MICRO-428: Metrology

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EPFL

Introduction

- 14 weeks @3h/week, 3 credits, Mon 9-12
  - "Office hours" *upon (email) request*
- The course deals with the concept of measuring in different domains, particularly in the electrical, optical, and microscale domains.
- The course will include a perspective on quantum measurements.
- Exercise sessions: series of 2-3 problems. We will discuss some of them and hand in the solutions of the remaining ones in the following session.
  - Ungraded homework, final graded *written* exam
  - Presence strongly encouraged
- Use of Matlab

Topics

- Introduction class (today)
- Classical metrology
- Basic statistics
- Electrical metrology
- Optical microscopy
- Optical imaging
- Electron Microscopy
- Atomic Force Microscopy
- Quantum metrology

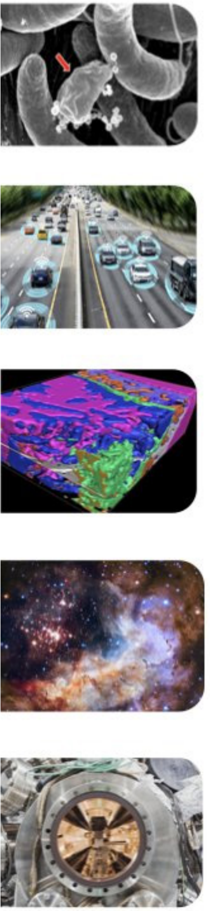
Course Structure

- Optical Metrology *(Weeks 2-4)*
  - Optical Image Sensors
  - SPADs
  - Microscopy
- Nanoscale *(Weeks 5-7)*
  - AFM
  - SEM
  - Nanomag.
- Probability and Statistics *(Weeks 8-9)*
  - Theory & Practical Examples
- Electrical Metrology *(Weeks 10-12)*
  - Noise
  - ADCs (amplitude)
  - TDC (time)
- Quantum *(Weeks 13-14)*
  - Quantum SI
  - Quantum Applications
  - Supercond.

The Minor in Imaging

Open to all EPFL students

Broaden your career horizon



- **Transversal & interdisciplinary** program
- Covers **theoretical and practical aspects** in imaging
- Useful in **industry and academic world**

Requirements

- **Mathematics**
  Linear algebra & analysis
- **Basis of programmation**
  One language
- **Basis of physics**
  Optics

Minor (30 ECTS):

- 22 ECTS of courses
- 8 ECTS for a project

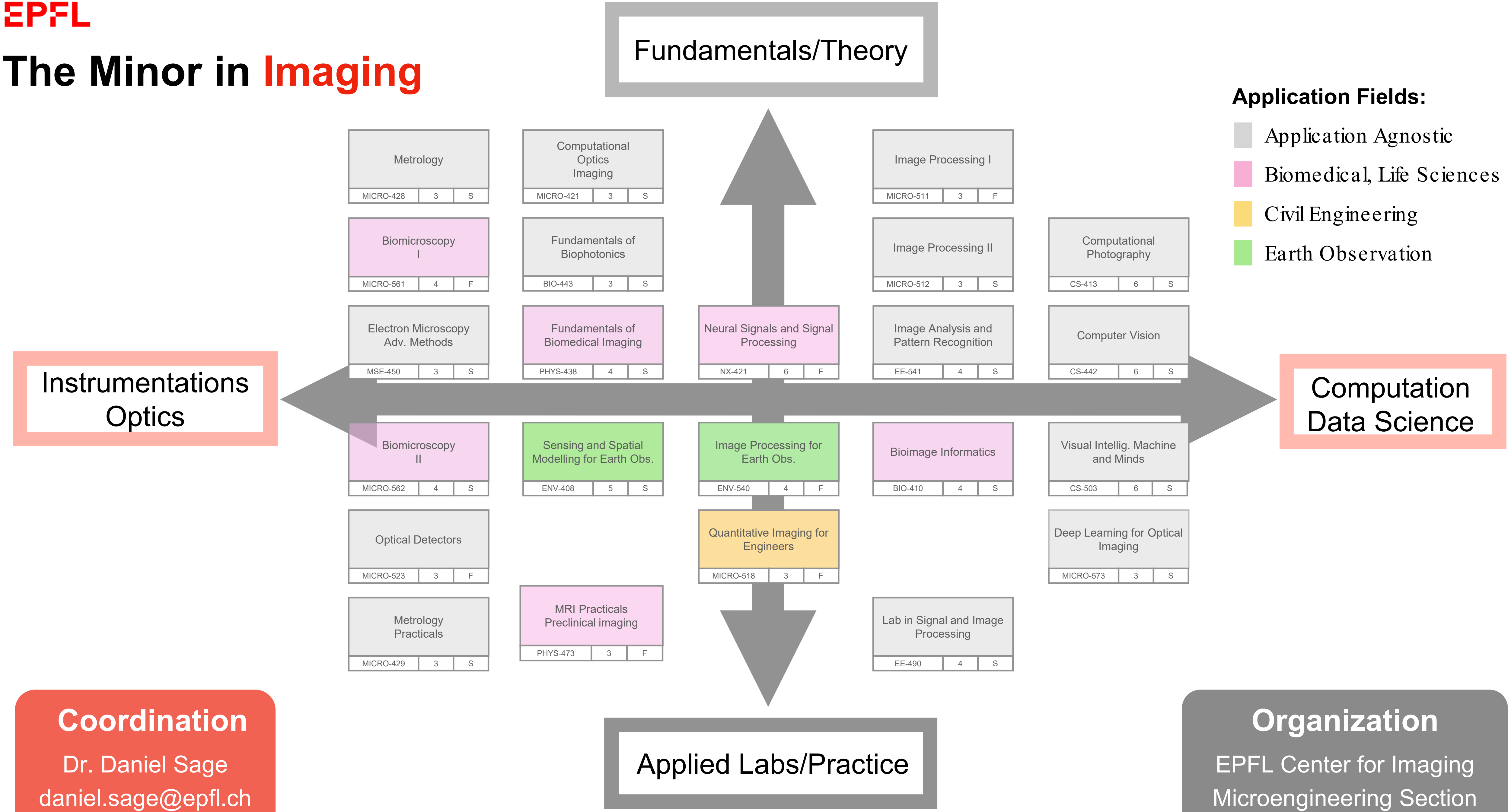
Info: imaging.epfl.ch/education

EPFL

The Minor in **Imaging**

Application Fields:

- ⬜ Application Agnostic
- 🟪 Biomedical, Life Sciences
- 🟨 Civil Engineering
- 🟩 Earth Observation



Fundamentals/Theory

Instrumentations Optics

Computation Data Science

Applied Labs/Practice

⬜	Metrology	MICRO-428	3	S
⬜	Computational Optics Imaging	MICRO-421	3	S
⬜	Image Processing I	MICRO-511	3	F
🟪	Biomicroscopy I	MICRO-561	4	F
⬜	Fundamentals of Biophotonics	BIO-443	3	S
⬜	Image Processing II	MICRO-512	3	S
⬜	Computational Photography	CS-413	6	S
⬜	Electron Microscopy Adv. Methods	MSE-450	3	S
🟪	Fundamentals of Biomedical Imaging	PHYS-438	4	S
🟪	Neural Signals and Signal Processing	NX-421	6	F
⬜	Image Analysis and Pattern Recognition	EE-541	4	S
⬜	Computer Vision	CS-442	6	S
🟪	Biomicroscopy II	MICRO-562	4	S
🟩	Sensing and Spatial Modelling for Earth Obs.	ENV-408	5	S
🟩	Image Processing for Earth Obs.	ENV-540	4	F
🟪	Bioimage Informatics	BIO-410	4	S
⬜	Visual Intellig. Machine and Minds	CS-503	6	S
⬜	Optical Detectors	MICRO-523	3	F
🟨	Quantitative Imaging for Engineers	MICRO-518	3	F
⬜	Deep Learning for Optical Imaging	MICRO-573	3	S
⬜	Metrology Practicals	MICRO-429	3	S
🟪	MRI Practicals Preclinical imaging	PHYS-473	3	F
⬜	Lab in Signal and Image Processing	EE-490	4	S

Coordination

Dr. Daniel Sage
daniel.sage@epfl.ch

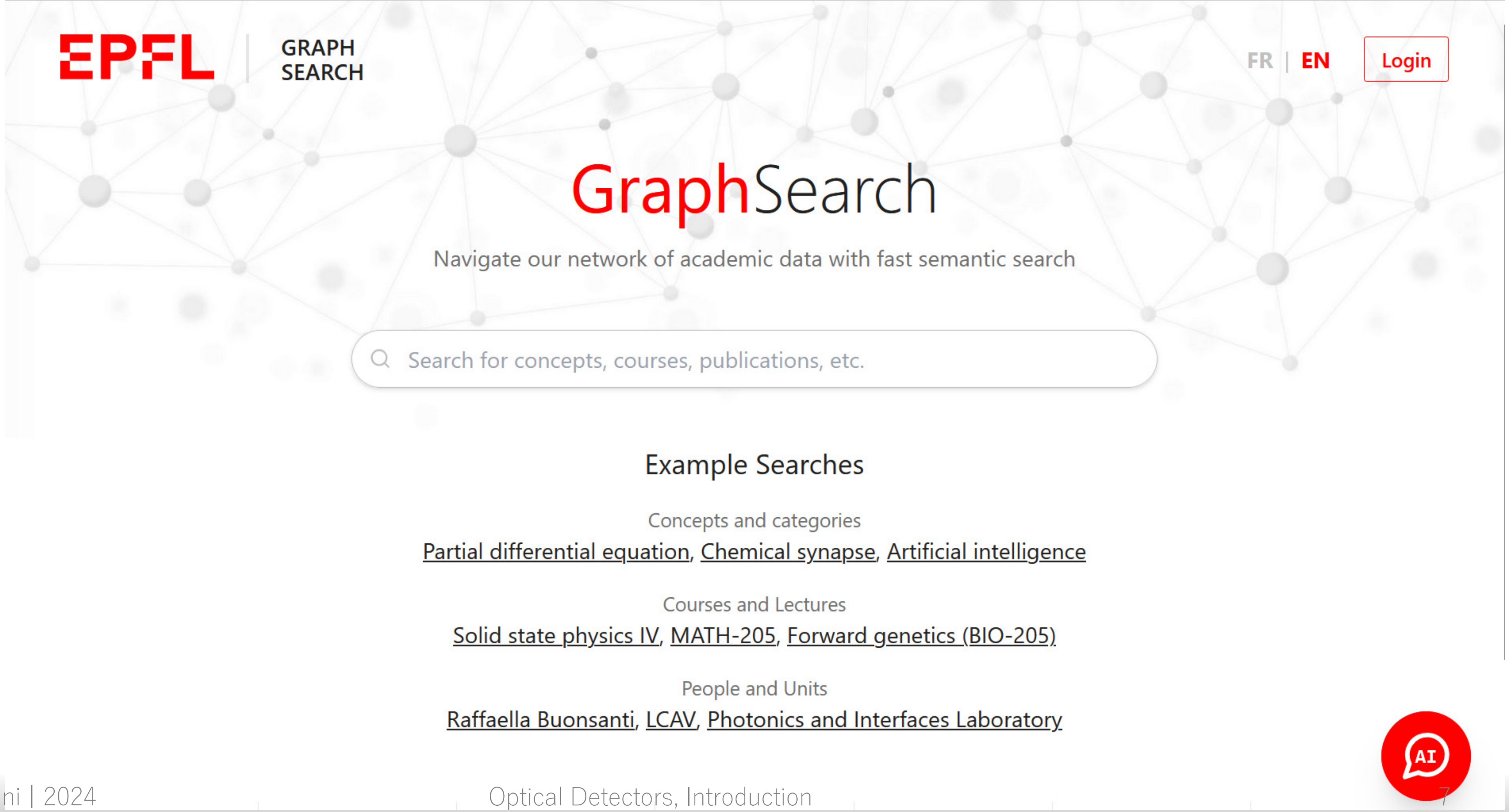
Organization

EPFL Center for Imaging
Microengineering Section

Info: imaging.epfl.ch/education

EPFL Tool: GraphSearch - https://graphsearch.epfl.ch

Cet outil permet d’explorer l’ensemble des contenus en ligne de l’EPFL (40’000 heures de vidéo, livrets de cours, publications, laboratoires, personnes, startups, news, etc...) ainsi que d’interagir avec un chatbot “maison”.



GraphSearch

Navigate our network of academic data with fast semantic search

Example Searches

Concepts and categories

Partial differential equation, Chemical synapse, Artificial intelligence

Courses and Lectures

Solid state physics IV, MATH-205, Forward genetics (BIO-205)

People and Units

Raffaella Buonsanti, LCAV, Photonics and Interfaces Laboratory

MICRO-429: Metrology Practicals

Edoardo Charbon, Claudio Bruschini, Georg Fantner

Institute of Electrical and Micro Engineering (IEM), School of Engineering (STI)

Ecole polytechnique fédérale de Lausanne (EPFL), Neuchâtel, Switzerland

TAs: Yang Lin, Prabhleen Singh, Marcos Penedo & LBNI TAs (2023@AQUA: Utku Karaca, Ekin Kizilkan)

Introduction

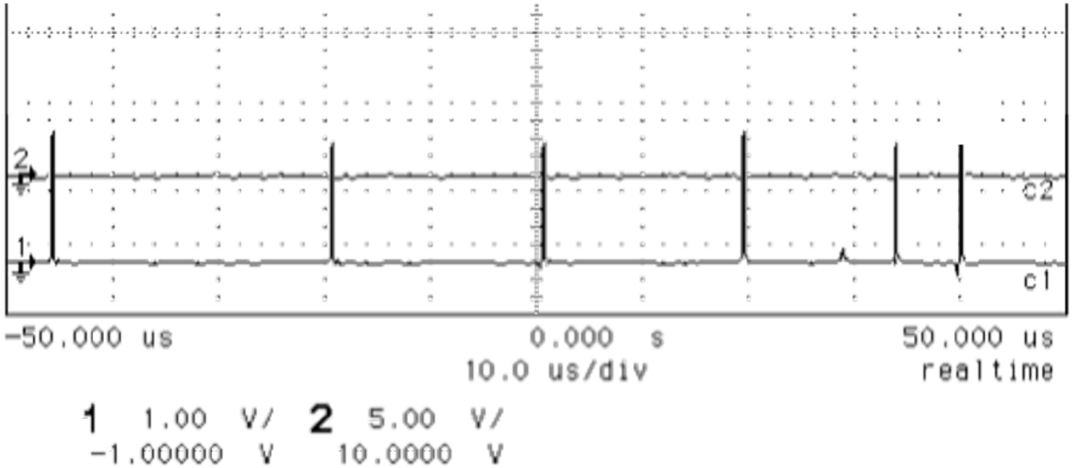
- 6 weeks @4-5h/week (+1x Intro +1x preparation), 3 credits, Tue 13-17/18
  - ➢ There will **not** be a Zoom link, due to the experimental nature of the course:
  - ➢ There will not be “Office hours”. Please make sure you ask all your questions during the practical.
- This course is intended as the experimental addition to MICRO-428 (Metrology).
- The students will have a chance to practice the theoretical concepts they learnt there.
- They will also learn good practices during measurements, while designing the experiments required for specific measurements.
- The course will propose 6 experiments in time slots of 4-5 hours in the second part of the semester.
- Learning outcome: become familiar with the measurement techniques and theory learnt in MICRO-428. The students will have the opportunity to work with real instruments and keep a lab notebook.

Topics

- Quantum metrology
  - Single-photon experiments
  - Correlated / uncorrelated noise
  - Time-resolved experiments
- AFM
- SEM

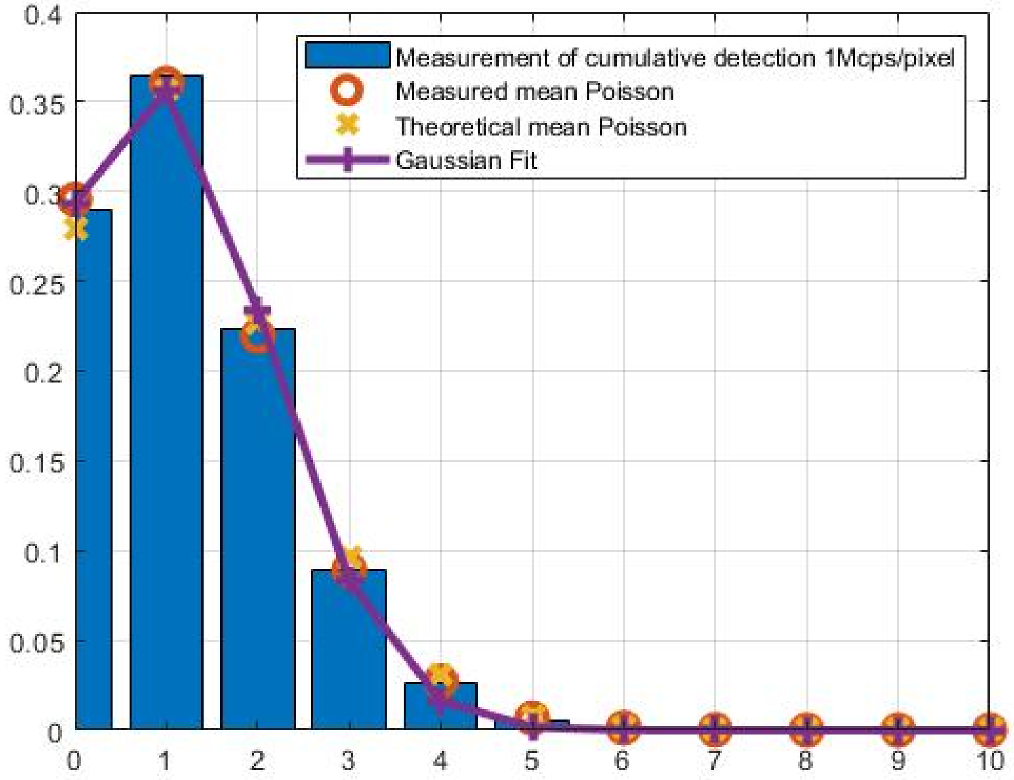
Content/1

- [T1] Dark count rate (DCR) and afterpulsing statistics in photon-counting devices
    - Understanding single-photon avalanche diodes (SPADs) & photon counting
    - DCR vs. excess bias voltage
    - Inter-arrival statistics, dead time, and afterpulsing
    - (Temperature dependency)



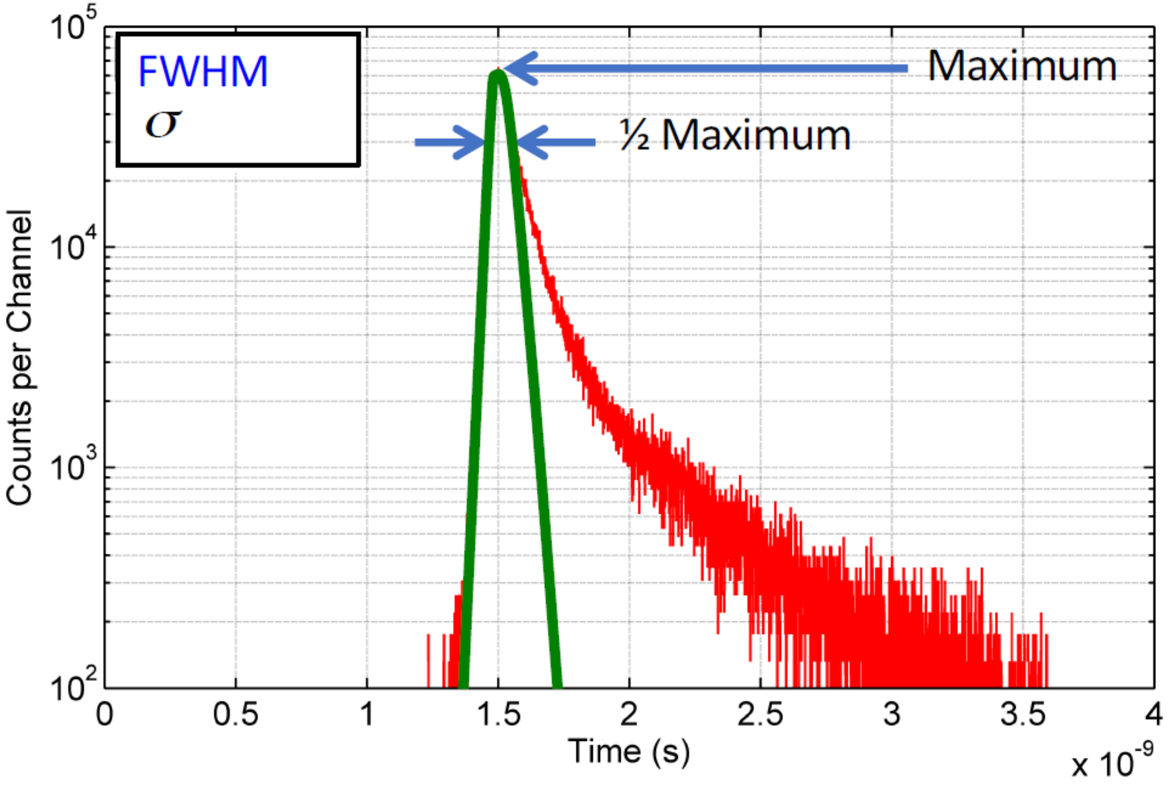
Content/2

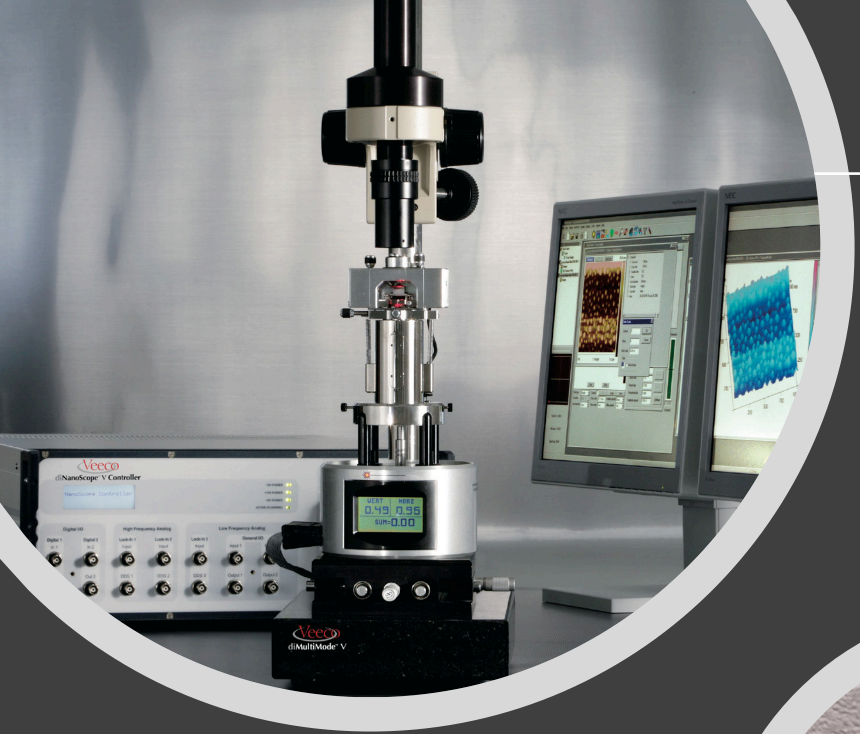
- [T2] Sensitivity in photon-counting devices
  - Photon detection probability (PDP) and efficiency (PDE)
  - Poisson nature of photons, “hand diagram”
  - Photo-response non-uniformity (PRNU)

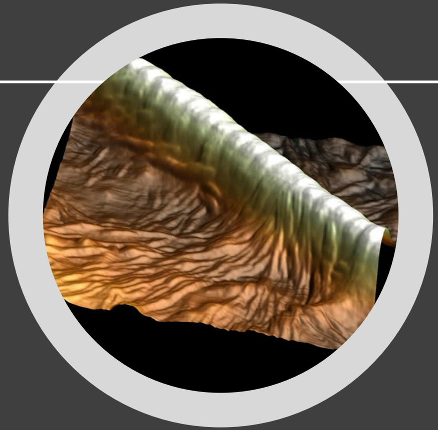


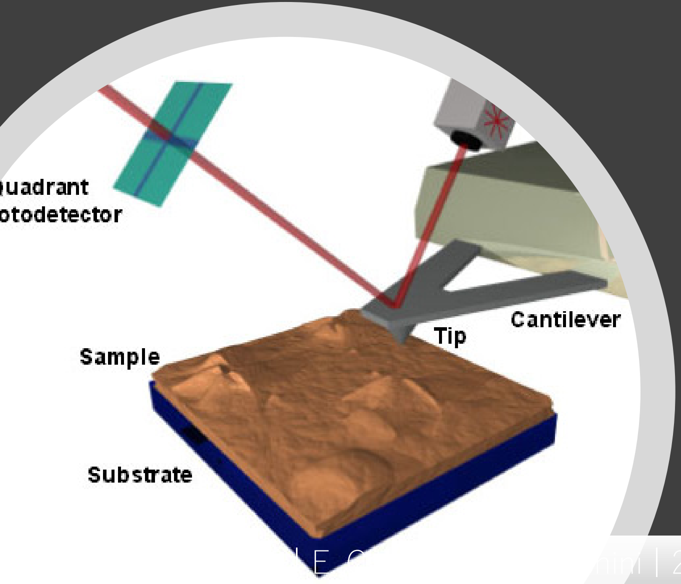
Content/3

- [T3] Timing jitter measurements in single-photon detectors
  - Time-correlated single-photon counting (TCSPC)
  - Single-photon timing resolution (SPTR)
  - Pile-up effect







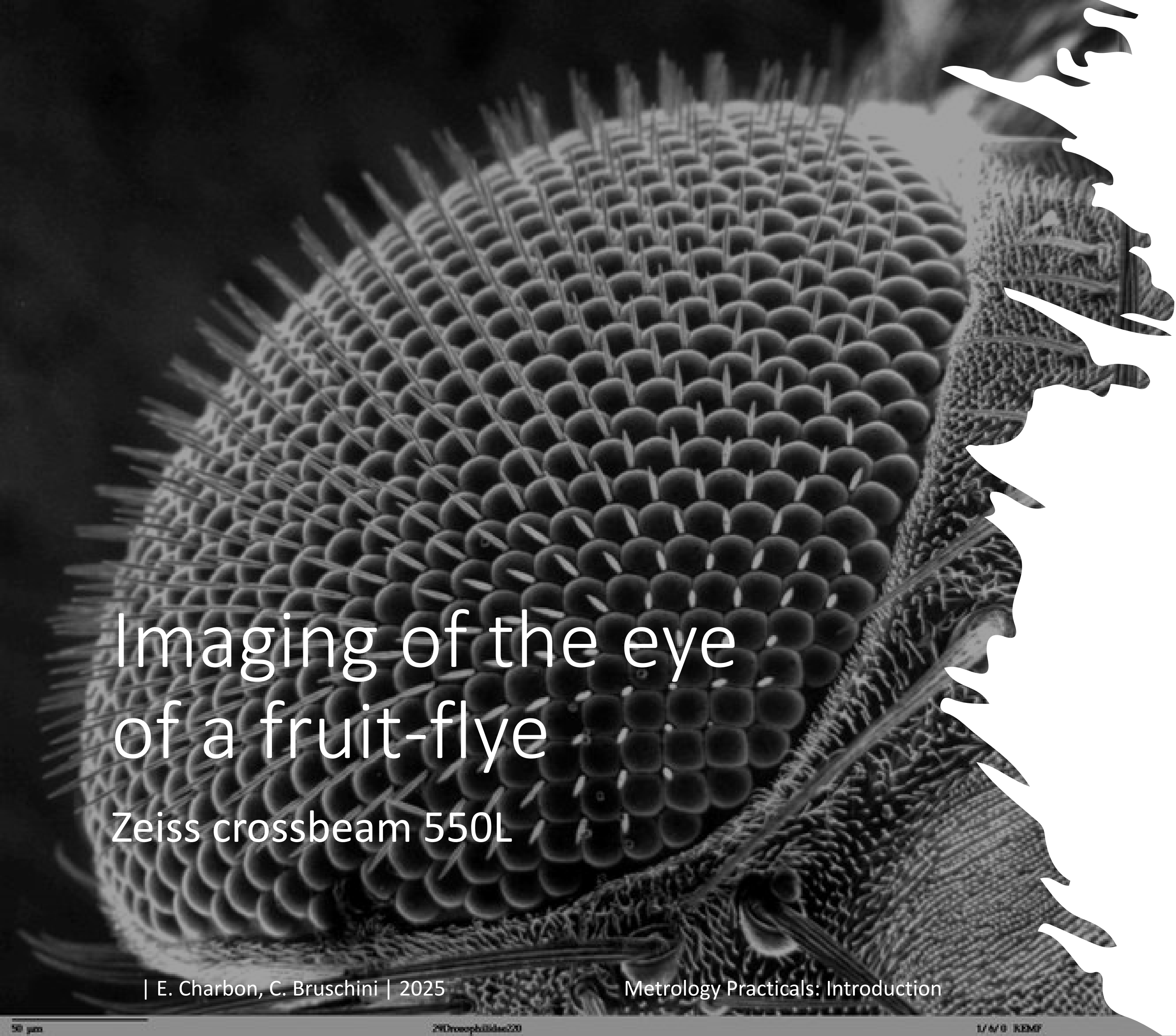


AFM a Versatile Tool for Nanoscale Measurements

- Things you will learn:
  - Make surface topography images with sub nanometer resolution
  - Nanoscale imaging of E.coli.
  - Extract tendons from rat tails, image microfibrils of collagen and measure the characteristic D-banding structure of collagen fibrils
  - How to process and analyze AFM data

Electron Microscopy

- Learn how to prepare samples for SEM use (drying, conductive coating)
- Learn to operate the top-of-the-line SEM from Zeiss:
  - Focus
  - Astigmatism
  - Saturation and contrast
  - Elemental analysis (EDX spectroscopy)
- Data processing:
  - Image interpretation
  - Effect of acceleration voltage
  - resolution



Imaging of the eye of a fruit-flye

Zeiss crossbeam 550L

Course Structure

- W1 – kickoff class (today): explain exercises, form groups, intro to lab notebook keeping, reminder intro to Matlab, reminder laser safety training
- W2: 2024 version of hand-outs of lab material available for ALL modules (T1-T6)
- W6 (Mar. 24) – W7 (Mar. 31): revised hand-outs as needed and preparation class (TBC)
- W8 (Apr. 07) – W13 (May 19) (every W): N groups of 2 students will go through all 6 modules (T1-T6)
- Students will get a grade on each module (1 point max per module). The final grade is going to be the sum of the individual grades.
- Quantum Metrology (photonics): each group will need to prepare Matlab code pieces in advance, using practice data where appropriate. Typical tasks: data input, understand data structure, fitting, plotting.
- Nanoscale Metrology: each group will have an entry quiz (multiple choice questions), so as to verify that they understood the material beforehand, while their lab notebook will be examined at the end of each module.

If they fail the Matlab code preparation or quiz, they will still be able to go through the module, but will get only 0.5-0.75 points in total if they succeed.

Group Study

Date	**Apr. 07**	**Apr. 14**	**Apr. 28**	**May 5**	**May 12**	**May 19**
Week	W8	W9	W10	W11	W12	W13
G1	T1	T2	T3	T4	T5	T6
G2	T2	T3	T1	T5	T6	T4
G3	T3	T1	T2	T6	T4	T5
G4	T4	T5	T6	T1	T2	T3
G5	T5	T6	T4	T2	T3	T1
G6	T6	T4	T5	T3	T1	T2

Example – G1-G6 = Groups, T1 – T6 = Modules, W7 – W12 = Weeks

Example – Task 1

Dark count rate (DCR) and afterpulsing statistics in photon-counting devices

Objective:

- Understanding single-photon avalanche diodes (SPADs) & photon counting
- DCR vs. excess bias voltage
- Inter-arrival statistics, dead time, and afterpulsing
- (Temperature dependency)

Reading:

- Read reference [1] for general understanding of SPAD technology
- Read week 8 lecture notes – Introduction to single-photon detection

Setup:

- 1 Voltage supply
- 1 SPAD23$^{\mathrm{TM}}$ detection unit
- (1 oscilloscope)

Example – Task 1

Dark count rate (DCR) and afterpulsing statistics in photon-counting devices

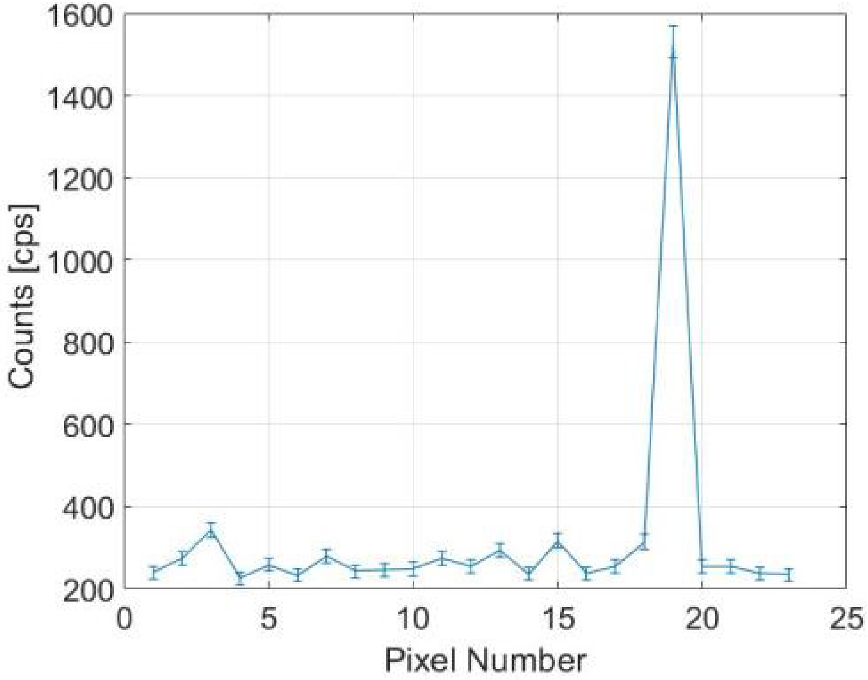
Methodology:

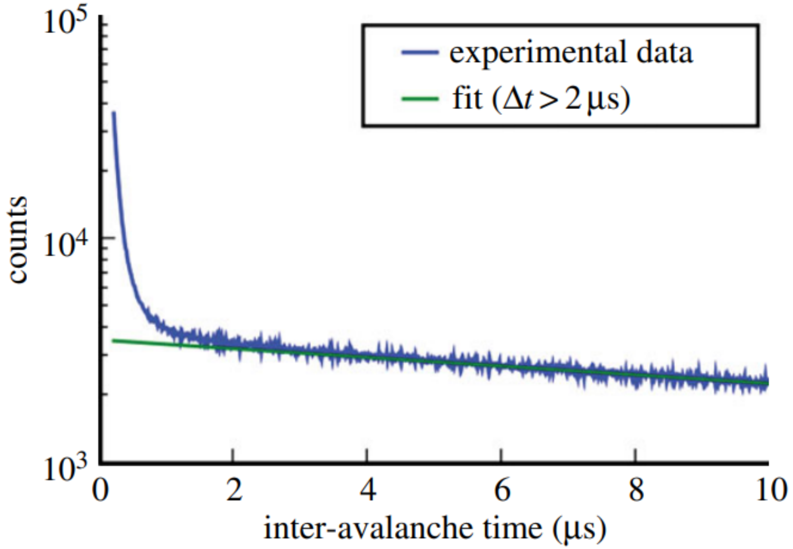
- Connect the SPADs to the power and observe the pulses generated by the device when exposed to light.
- Test the built-in oscilloscope and compare the curves with the external oscilloscope.
- Use the counter option and measure DCR vs. Excess bias.
- Repeat with the other SPADs at one configuration (VEX=3V) and compute median and mean DCR. Which one is higher? Why?
- Set up the detection unit to extract inter-arrival times.
- Construct the histogram and compute dead time and afterpulsing with VEX=3V.
- Document your findings on the Lab Notebook along the way.

[1] E. Charbon, “Single-photon imaging in complementary metal oxide semiconductor processes”, Phil. Trans. Royal Society, 28 March 2014. DOI: 10.1098/rsta.2013.0100.

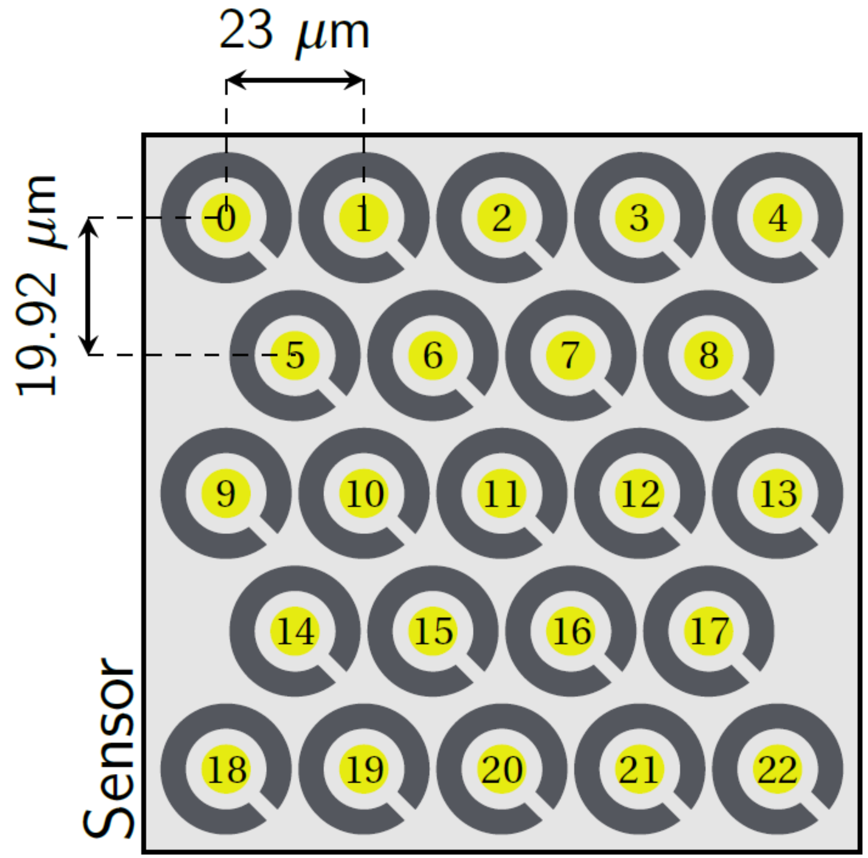
Example – Task 1

Dark count rate (DCR) and afterpulsing statistics in photon-counting devices

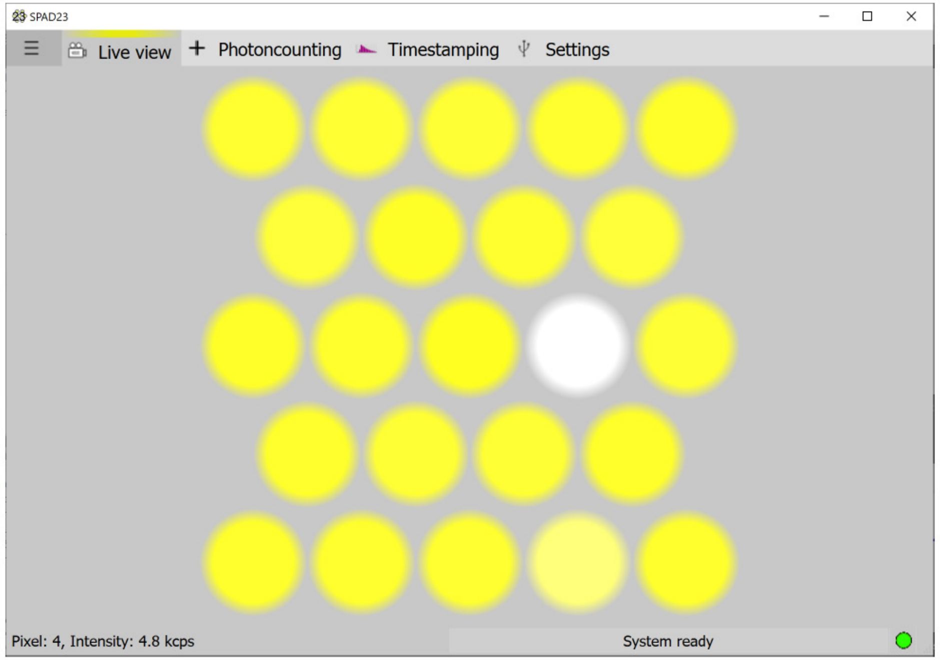




Key Instrumentation – SPAD23 single-photon sensor



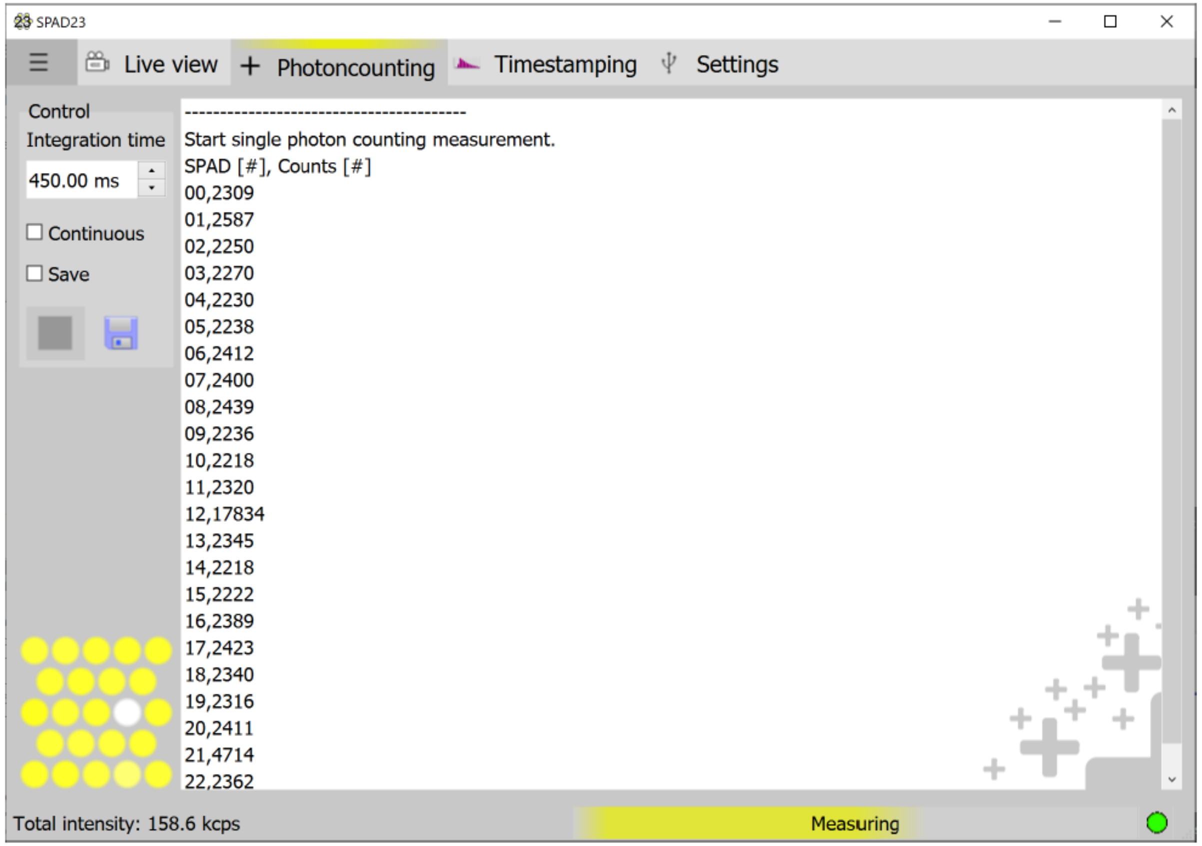
SPAD23: photon-counting



Pixel: 4, Intensity: 4.8 kcps

System ready

Photoncounting



Integration time: 450.00 ms

☐ Continuous

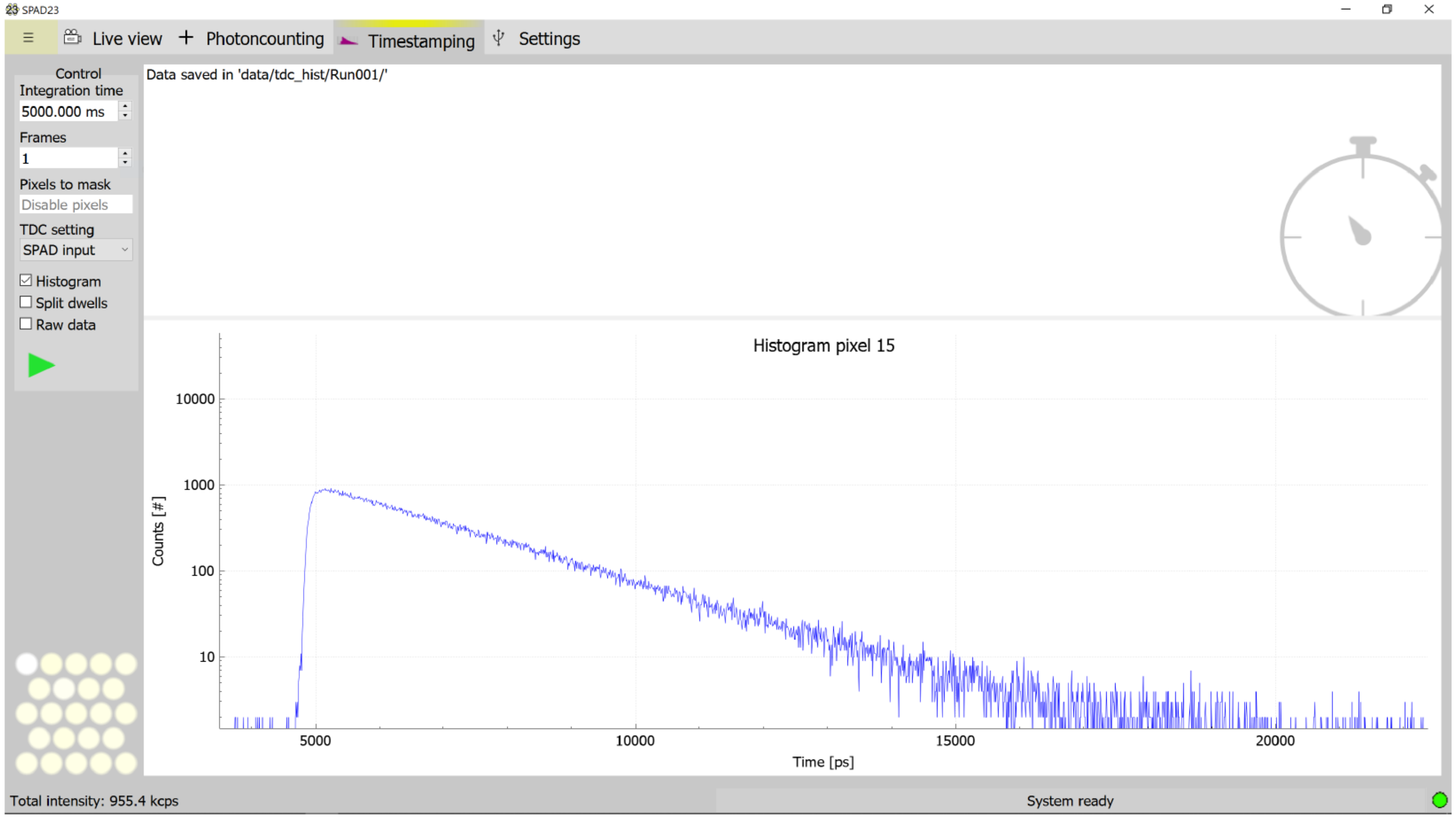
☐ Save

```
----------------------------------------
Start single photon counting measurement.
SPAD [#], Counts [#]
00,2309
01,2587
02,2250
03,2270
04,2230
05,2238
06,2412
07,2400
08,2439
09,2236
10,2218
11,2320
12,17834
13,2345
14,2218
15,2222
16,2389
17,2423
18,2340
19,2316
20,2411
21,4714
22,2362
```

Total intensity: 158.6 kcps

Measuring

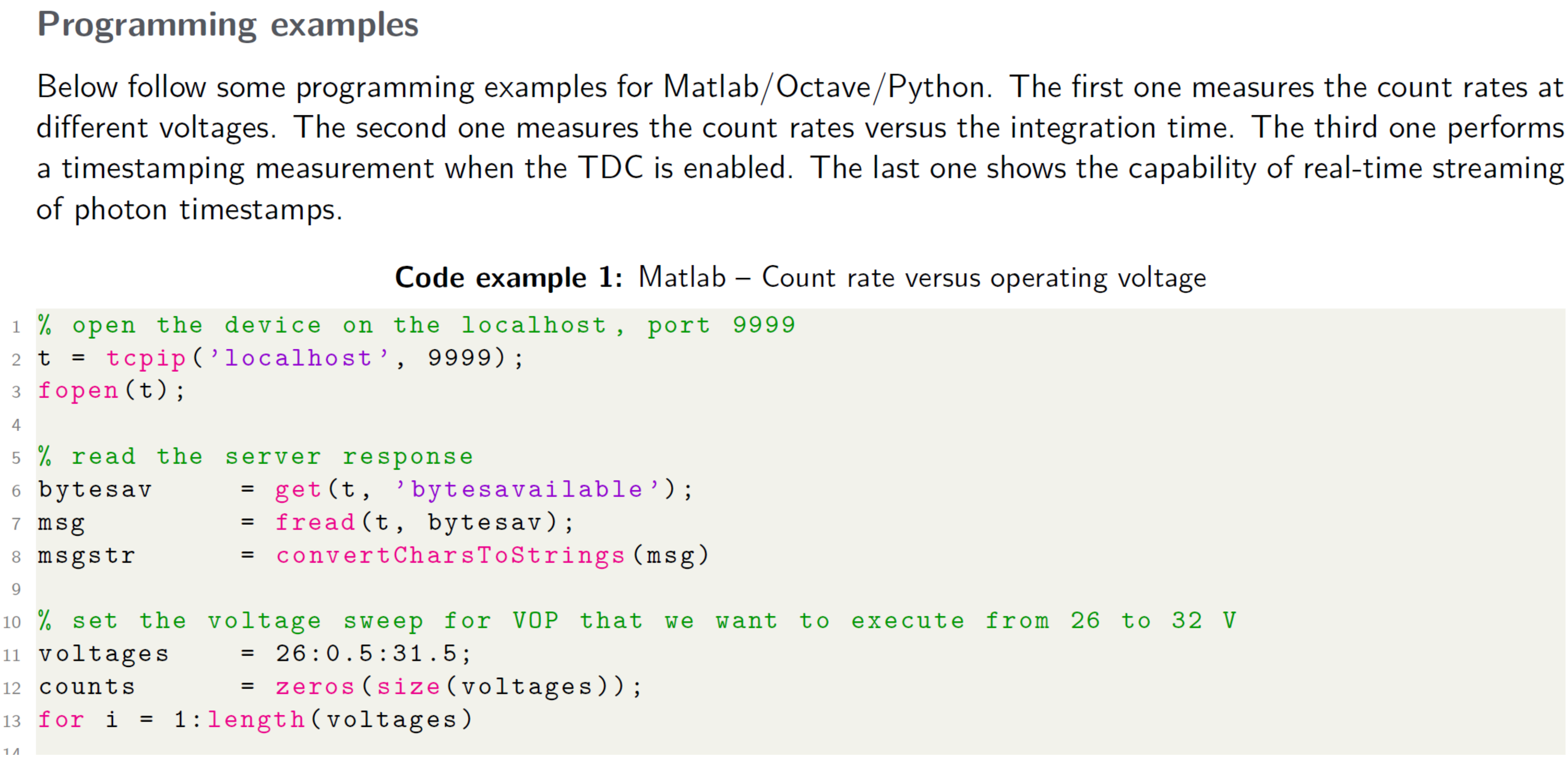
SPAD23: time-stamping



Data saved in 'data/tdc_hist/Run001/'

Total intensity: 955.4 kcps

SPAD23: programming



Programming examples

Below follow some programming examples for Matlab/Octave/Python. The first one measures the count rates at different voltages. The second one measures the count rates versus the integration time. The third one performs a timestamping measurement when the TDC is enabled. The last one shows the capability of real-time streaming of photon timestamps.

Code example 1: Matlab – Count rate versus operating voltage

```
% open the device on the localhost, port 9999
t = tcpip('localhost', 9999);
fopen(t);

% read the server response
bytesav     = get(t, 'bytesavailable');
msg         = fread(t, bytesav);
msgstr      = convertCharsToStrings(msg)

% set the voltage sweep for VOP that we want to execute from 26 to 32 V
voltages    = 26:0.5:31.5;
counts      = zeros(size(voltages));
for i = 1:length(voltages)
```

Other Key Instrumentation – ps Laser Diode