and sensor settings:
 - Exposure time: 17500 ms / 1500 ms
 - Reperitions: 7
 - Delay time: 5 s
 - HV: 20.7 V – 22.2 V in steps of 0.25 V
→ Overvoltage (OV) = bias – breakdown voltage



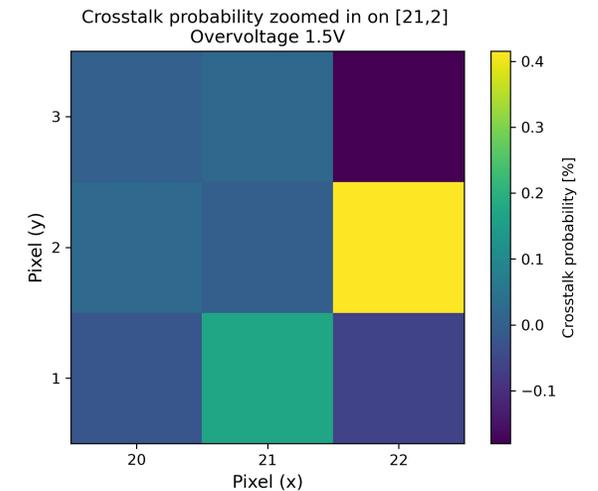
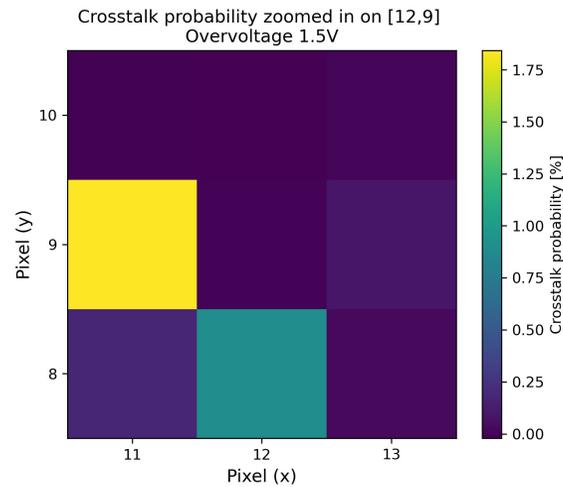
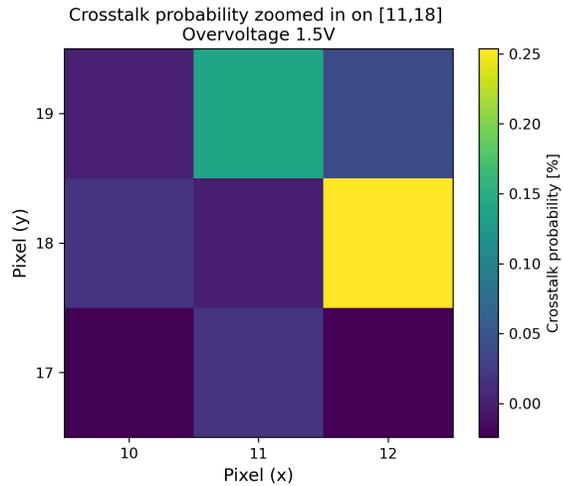
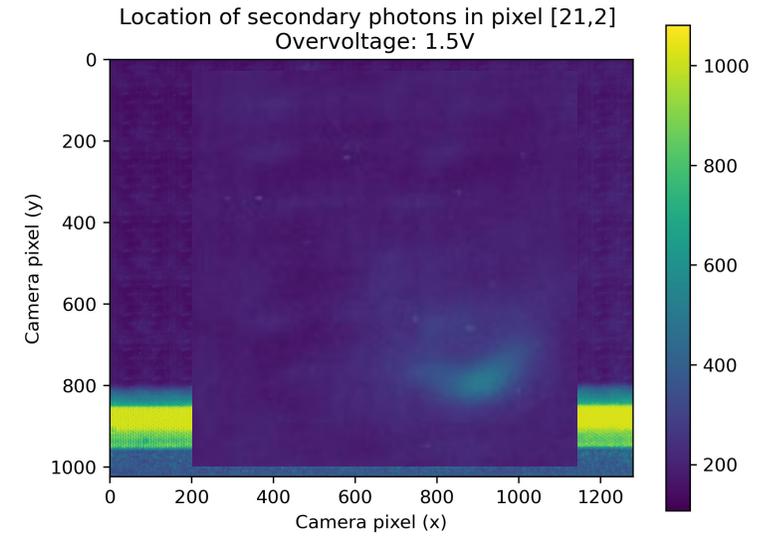
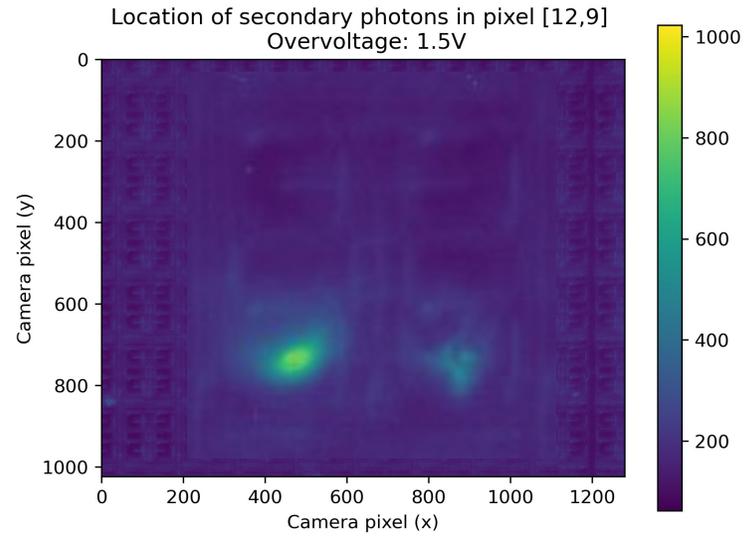
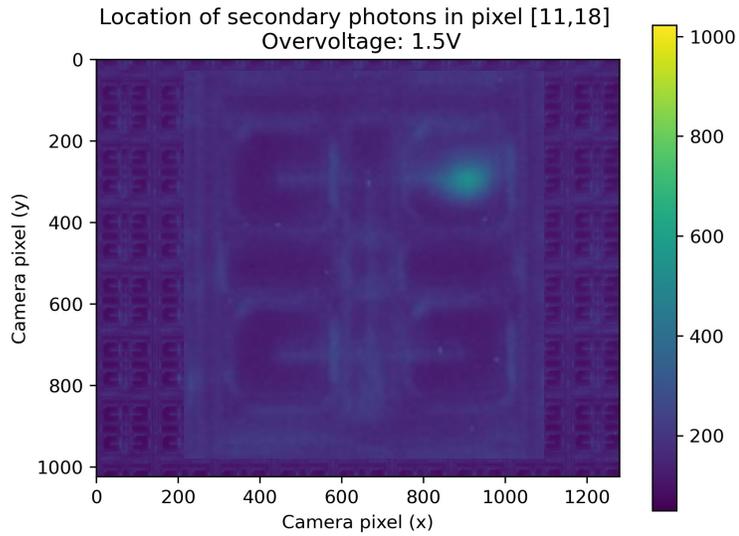
Results

Identifying the noisy SPAD



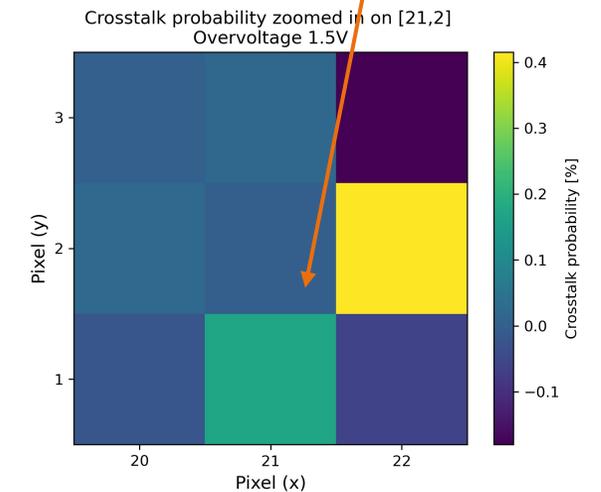
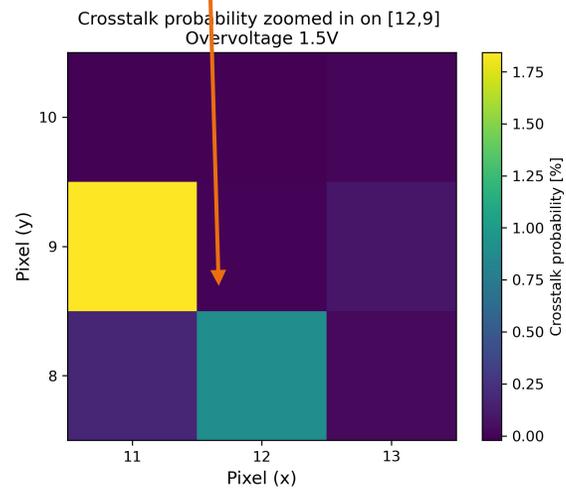
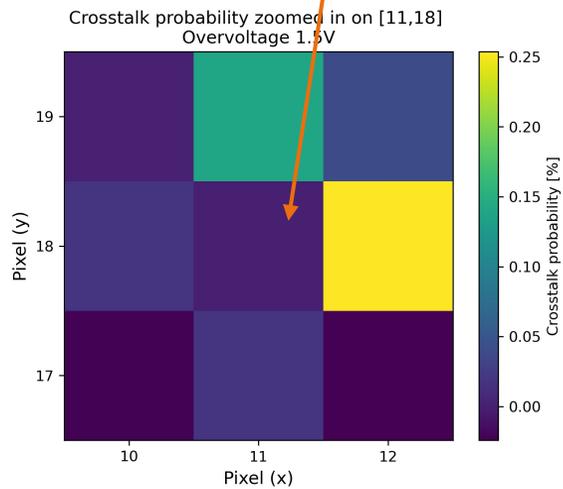
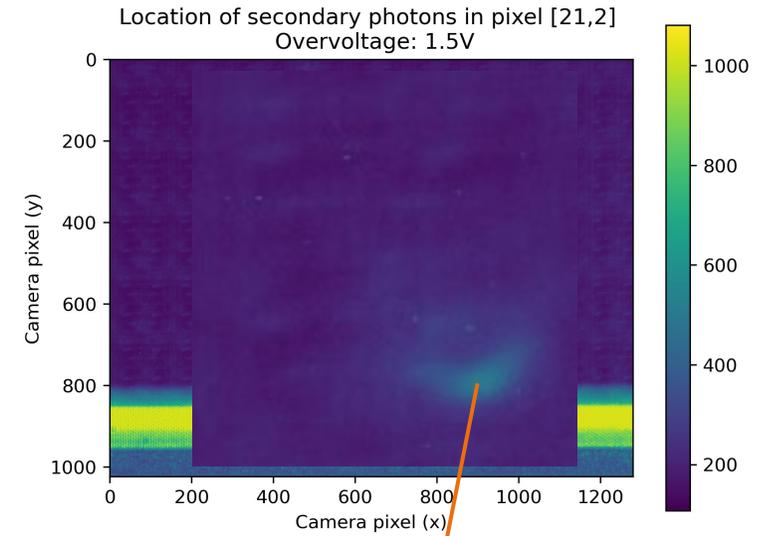
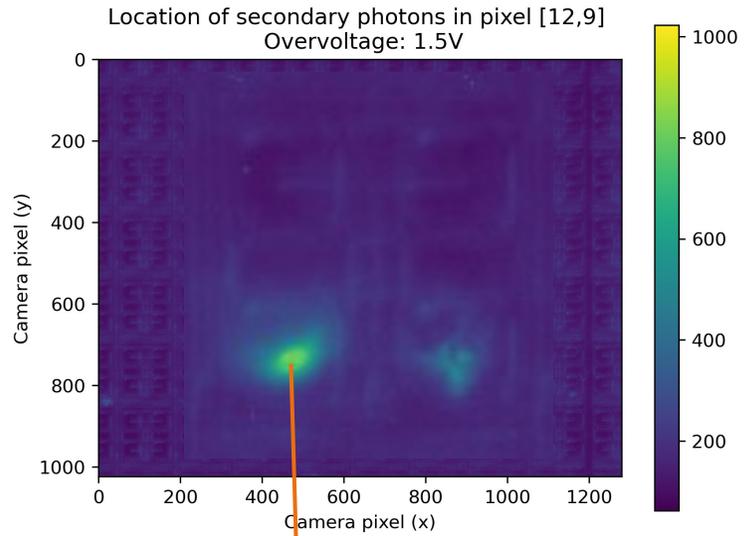
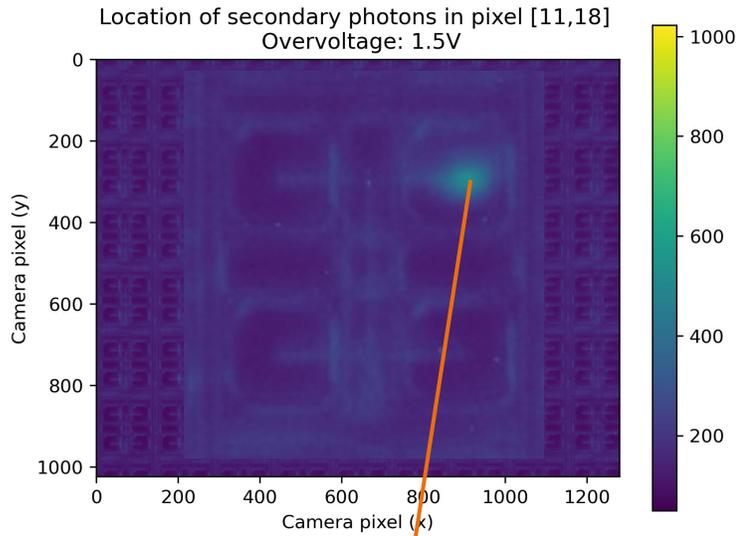
Results

Defining the noisy SPAD



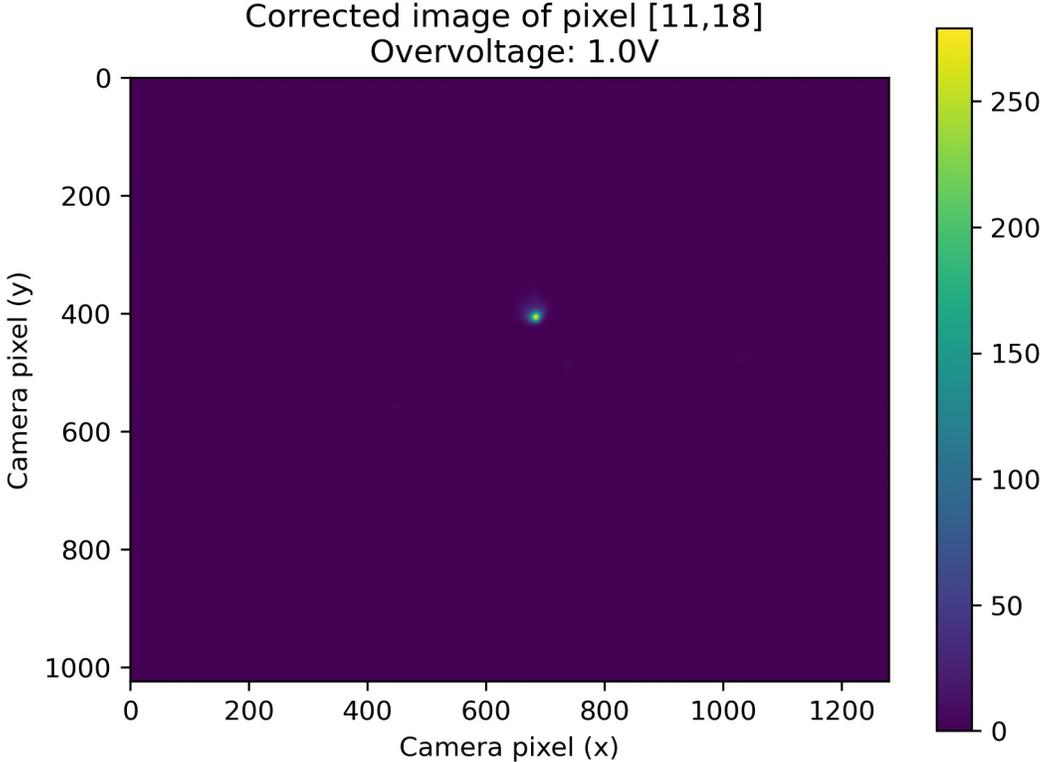
Results

Defining the noisy SPAD

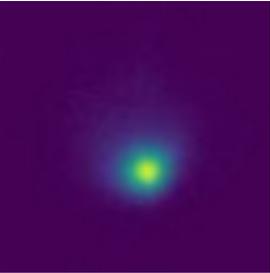


Results

Shape of secondary photons → location of defect within the SPAD

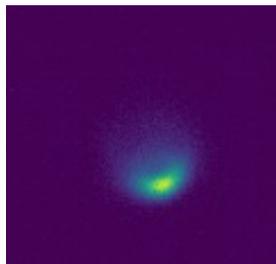
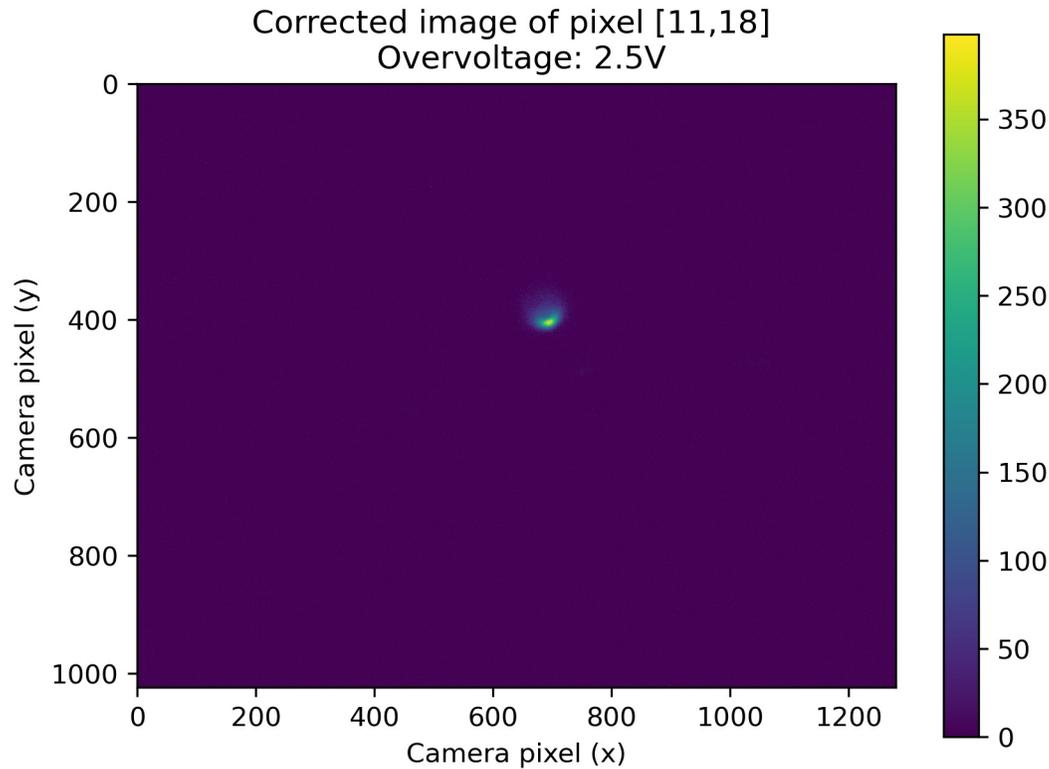


Sort of a droplet shape, but seen in all measurements
→ probaby **just a camera effect**

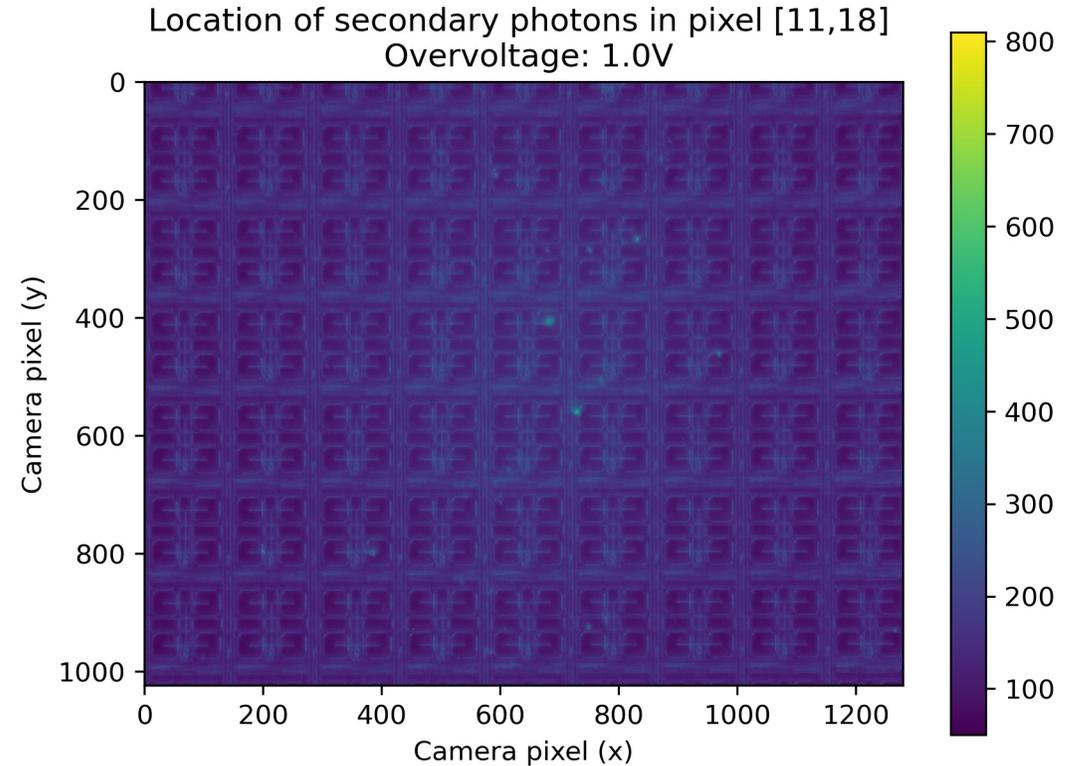


Results

Shape of secondary photons → location of defect within the SPAD



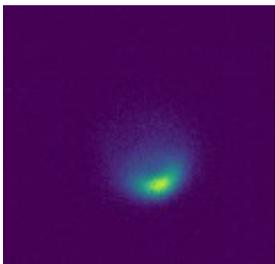
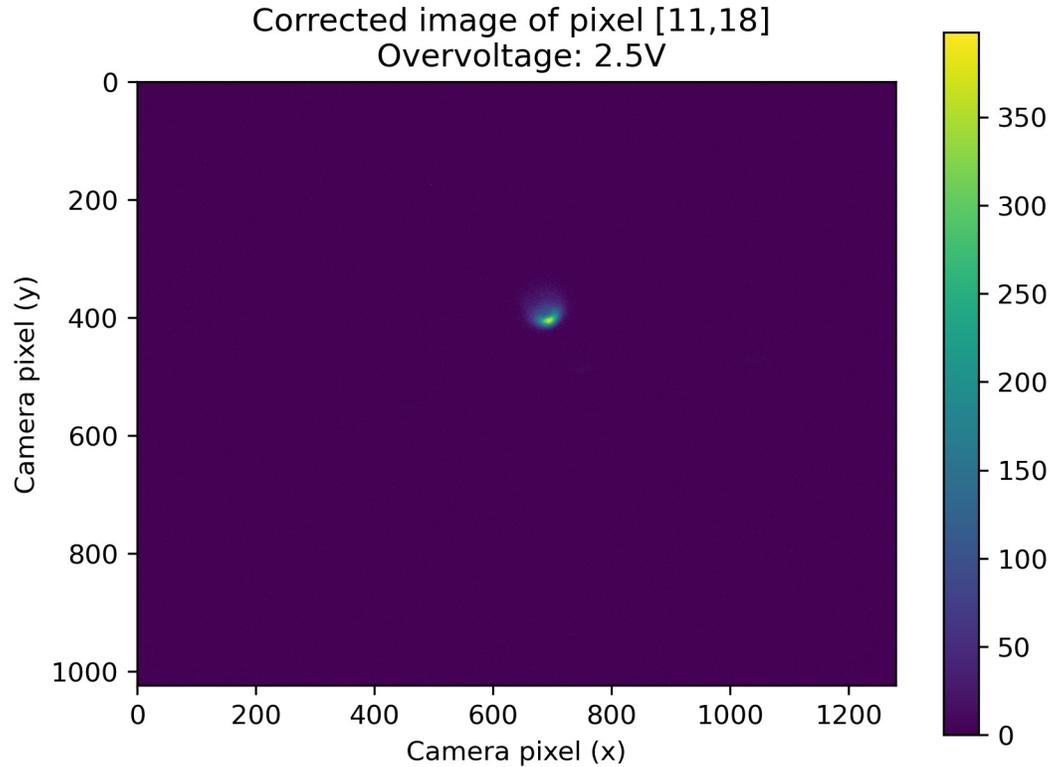
U-shape, often seen at higher overvoltages, after a lot of measurements



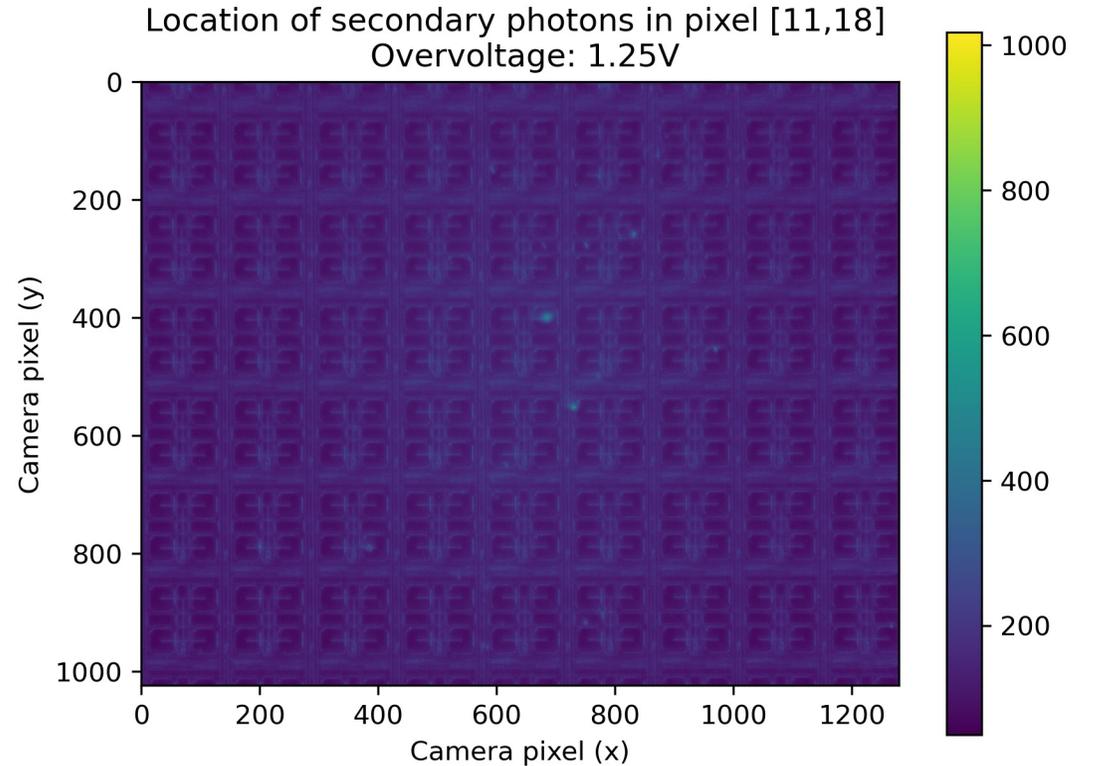
Not only does the emission shape changes, also the reference image becomes more blurred → **systematics**, maybe we lose focus due to heating and thus extension of materials

Results

Shape of secondary photons → location of defect within the SPAD



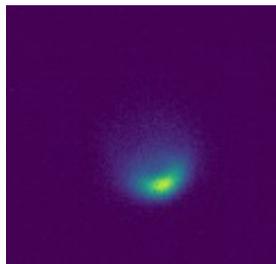
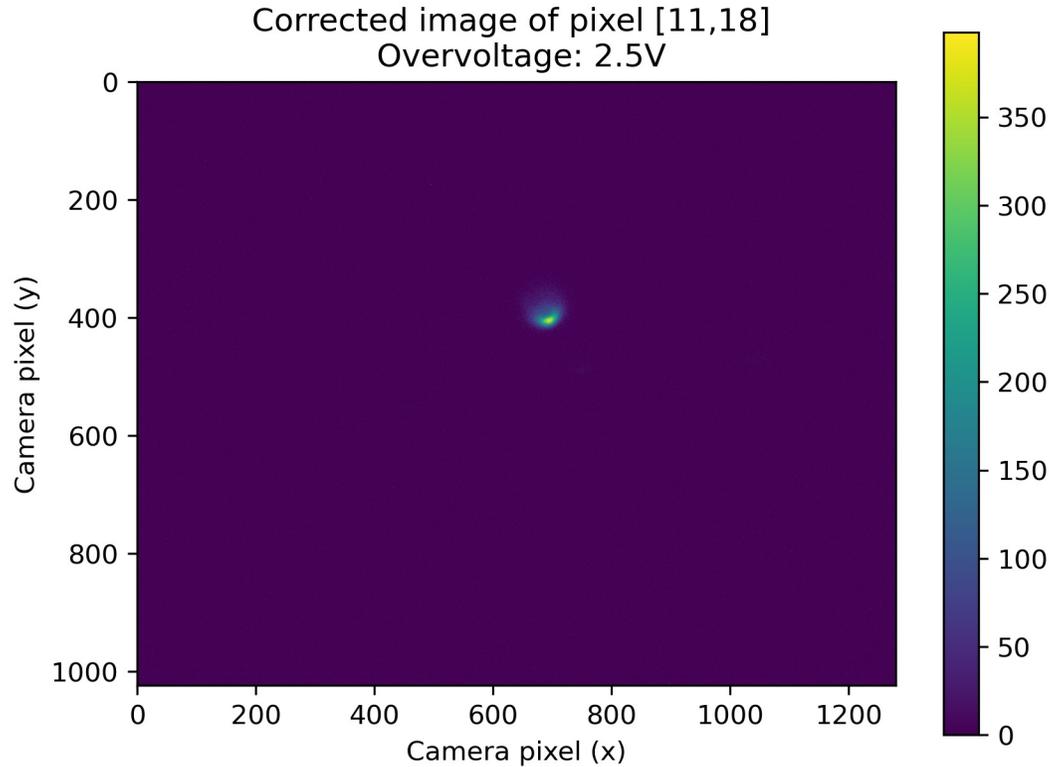
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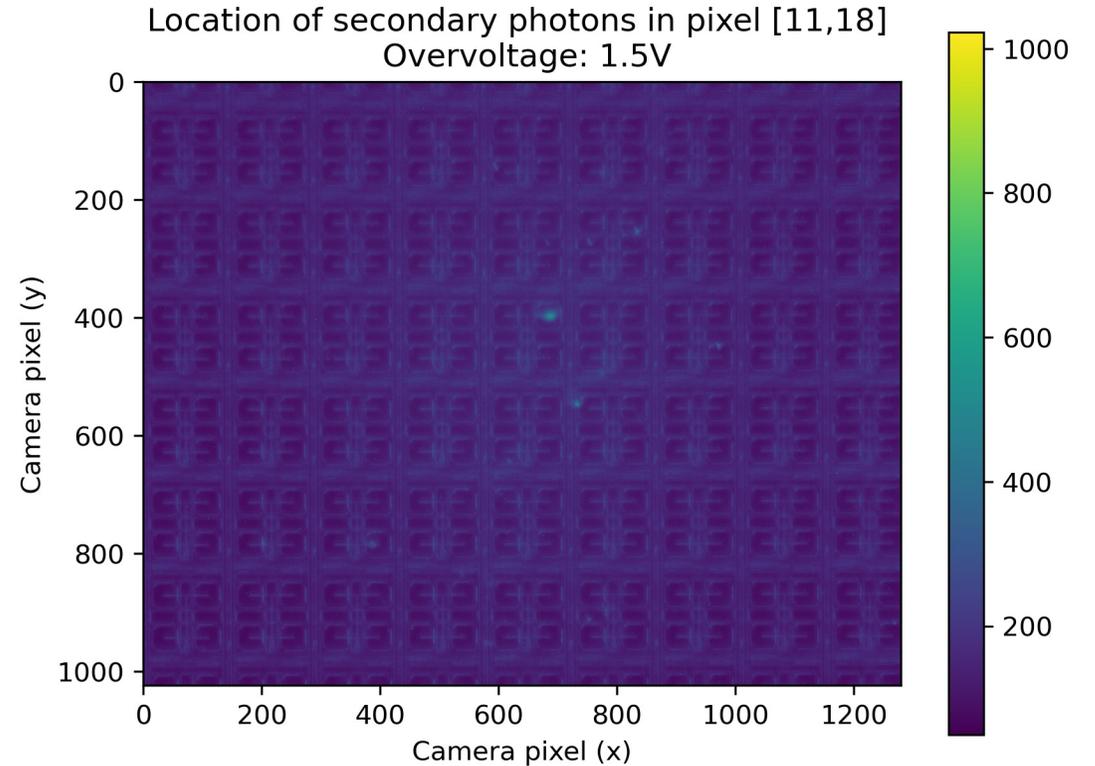
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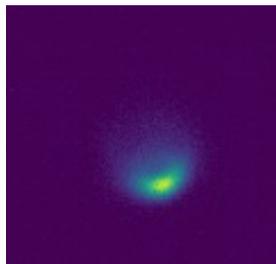
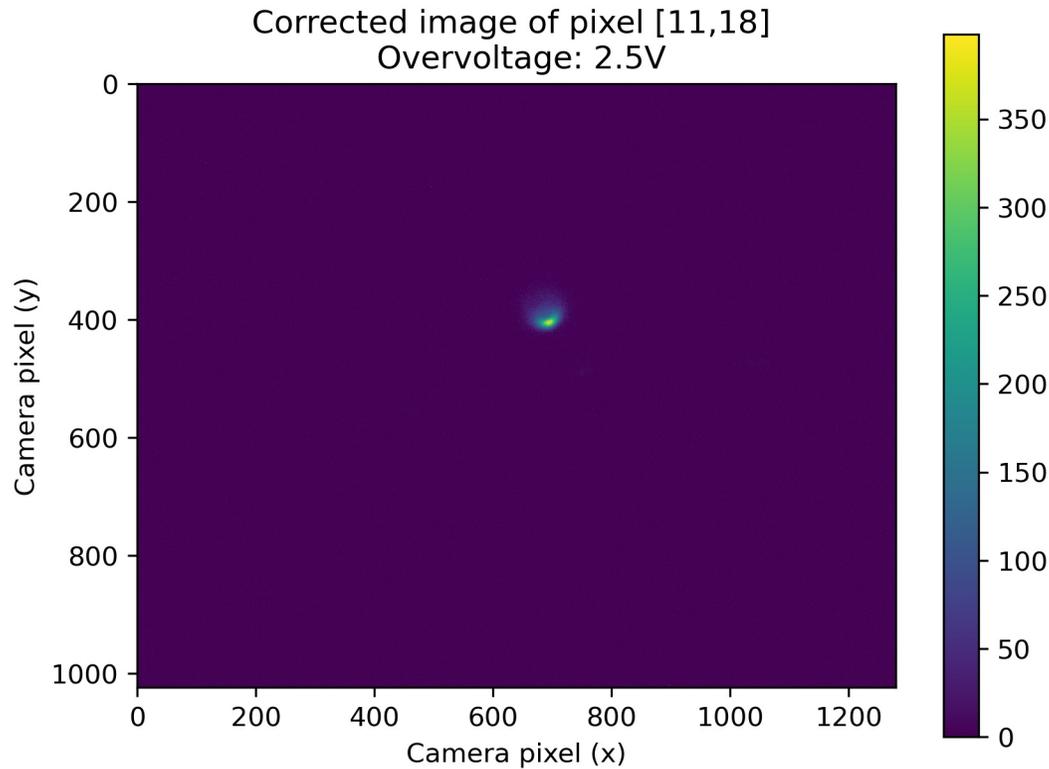
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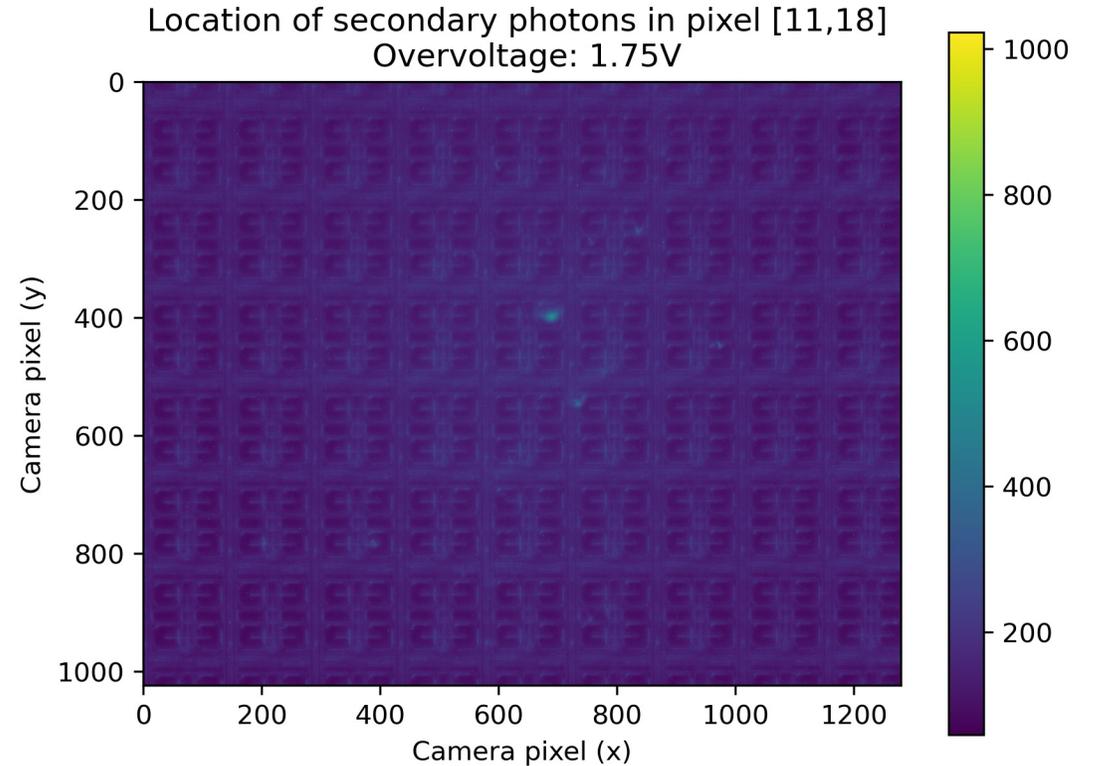
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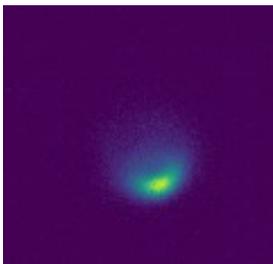
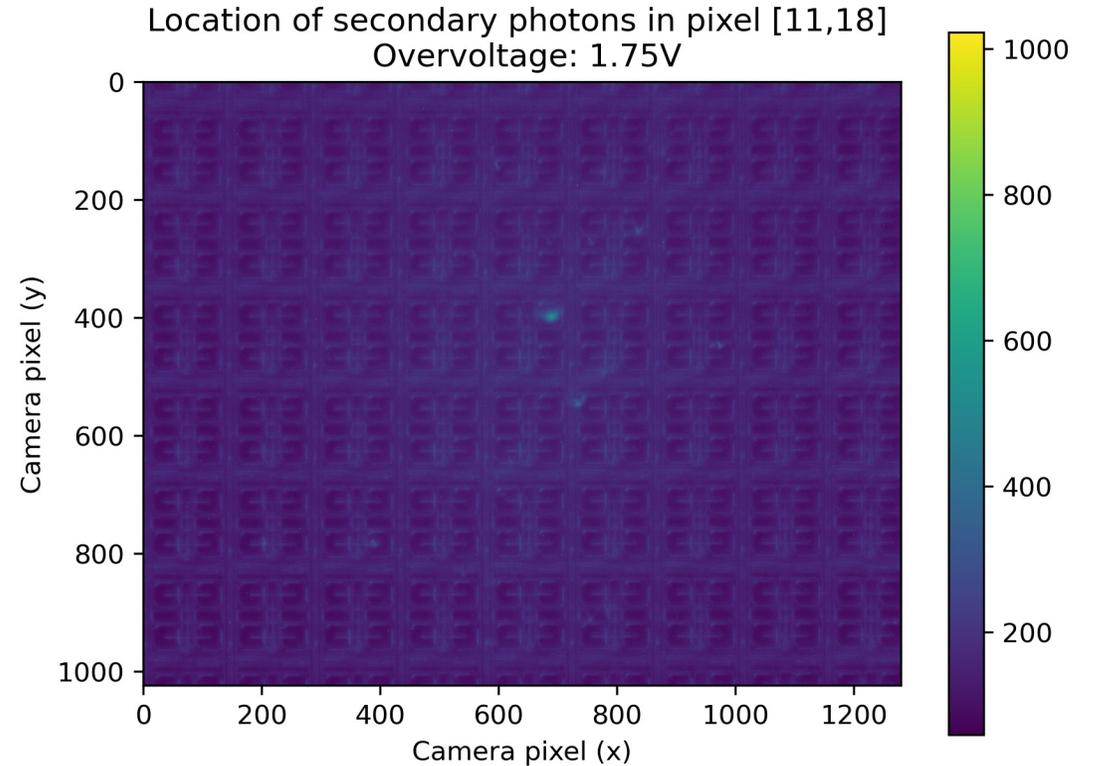
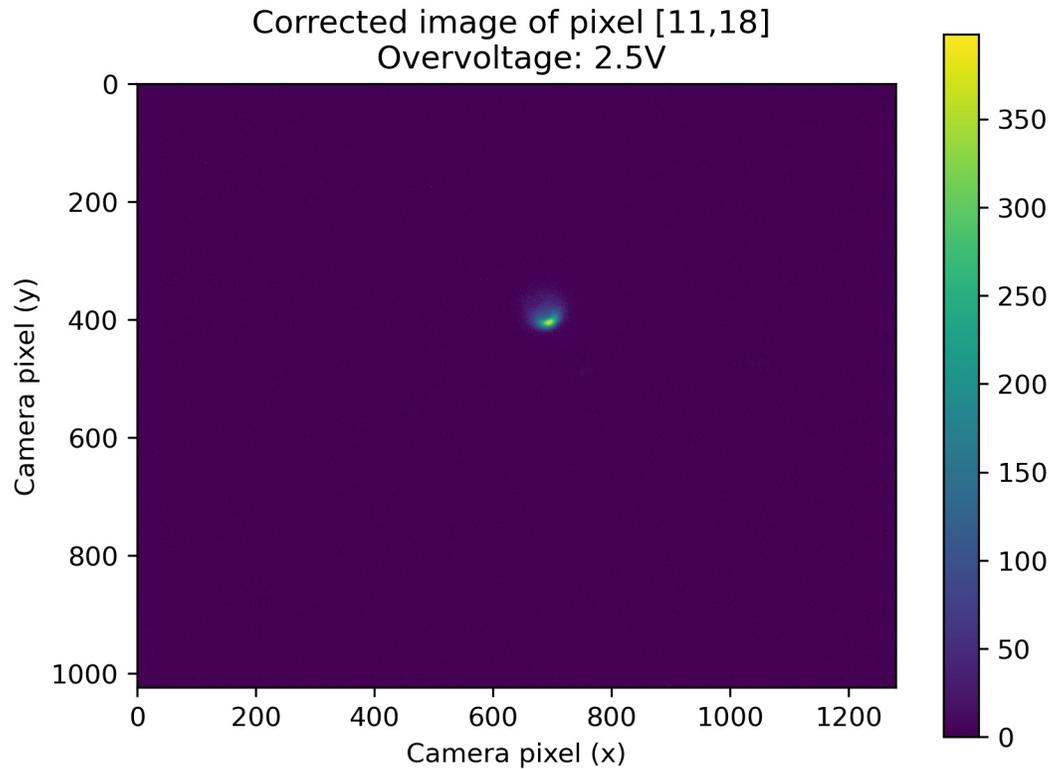
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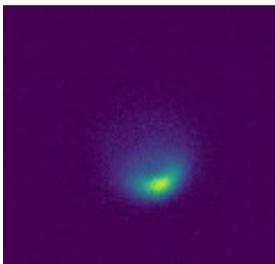
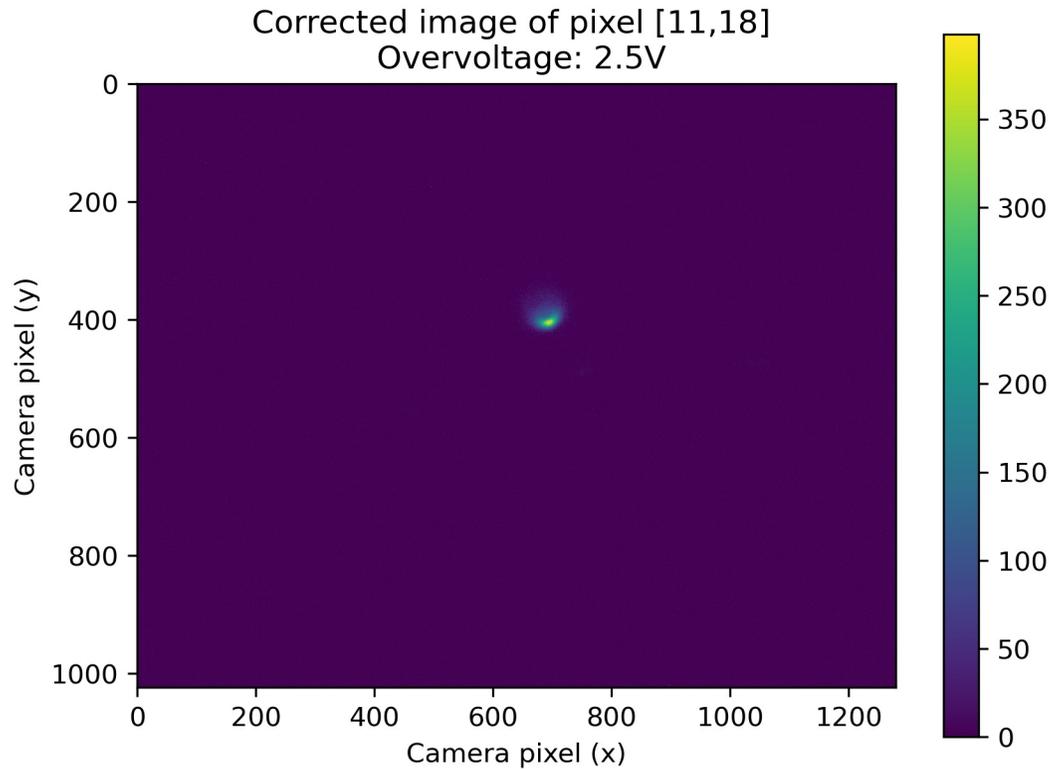


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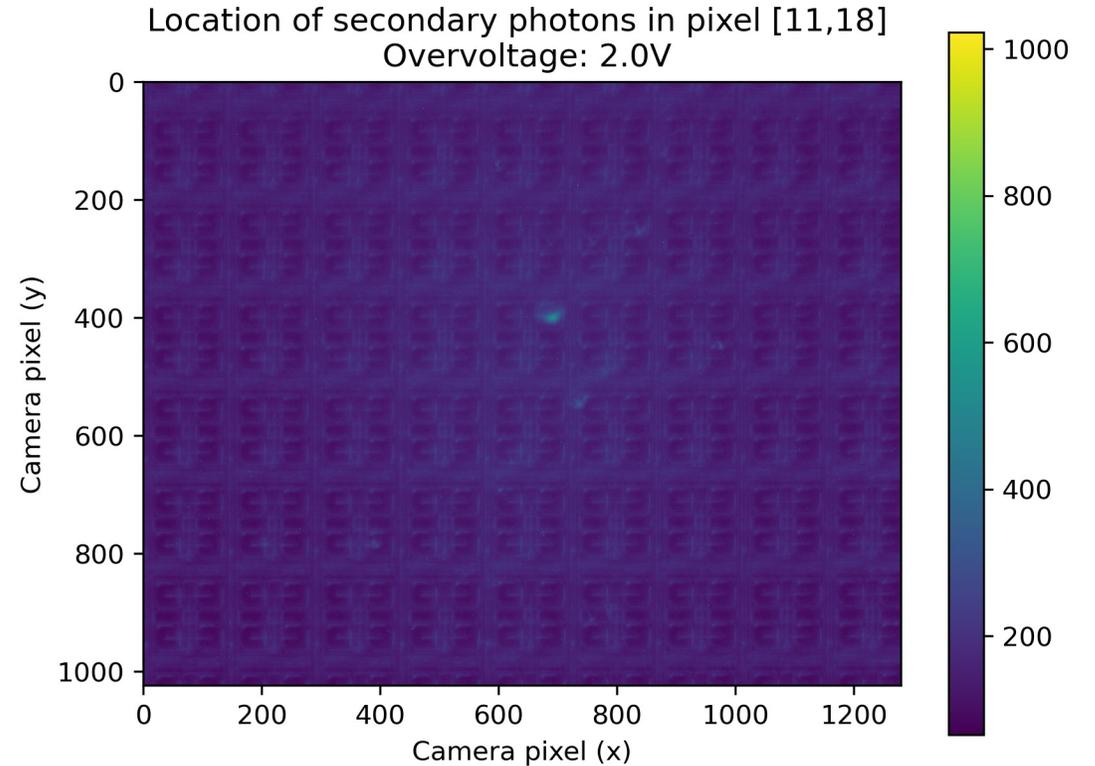
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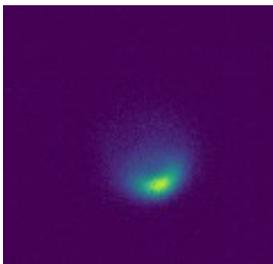
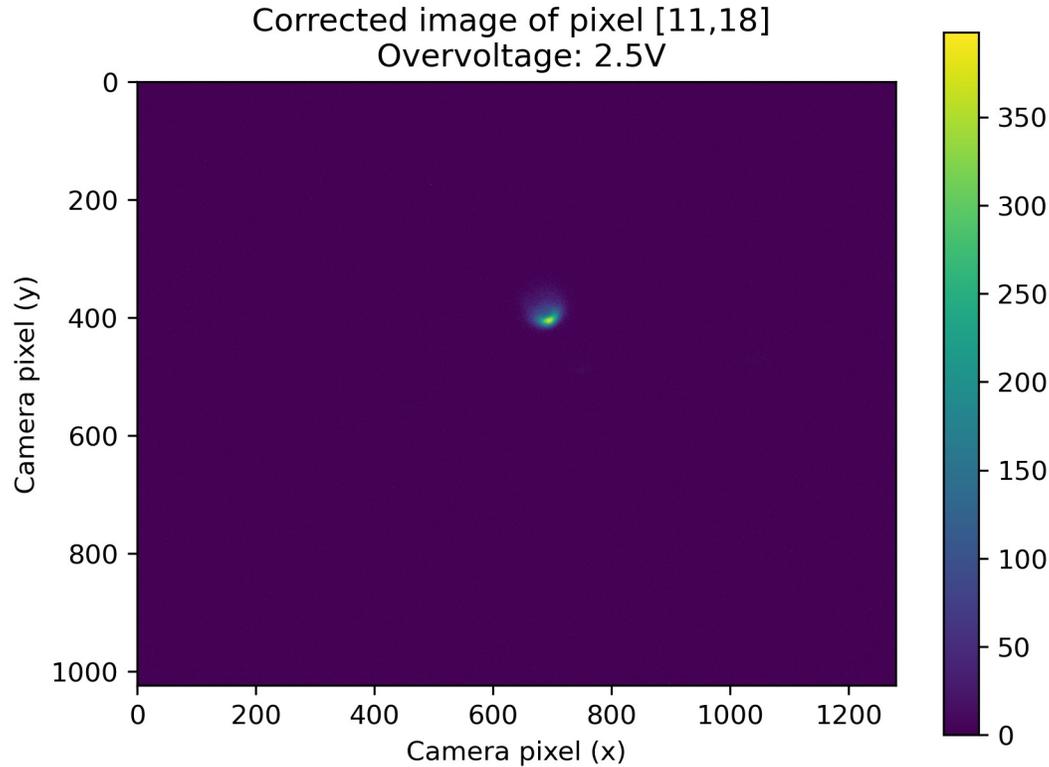
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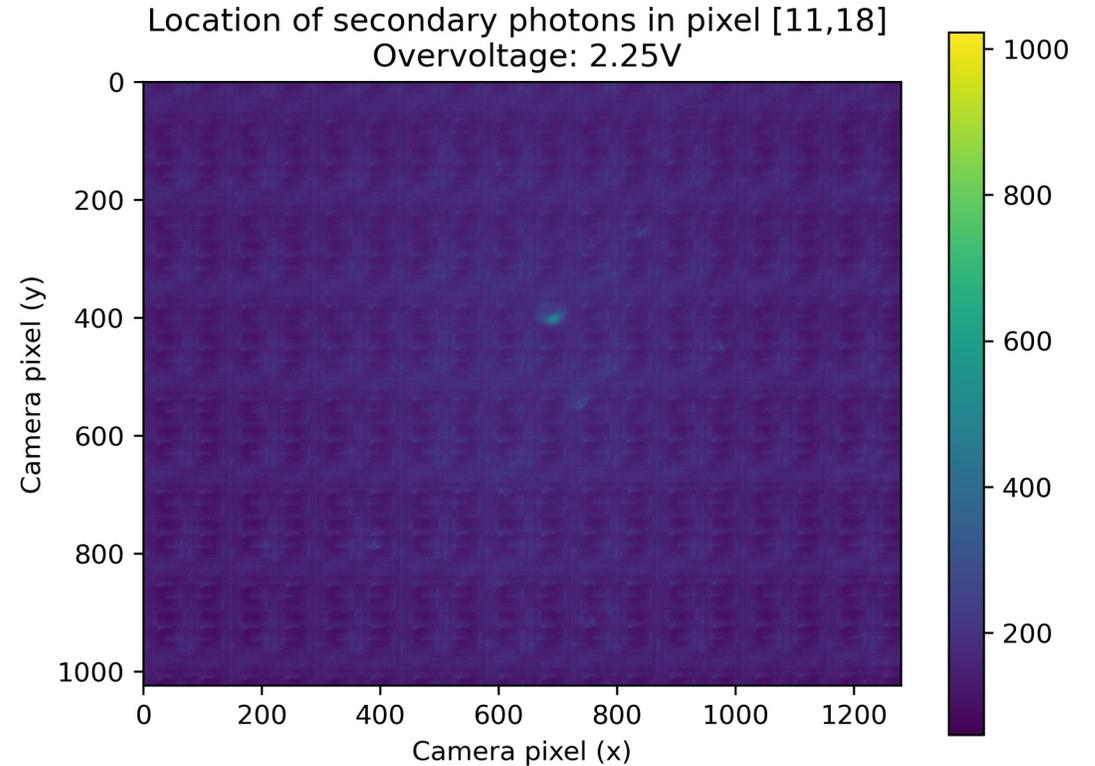
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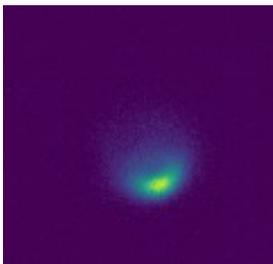
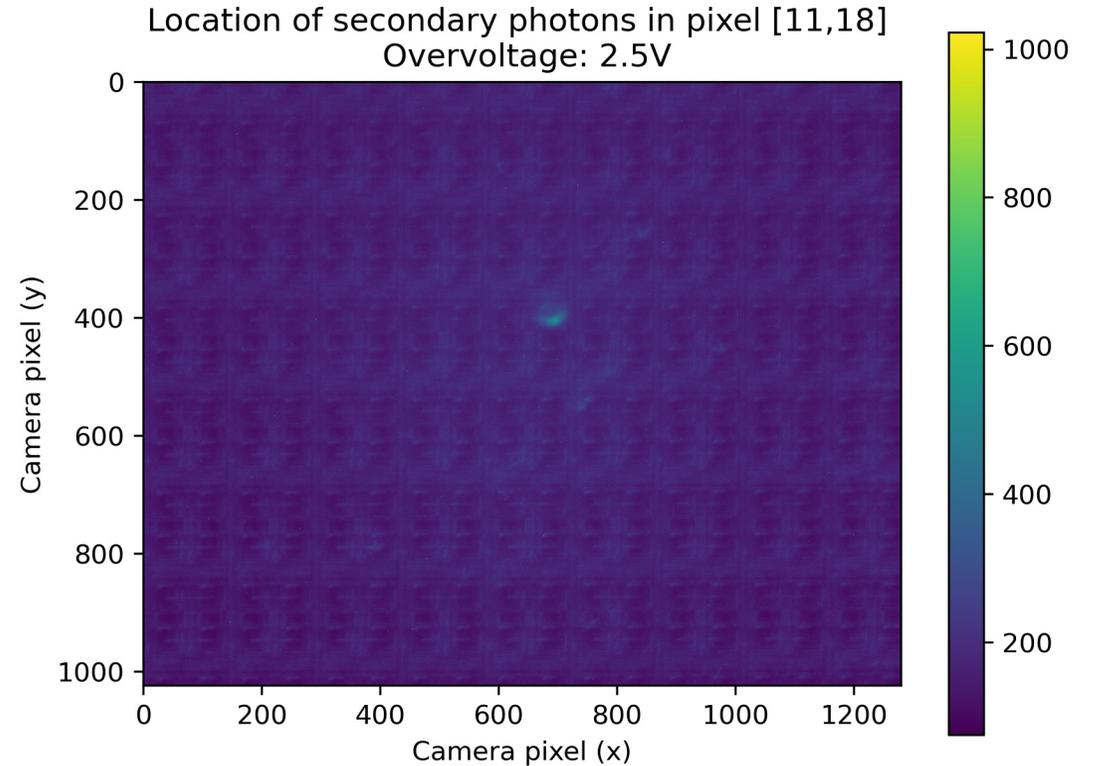
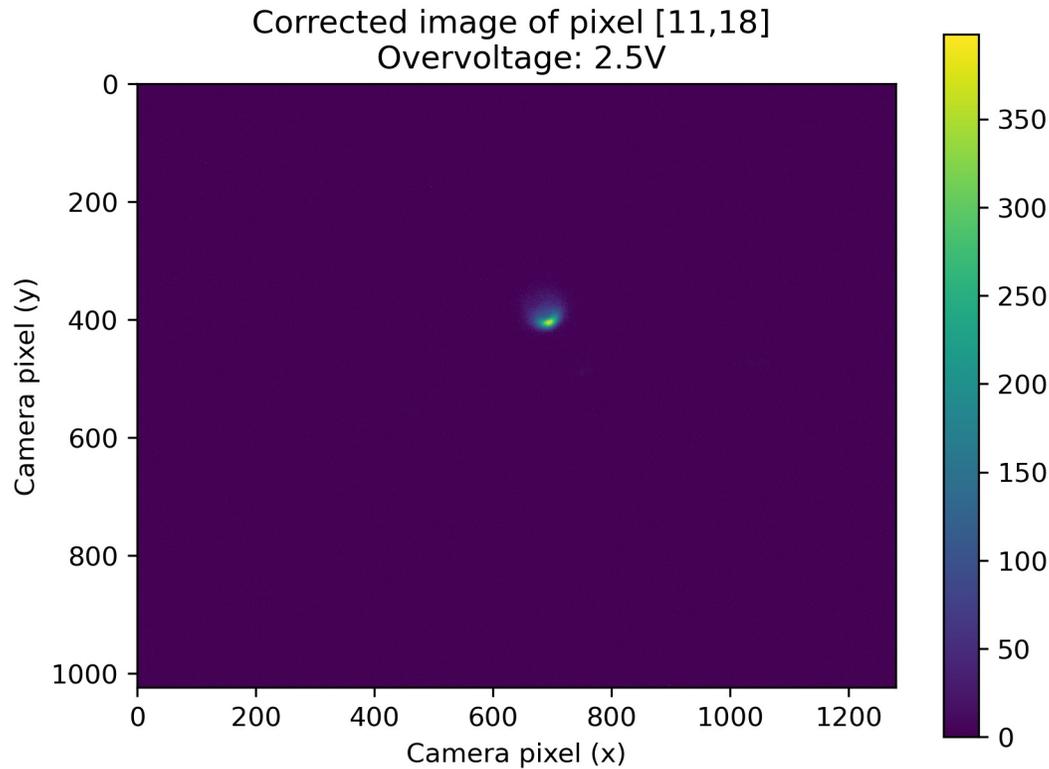
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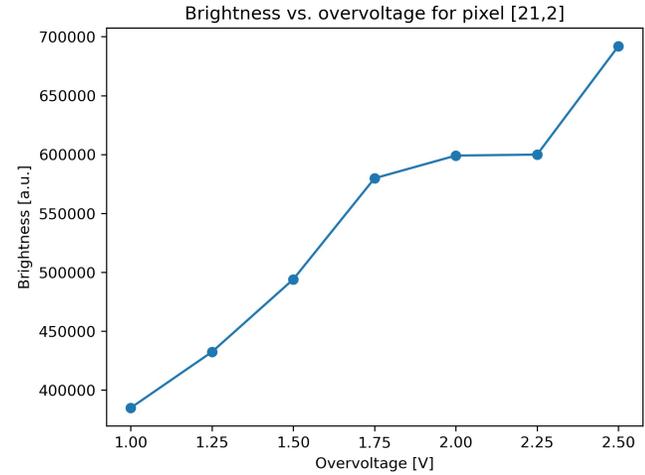
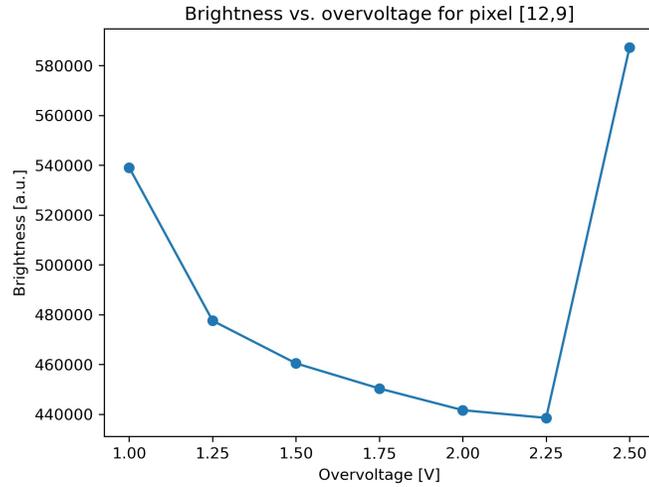
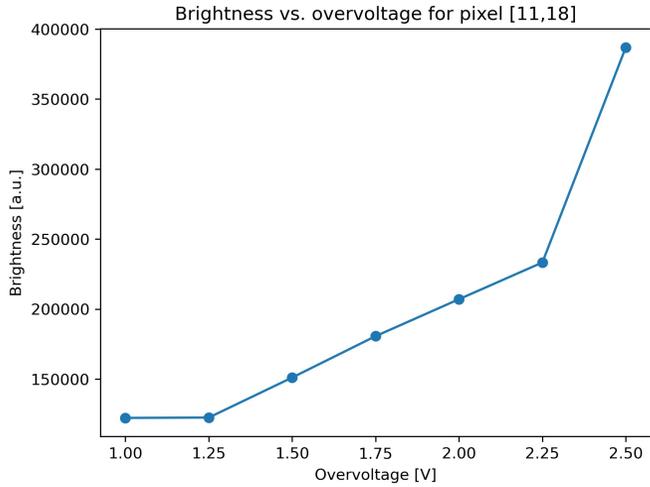


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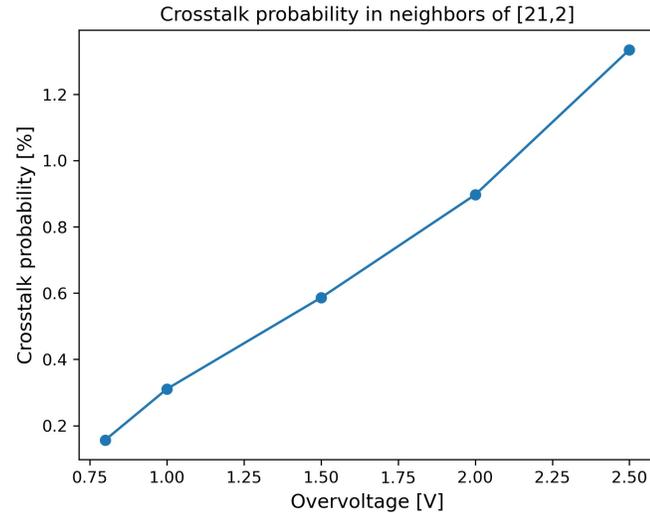
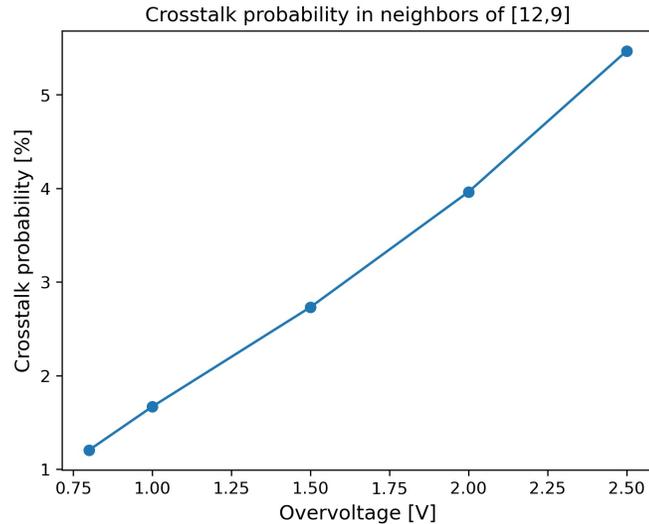
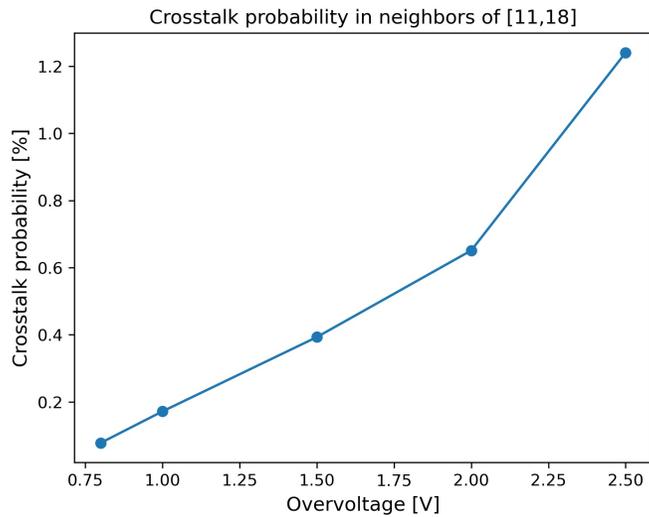
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Results

Quantitative data

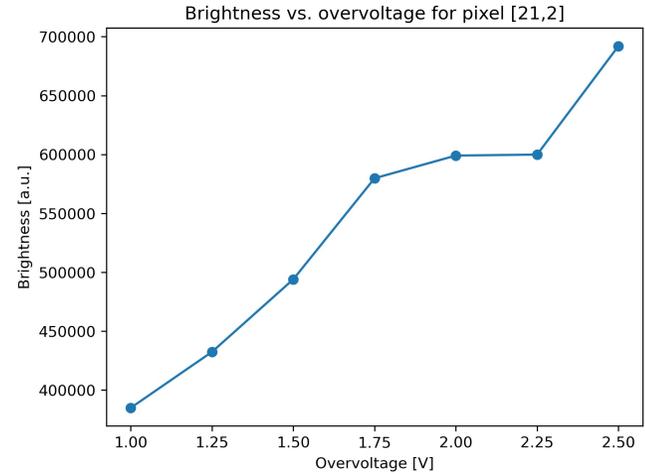
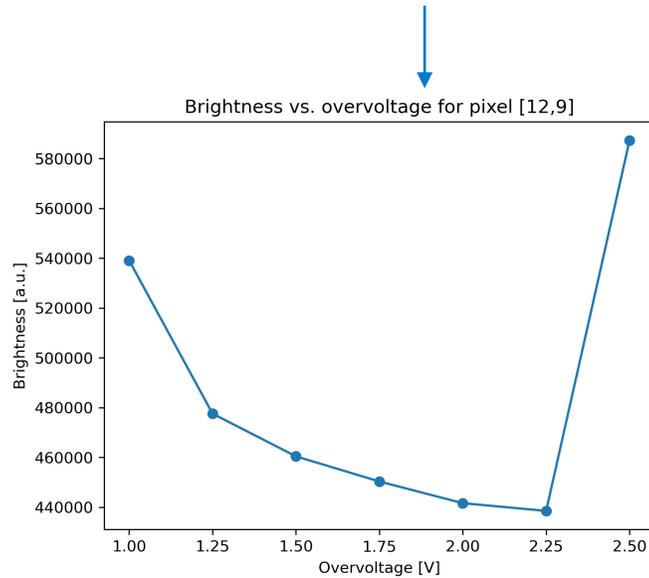
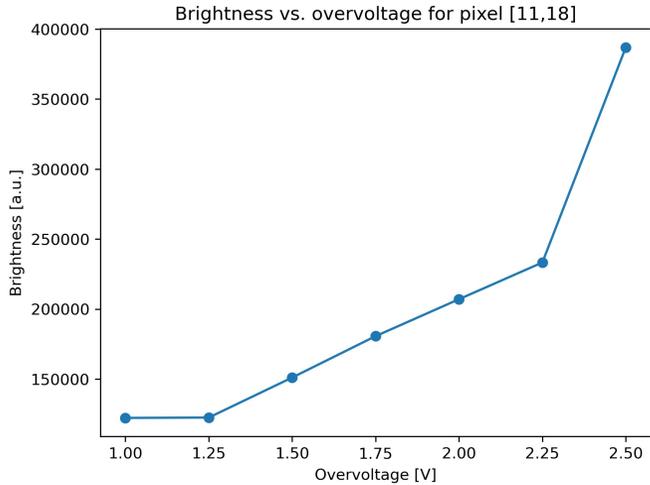


[11,18], [21,2]:
Quantitative data
confirms correlation
between brightness
(amount of
secondary photons)
and CT

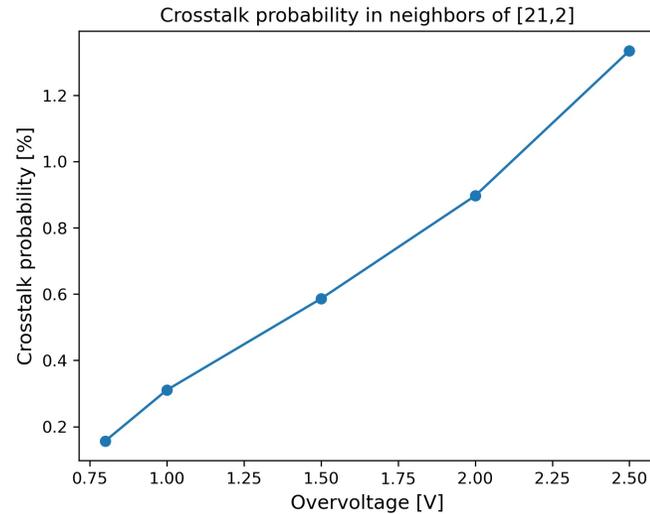
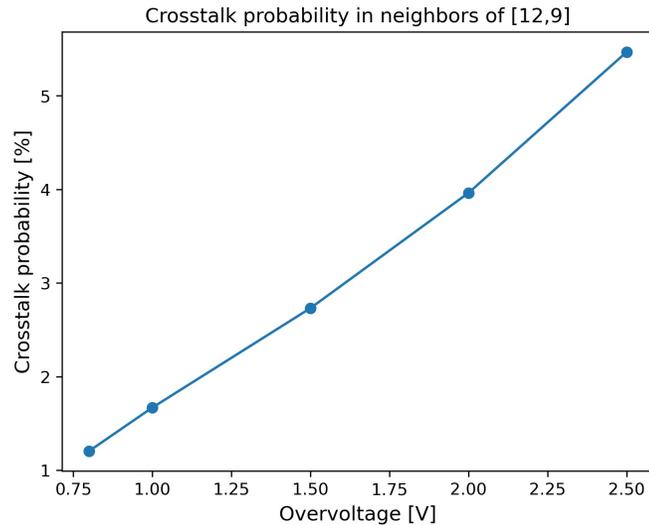
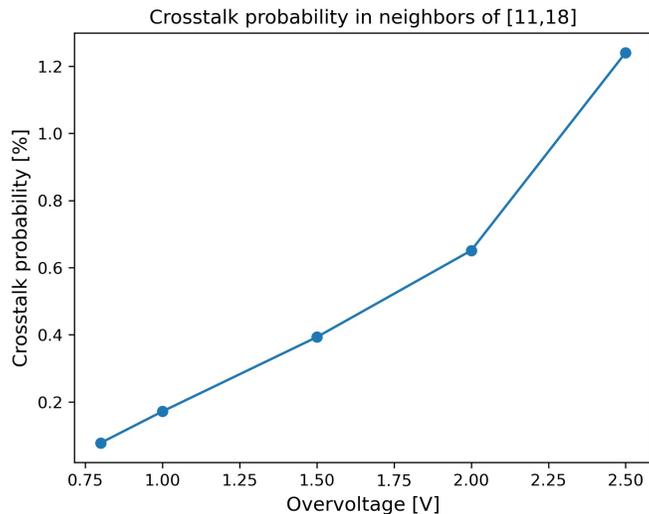


Results

Quantitative data



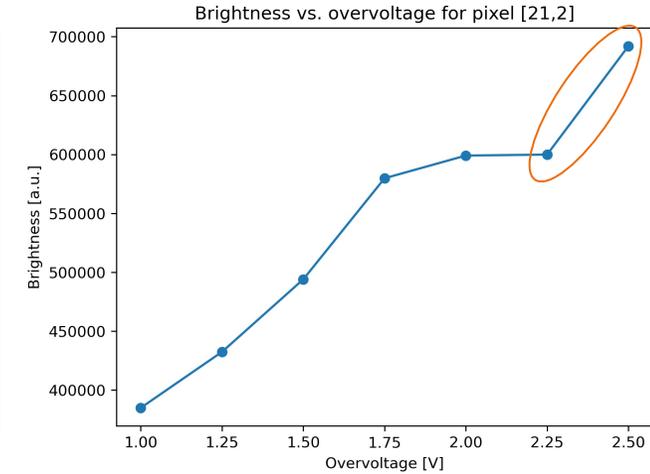
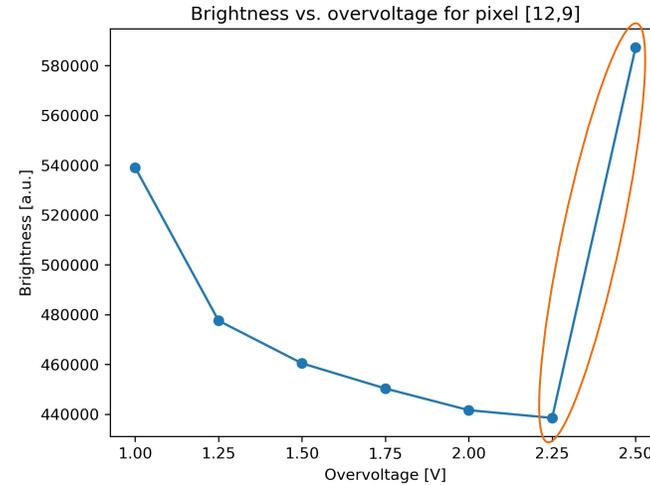
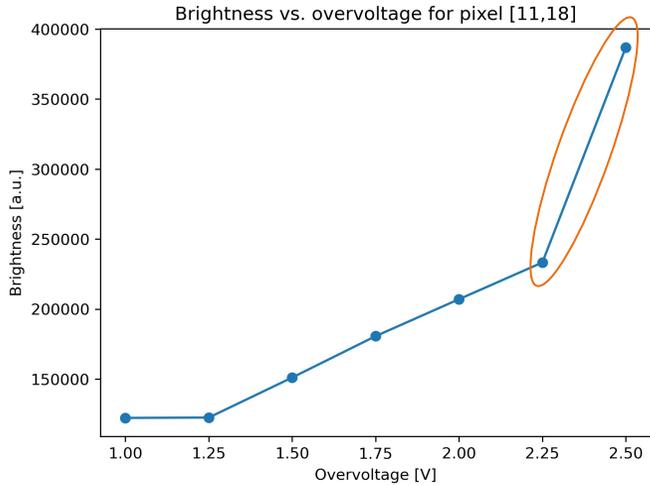
[12,9]: Decrease in brightness due to overcorrection → SPAD is too noisy, delay time should be increased



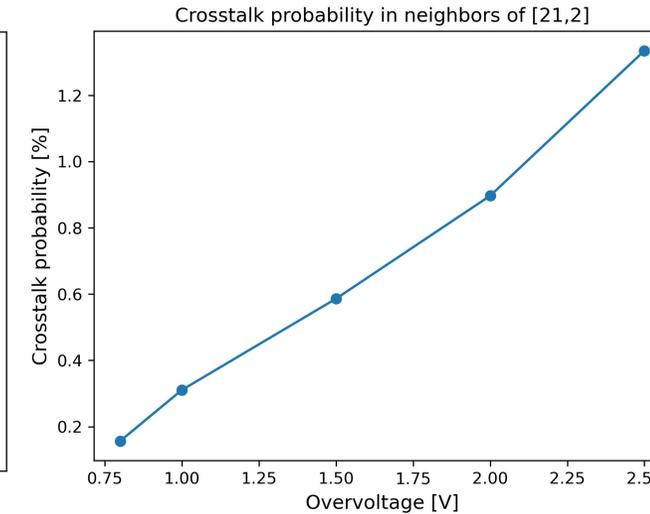
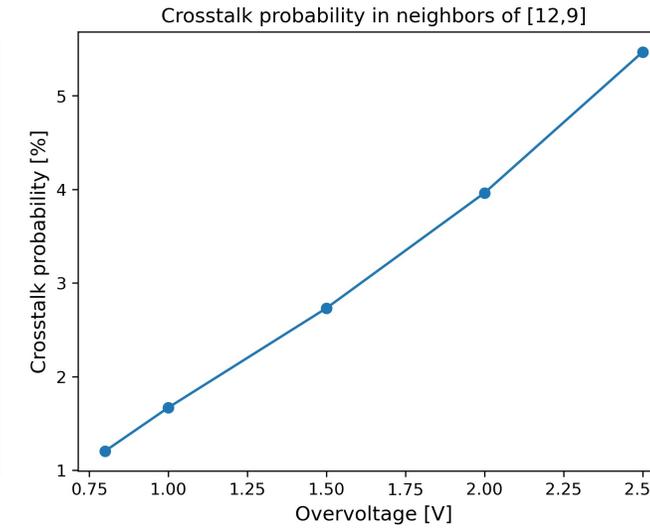
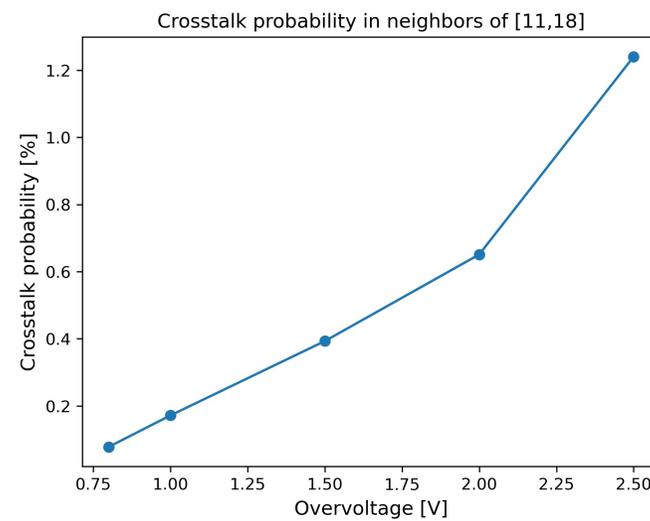
CT also only qualitatively correct

Results

Quantitative data



Sudden increase in brightness at higher OV → no explanation yet, should check what is going on at even higher OVs



Conclusion and outlook

- The new NIR camera is well suited to detect the secondary photons
- We can determine the noisy SPAD in the pixel by looking at the CT probabilities to neighbors
- Quantitative data confirms correlatoin between brightness and CT

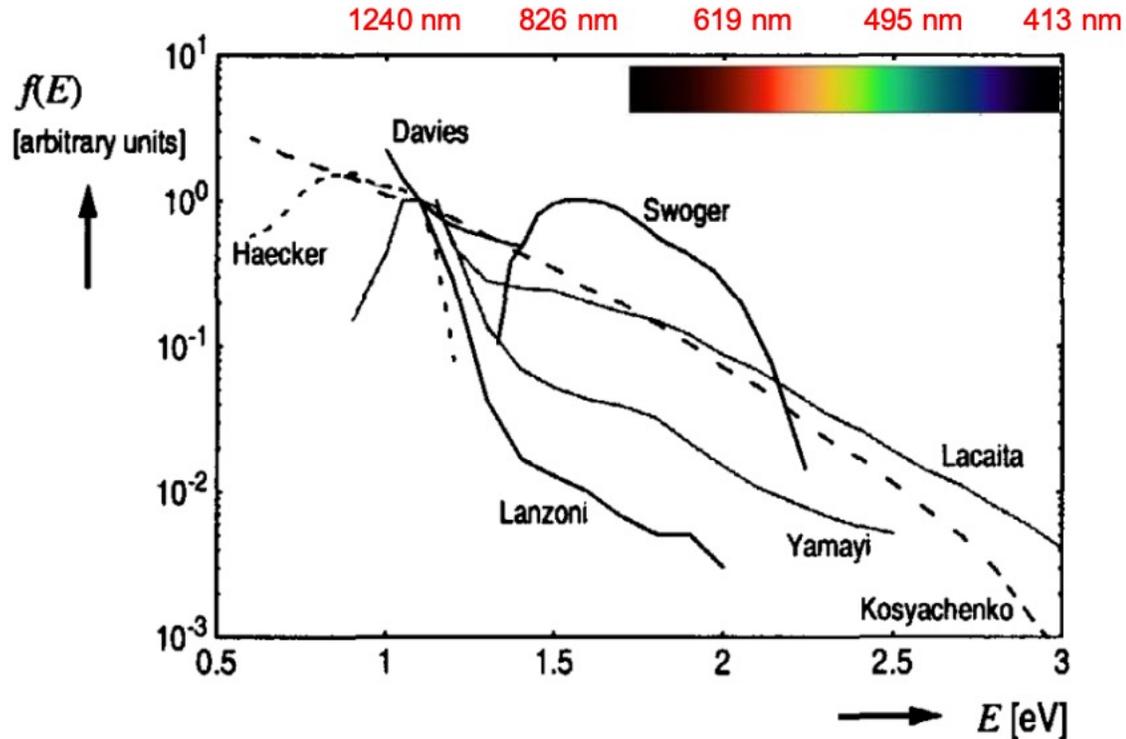
- A lot of systematics, not yet all under control (heating → lose focus?)
- Have to watch out for very noisy SPADs (both in CT calculation and emission measurements)
- No good understanding of how the brightness depends on the OV

- What happens at even higher OVs?
- Investigate systematics
- Investigate characteristics of the camera

Thank you! Questions?

Back-up slides

Secondary photon emission in avalanche process



@ Gianpiero for conversion into wavelengths

https://repository.tudelft.nl/file/File_1833dbea-790d-4846-aeff-41b19ad2dd69?preview=1 W.J Kindt PhD thesis:
Geiger Mode Avalanche Photodiode Arrays

Definition of the crosstalk probability

$$p_c = \frac{N_c}{N},$$

$$p_n = \frac{N_n}{N}.$$

$$p_{c \wedge n} = \frac{N_{c \wedge n}}{N}$$

$$p_x = \frac{p_{c \wedge n} - p_c p_n}{p_c(1 - p_n)};$$

The NIR camera

CS135MUN - Kiralux 1.3 MP NIR-Enhanced CMOS Camera, USB 3.0 Interface

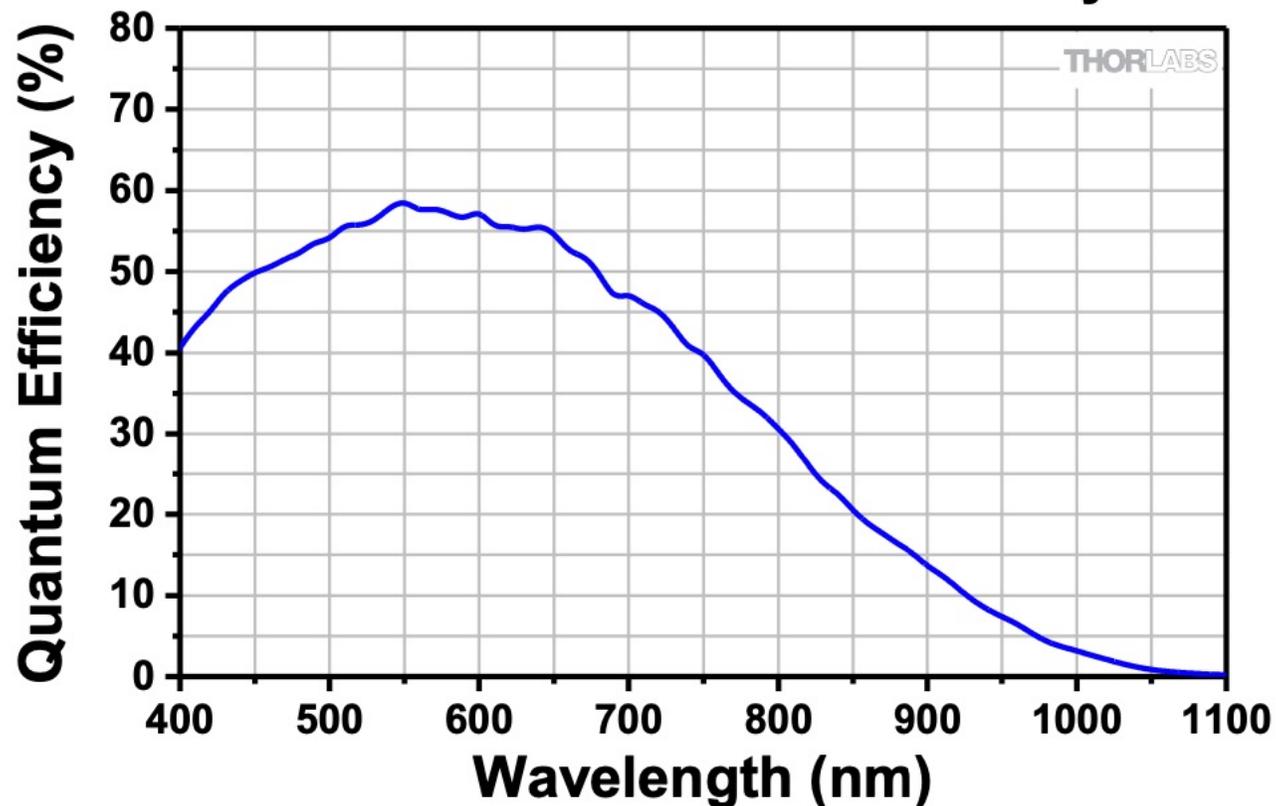


Zoom

Part Number: CS135MUN - [Ask a technical question](#)
 Package Weight: 0.73 kg / EACH
 Available: 7-10 Days
 RoHS: **RoHS Exempt**
 Price: **1.728,51 €**
 Add To Cart: Qty:
 Release Date: 27.03.2020

Item #	CS135MU	CS135CU	CS135MUN
Sensor Type	Monochrome CMOS	Color CMOS	NIR-Enhanced CMOS
Effective Number of Pixels	1280 x 1024 (H x V)		
Imaging Area	6.144 mm x 4.915 mm (H x V)		
Pixel Size	4.8 μm x 4.8 μm		
Optical Format ^a	1/2" (7.76 mm Diagonal)		
Max Frame Rate	165.5 fps (Full Sensor)		
ADC ^b Resolution	10 Bits		
Sensor Shutter Type	Global		
Read Noise	<7.0 e ⁻ RMS		
Full Well Capacity	≥10 000 e ⁻		
Exposure Time	0.100 ms to 59269 ms in 0.001 ms Increments		
Vertical and Horizontal Digital Binning ^c	1 x 1 to 5 x 5		
Region of Interest (ROI)	16 x 2 Pixels ^d to 1280 x 1024 Pixels, Rectangular		
Dynamic Range	>60 dB		

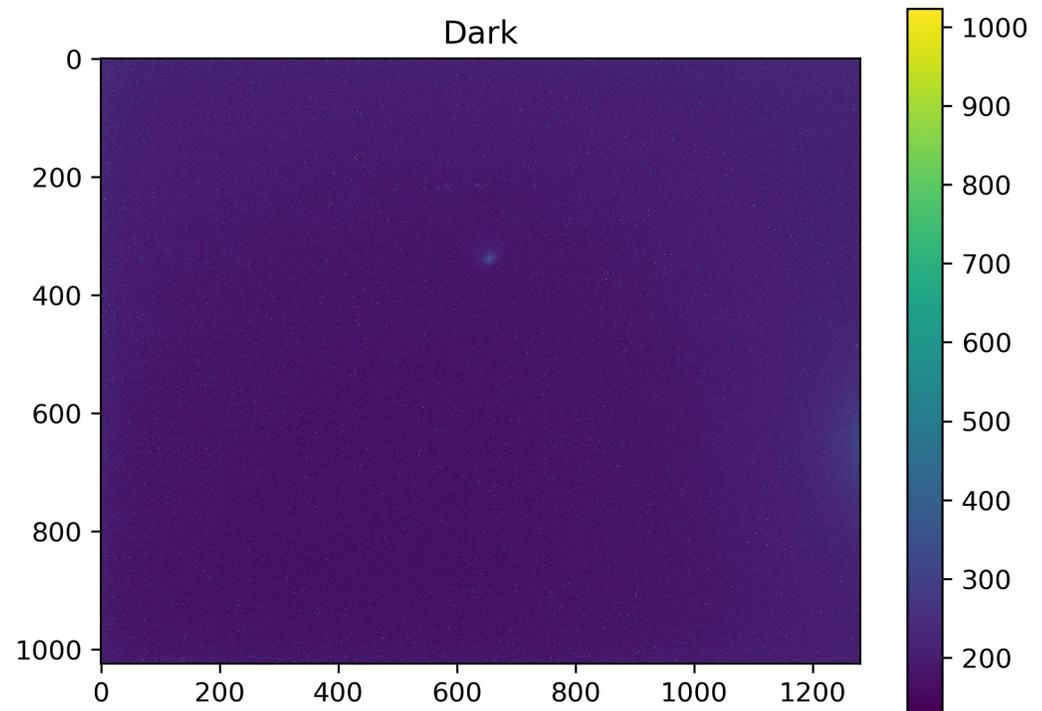
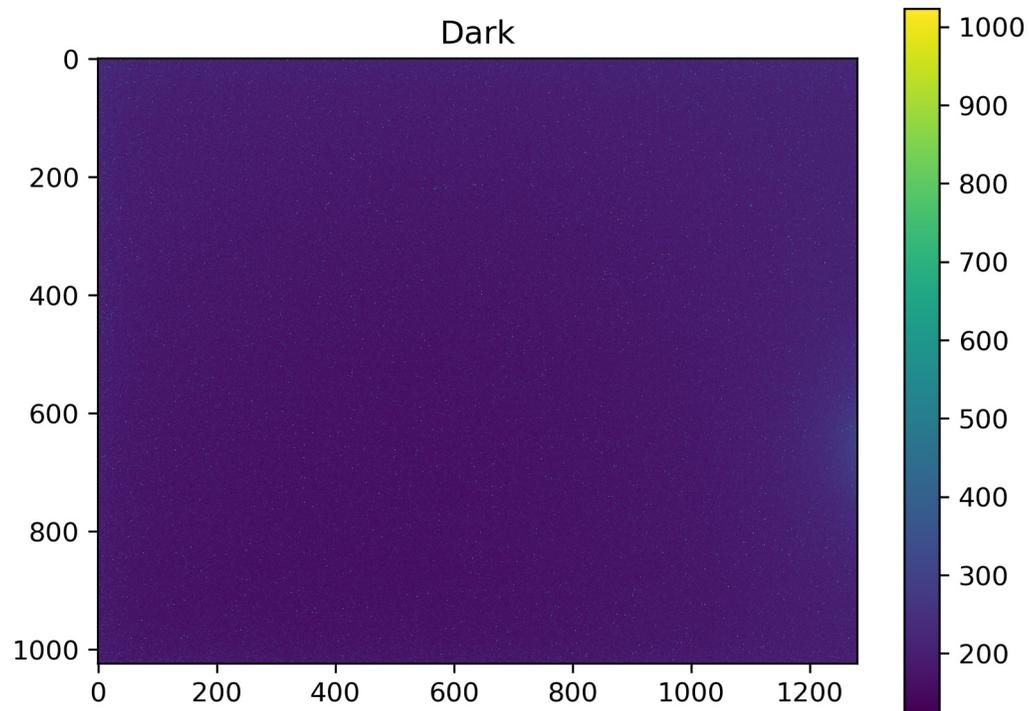
CS135MU Quantum Efficiency



<https://www.thorlabs.com/thorproduct.cfm?partnumber=CS135MUN>

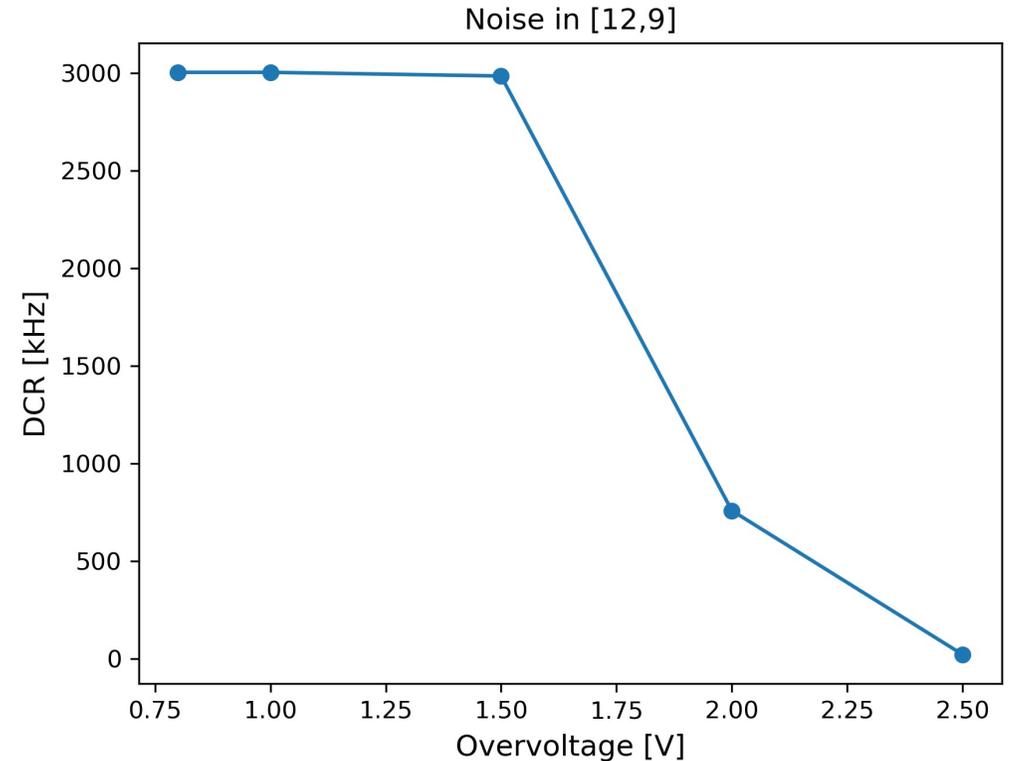
Overcorrection problem with too noisy SPADs (see pix [21,9])

- Difference between first and second dark frame
 - First only camera effects
 - Second still some afterglow → overcorrecting



Too noisy pixels (see pix [21,9]) → problem in DCs & CT

- CT calculation assumes only one hit per frame
- If too noisy → multiple hits per frame, but only measure when current crosses a certain threshold, if it just stays above (as the case is for multiple hits happening fast after each other) this is counted as one hit → DCR decreases and CT probability is overestimated in too noisy pixels



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