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Imaging system based on silicon photomultipliers and light emitting diodes for functional near-infrared spectroscopy

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2. Department of Neuroscience, Imaging and Clinical Sciences University G. D'Annunzio of Chieti – Pescara
3. Department of Electrical Electronic and Computer Engineering, University of Catania
4. STMicroelectronics (Catania)

** Now at STMicroelectronics (Catania)*

IMM Institute for Microelectronics and Microsystems

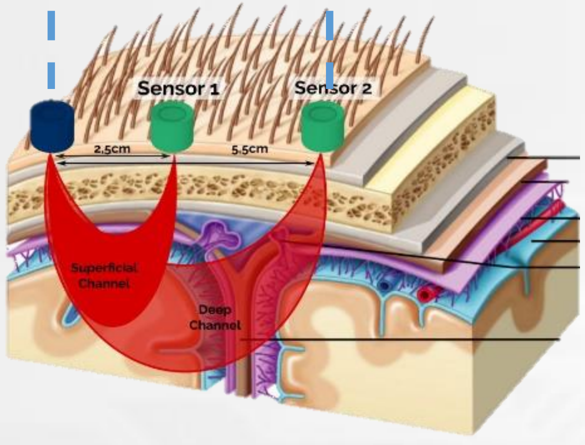
General Context:

CW - functional Near Infrared Spectroscopy

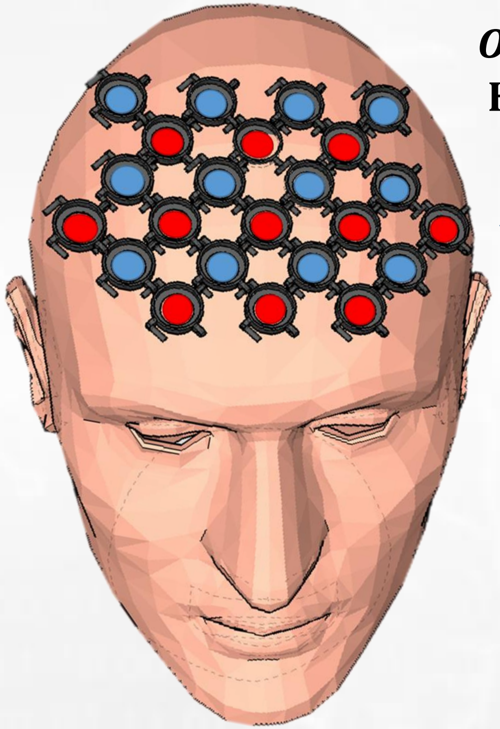
Scattering + Absorption
in a «**semitransparent tissue**»

SDS

(Source – detector separation)

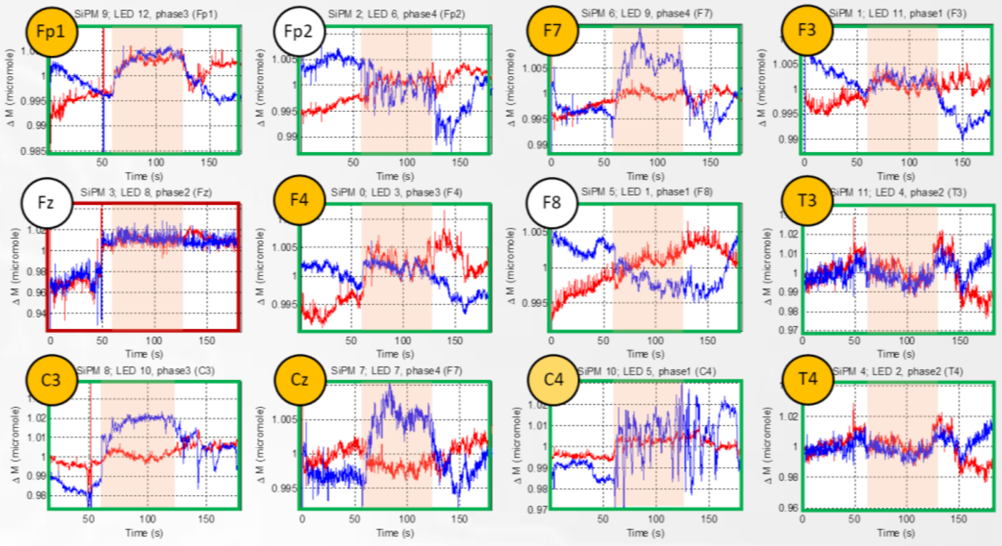


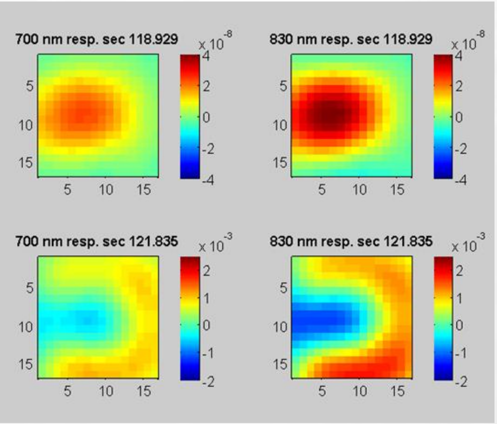
1 channel

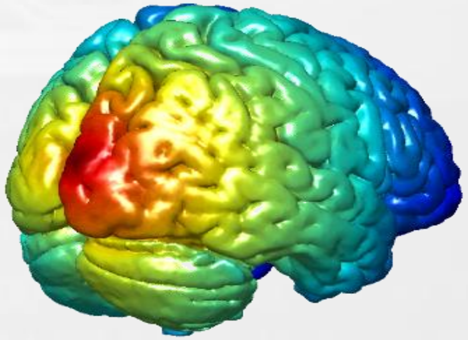


N channels
(time division)

$O_2\mathrm{Hb}(t)$
$\mathrm{HHb}(t)$





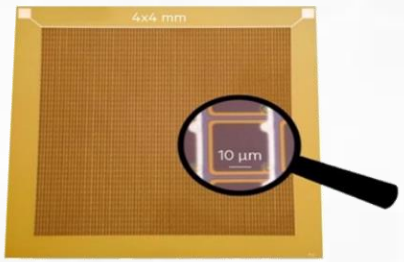


Topics and Objectives

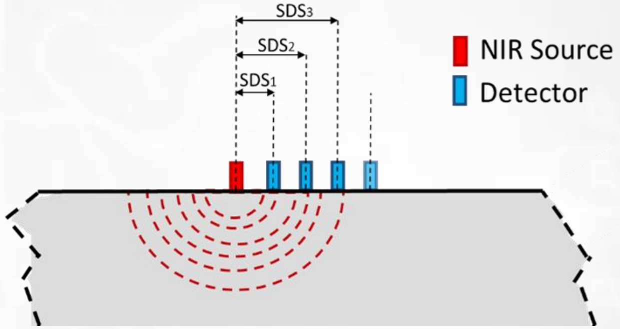
Identify a class of
Solid State photodetectors
with **improved responsivity** in
order to detect weak optical signals

Silicon Photomultipliers

- right typology
- suitable operation conditions



SDS



Knowledge of
Light Scattering in
diffusive media

Optical Phantoms

- Modeling
- Measurements

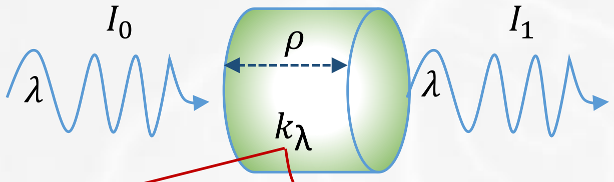
- number of channels (spatial resolution) ↑
- depth ↑

General Context:

functional Near Infrared Spectroscopy

modified Beer-Lambert Law

$$\frac{I_1}{I_0} = e^{-\rho \cdot k_\lambda}$$



Attenuation coefficient

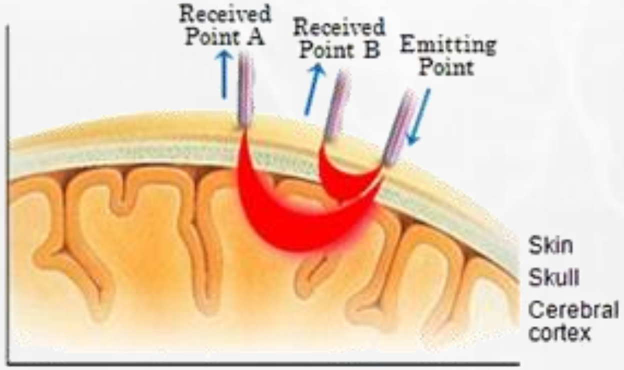
In a solution with 2 species: $k_\lambda \rightarrow \varepsilon_1 \cdot M_1 + \varepsilon_2 \cdot M_2$

«banana shape» ⇒ «differential pathlenght factor» $DPF(\lambda)$

$$M(t) = -\frac{1}{\rho \cdot \varepsilon_\lambda \cdot DPF(\lambda)} \, ln\left[\frac{I(t)}{I_o}\right] (*)$$

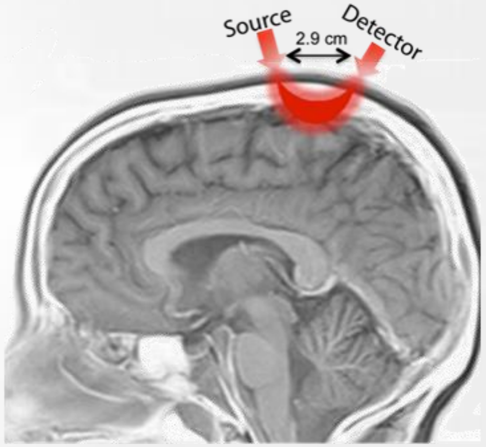
Optical Density

$$OD = -\ln\left[\frac{I(t)}{I_o}\right]$$



Rule of thumb:
Max sensitivity
at SDS/2

SDS



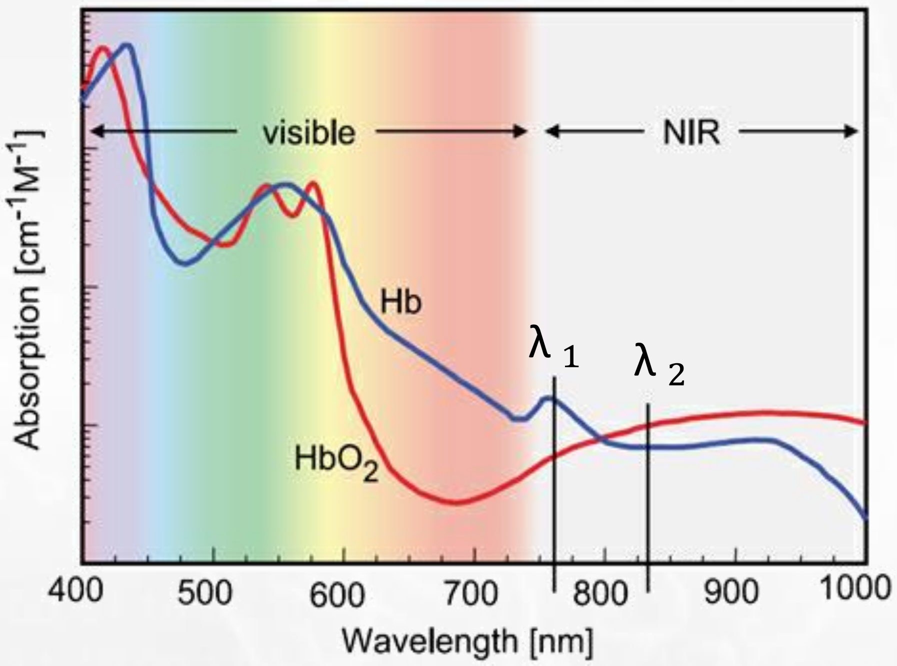
* **Felix Scholkmann** and **Martin Wolf**, *General equation for the differential pathlength factor of the frontal human head depending on wavelength and age,* Journal of Biomedical Optics 18(10), 105004 (October **2013**)

General Context:

functional Near Infrared Spectroscopy

O_2Hb and HHb, modified Beer-Lambert Law

$$\begin{bmatrix} O_2Hb(t) \\ HHb(t) \end{bmatrix} = \frac{1}{\rho} \begin{bmatrix} \varepsilon_{O_2Hb}(\lambda_1) \cdot DPF(\lambda_1) & \varepsilon_{HHb}(\lambda_1) \cdot DPF(\lambda_1) \\ \varepsilon_{O_2Hb}(\lambda_2) \cdot DPF(\lambda_2) & \varepsilon_{HHb}(\lambda_2) \cdot DPF(\lambda_2) \end{bmatrix}^{-1} \begin{bmatrix} OD(\lambda_1, t) \\ OD(\lambda_2, t) \end{bmatrix}$$



$$\varepsilon_{O_2Hb}(700\,nm) = 9x10^{-5}mm^{-1}$$

$$\varepsilon_{HHb}(700\,nm) = 4.4x10^{-4}mm^{-1}$$

$$\varepsilon_{O_2Hb}(830\,nm) = 2.4x10^{-4}mm^{-1}$$

$$\varepsilon_{HHb}(830\,nm) = 1.9x10^{-4}mm^{-1}$$

By choosing 2 different wavelengths near the **isosbestic point** (the first lower and the second greater), it is possibile to calculate the variation of the two molecular concentrations.

CW - fNIRS State of the Art

Measured Parameters: EROS	• Signal intensity • Signal phase delay
Light Sources:	• Fiber coupled laser diodes • Wavelengths: 690 nm and 830 nm • Laser power: 10 mW average
Light Detectors:	Photomultiplier tubes
Optodes:	• Paired fibers in excitation, 400µm diameter • Fiber bundle in collection, 3mm diameter

Imagent™
Functional Brain Imaging System Using Infrared Photons

(2016)

Photomultiplier tubes with fibers as probe

Intrinsic Gain: **10^7** electrons per detected photon

(1) Wearable design with compact capsule and **no optical fibers**
(2) High sensitivity by APDs (linear mode)
(3) Support multi-distance measurement mode
(4) LED for checking sensor fitting status

HITACHI
Inspire the Next

(2016)

Avalanche photodiodes directly placed on the scalp

Intrinsic Gain: **10^2** electrons per detected photon

Number of Detector Channels	8
Sensitivity	< 1pW
Dynamic Range	60 dBopt
Sensor Type	Si Photodiode, Active Sensor
Number of Illumination Sources	8 (Time-Multiplexed)
Source Wavelengths, Emitter Type	760nm & 850nm LED

NIRX

(2018)

Silicon Photodiodes directly placed on the scalp

Intrinsic Gain: **1** electron per detected photon

Solid State photodetectors:
Silicon Photomultipliers

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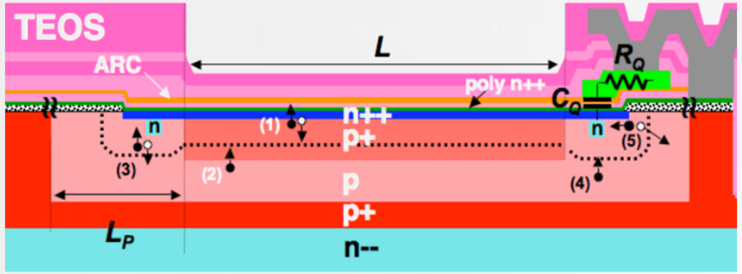
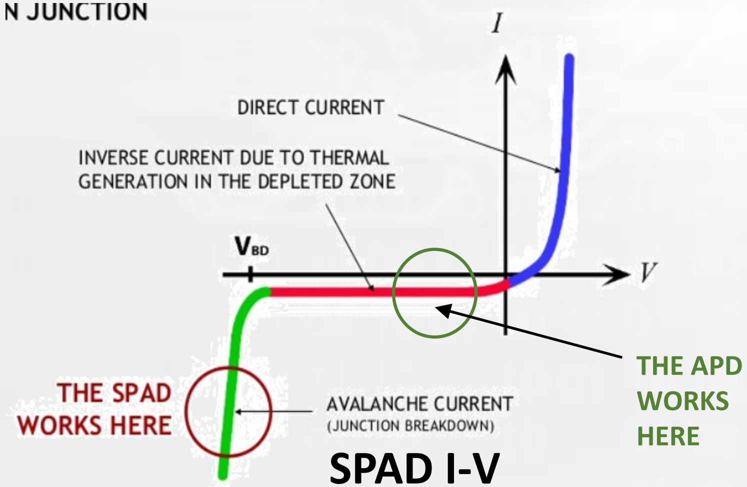
SPAD



Geiger mode:
gain 10^6 ÷ 10^7



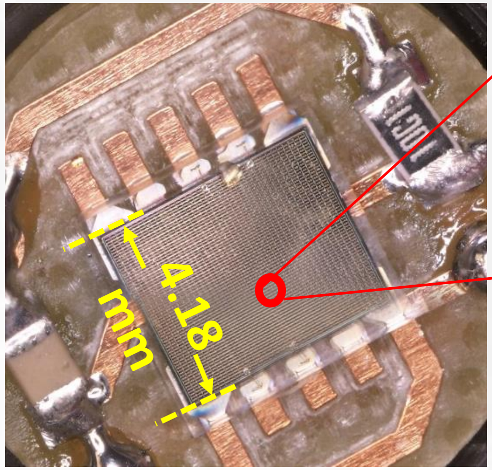
SPAD I-V

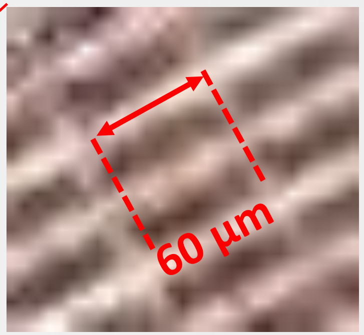
Photomultiplier Tubes (PMTs) for scintillators:

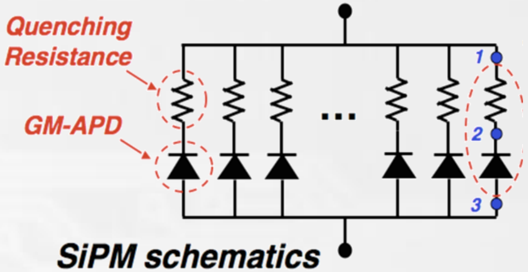
LARGE AREA
High Responsivity

bi-dimensional array of SPADs

SiPM

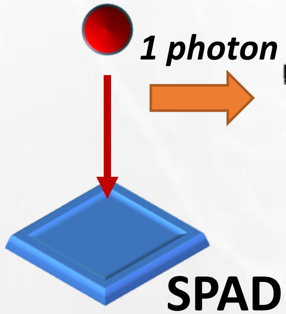


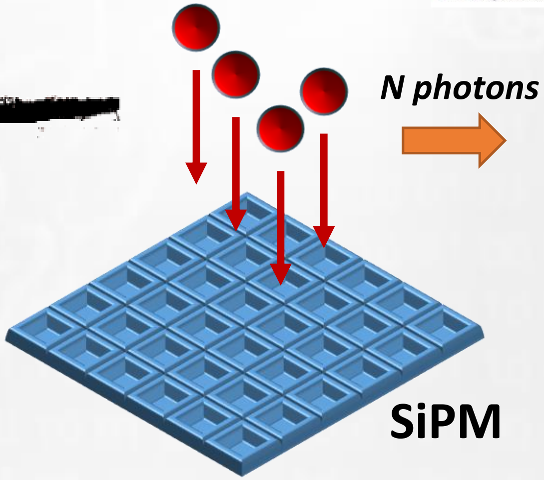


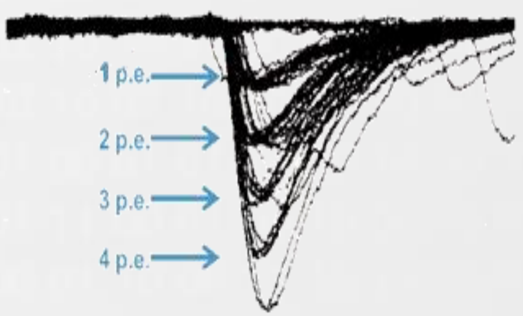


SiPM schematics

life.augmented







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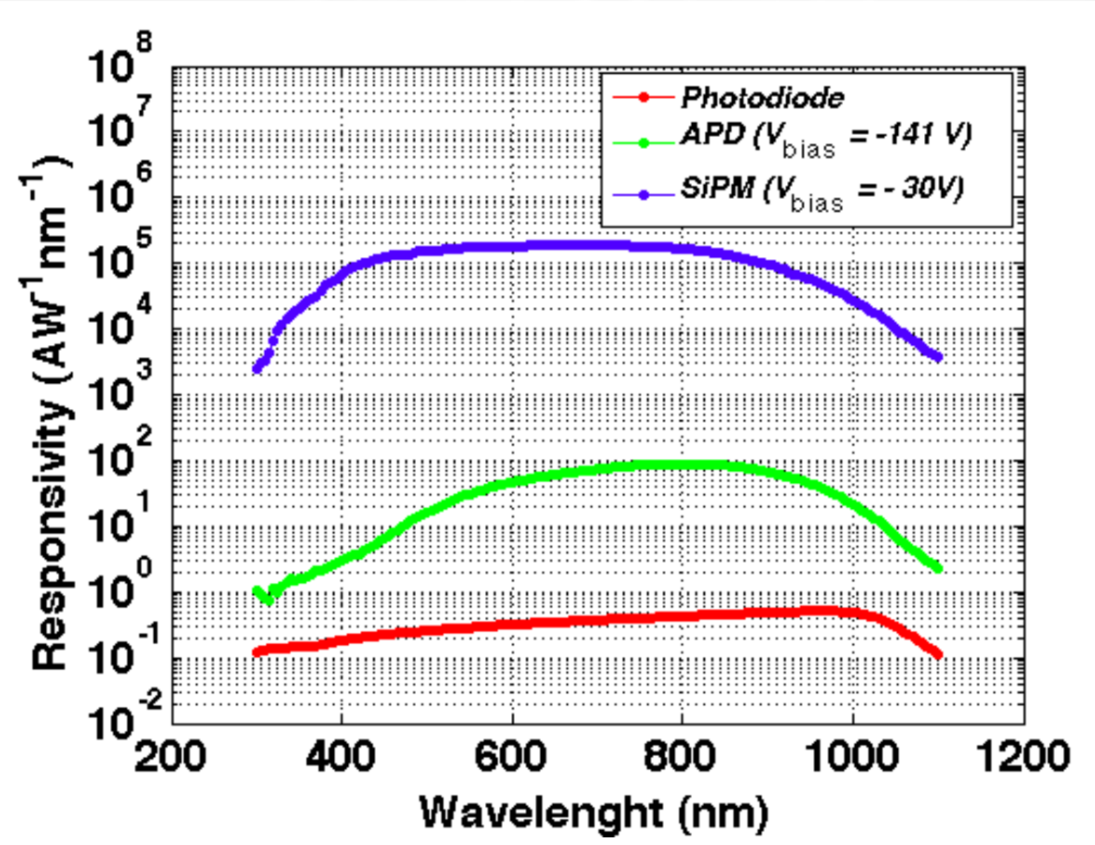
Solid State photodetectors:
Silicon Photomultipliers

SiPM responsivity:
Comparable to PMT responsivity
(orders of magnitude higher than APDs and PDs)



Responsivity: output signal / optical power impinging the detector.

The In-Vivo Stimulus (N on P SiPM)

off-line

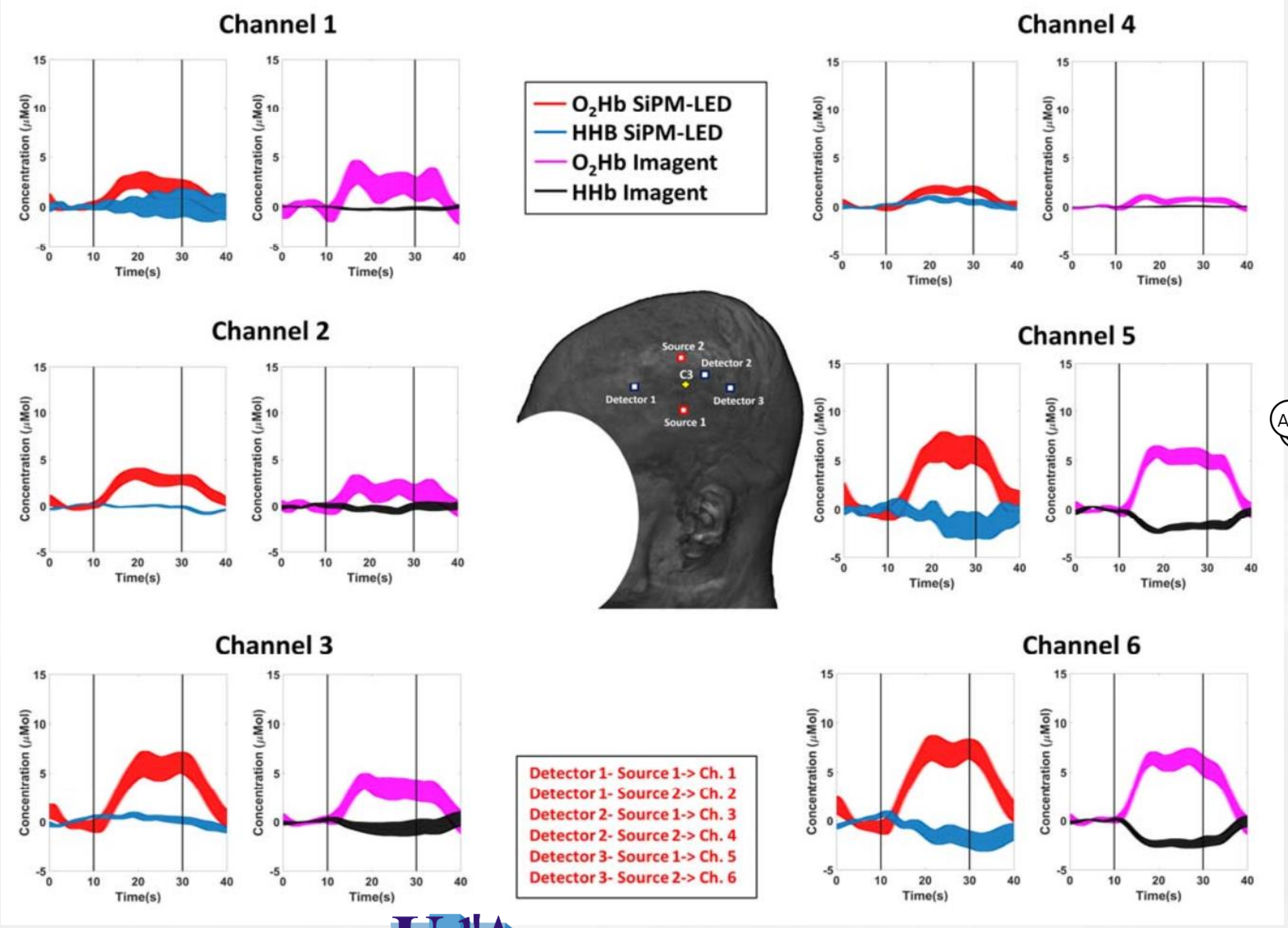
Sensors located in **C3** location (based on the 10-20 system for EEG)
Subject right-handed in sitting comfortably on a chair

Right-hand finger tapping task locked to an auditory stimulation (‘start’, ‘stop’ commands),

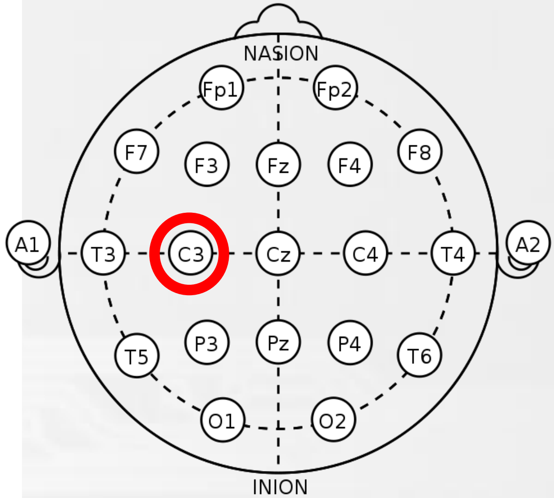
4 consecutive runs. One run: **40** seconds of rest, **20** seconds’ task and **20** seconds rest X 4 times
Total of 16 finger tappings

Same procedure for the two systems.

SiPM - LED Imagent SiPM - LED Imagent



10-20 system for EEG



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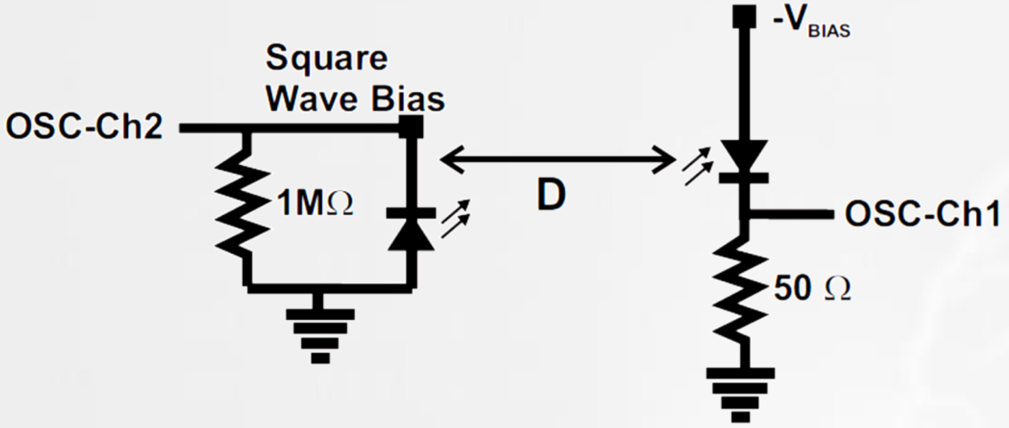
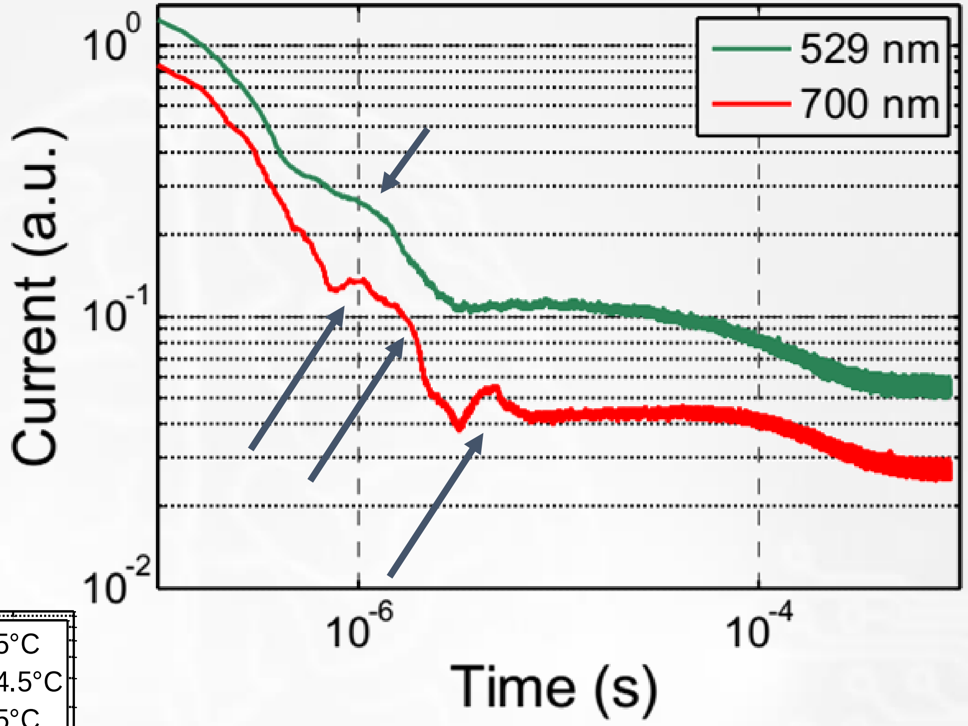
life.augmented

Ud'A Università degli studi "G. d'Annunzio"

A. M. Chiarelli, S. Libertino, F. Zappasodi, M. Mazzillo, F. Di Pompeo, A. Merla, S. Lombardo, G. Fallica, Neurophotonics 4(3), 035002 (**2017**)

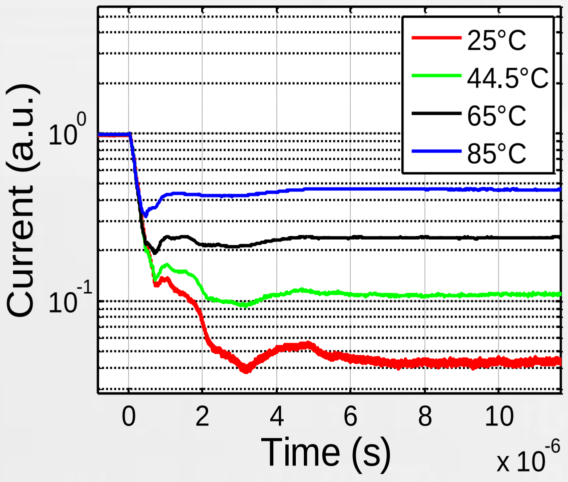
SiPM characterization: Afterpulsing



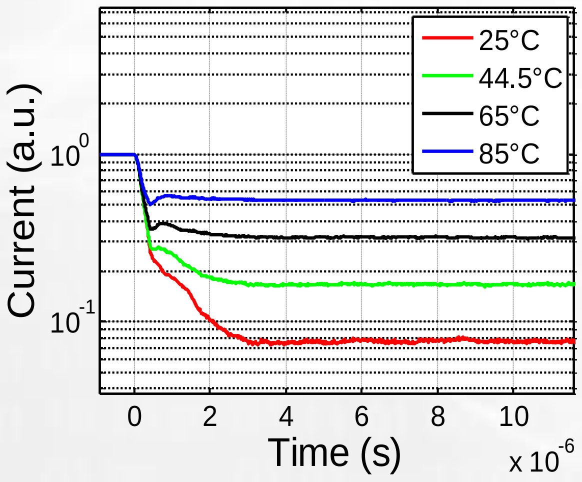


SiPM transient after 529 nm (green) and 735 nm (red) wavelenght LED switch-off, averaged on **500 traces at 100 MHz** sampling frequency

(a) **700 nm**



(b) **529 nm**



The absorption coefficient (α) is ~3 × 10^3 and ~8 × 10^2 cm^-1 at 529 and 700 nm, corresponding to absorption lengths of ~3.3 and ~12.5 μm, respectively. Since 95% of the light is absorbed within a 3/α thickness, we estimate that the **"illuminated" region**, i.e. the detector absorption region, is about **10 μm** and **37.5 μm** at 529 nm and 700 nm, respectively

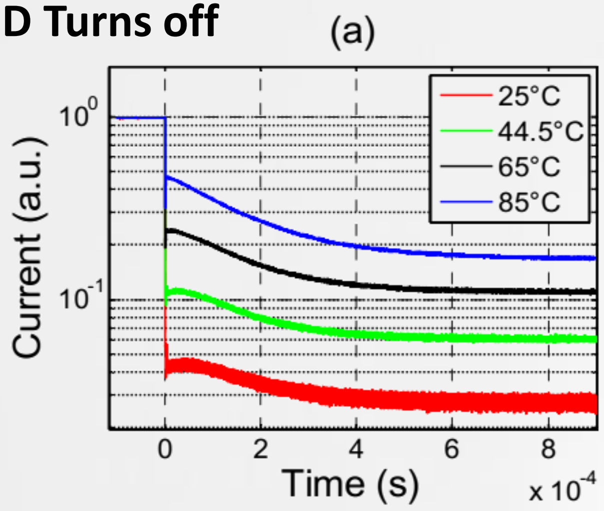
At 700 nm the peaks are at t = 1; 1.5; 4.5 μs, which correspond to depths estimated as $\sqrt{(D * t)/3}$ (D =12 cm^2/s) is the hole diffusivity, of **20, 25, and 43 μm**

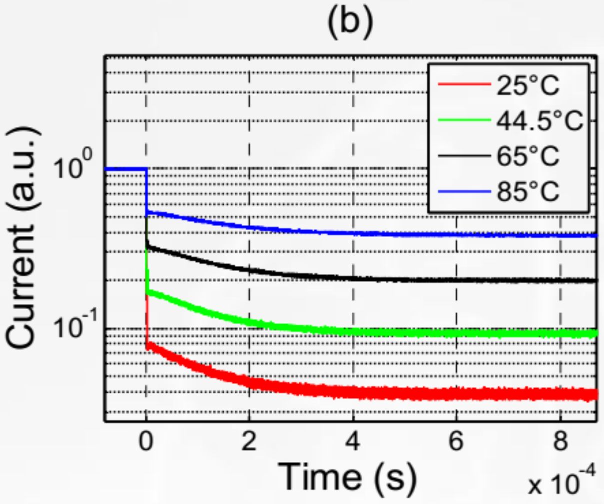
G. Maira, M. Mazzillo, S. Libertino, G. Fallica, S. Lombardo, «Crucial Aspects for the use of Silicon Photomultiplier devices in continuous wave functional near-infrared Spectroscopy», Biomedical Optics Express (**2018**)

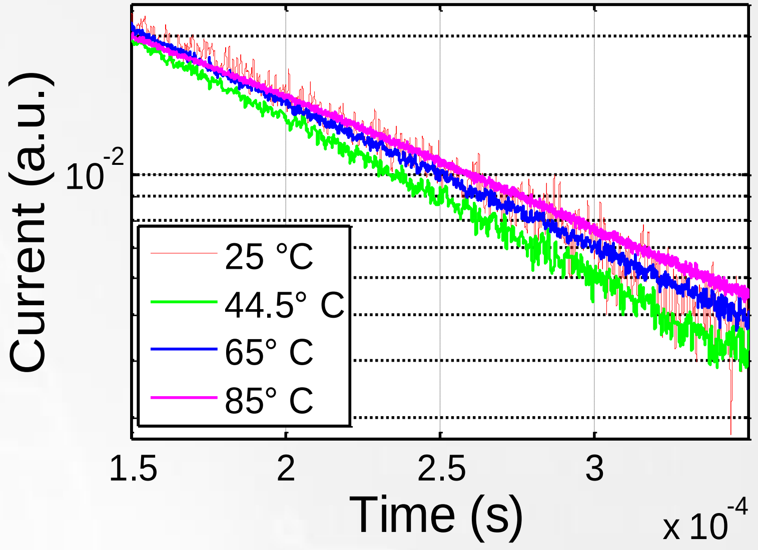
SiPM characterization: Transients

Institute for Microelectronics and Microsystems

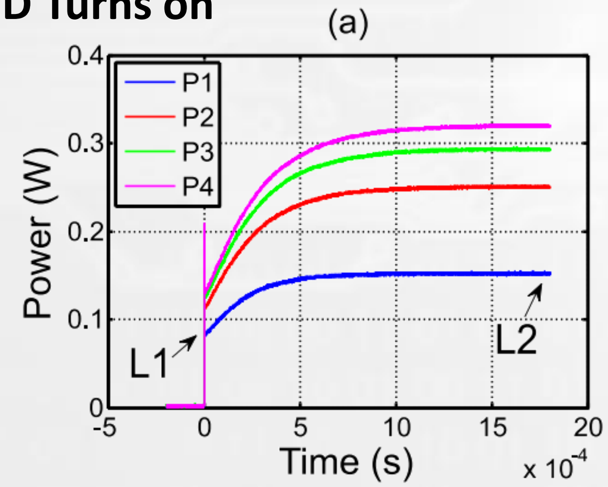
LED Turns off

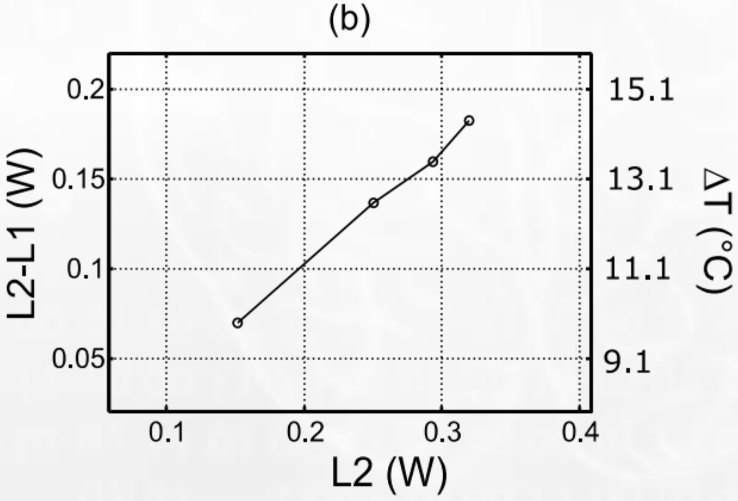


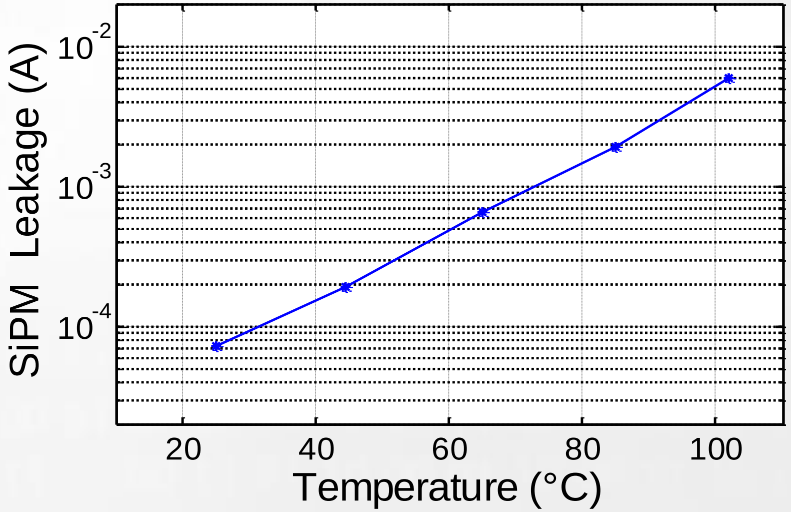




LED Turns on







G. Maira, M. Mazzillo, S. Libertino, G. Fallica, S. Lombardo, «Crucial Aspects for the use of Silicon Photomultiplier devices in continuous wave functional near-infrared Spectroscopy», Biomedical Optics Express (**2018**)

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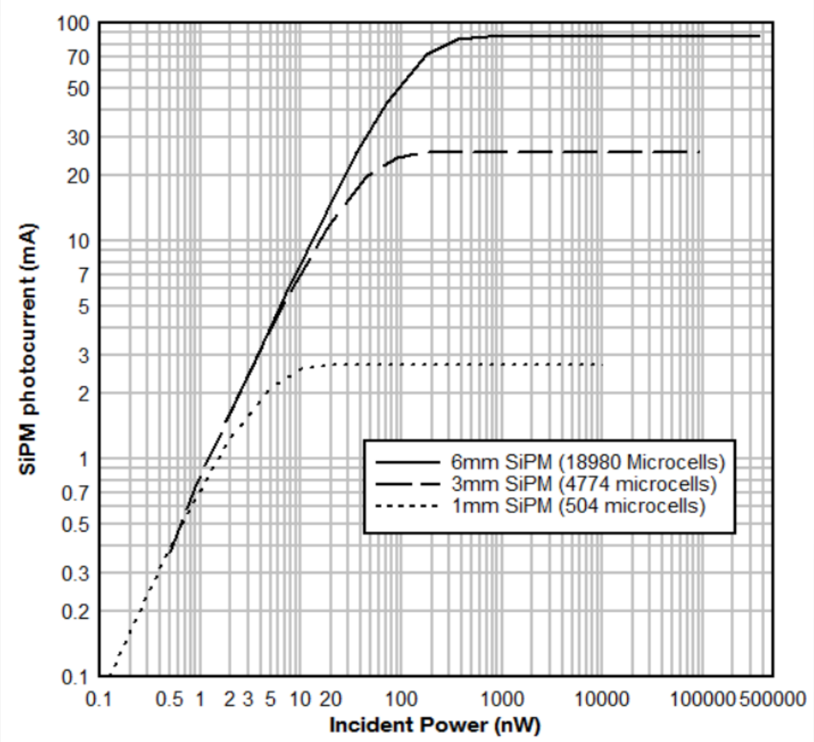
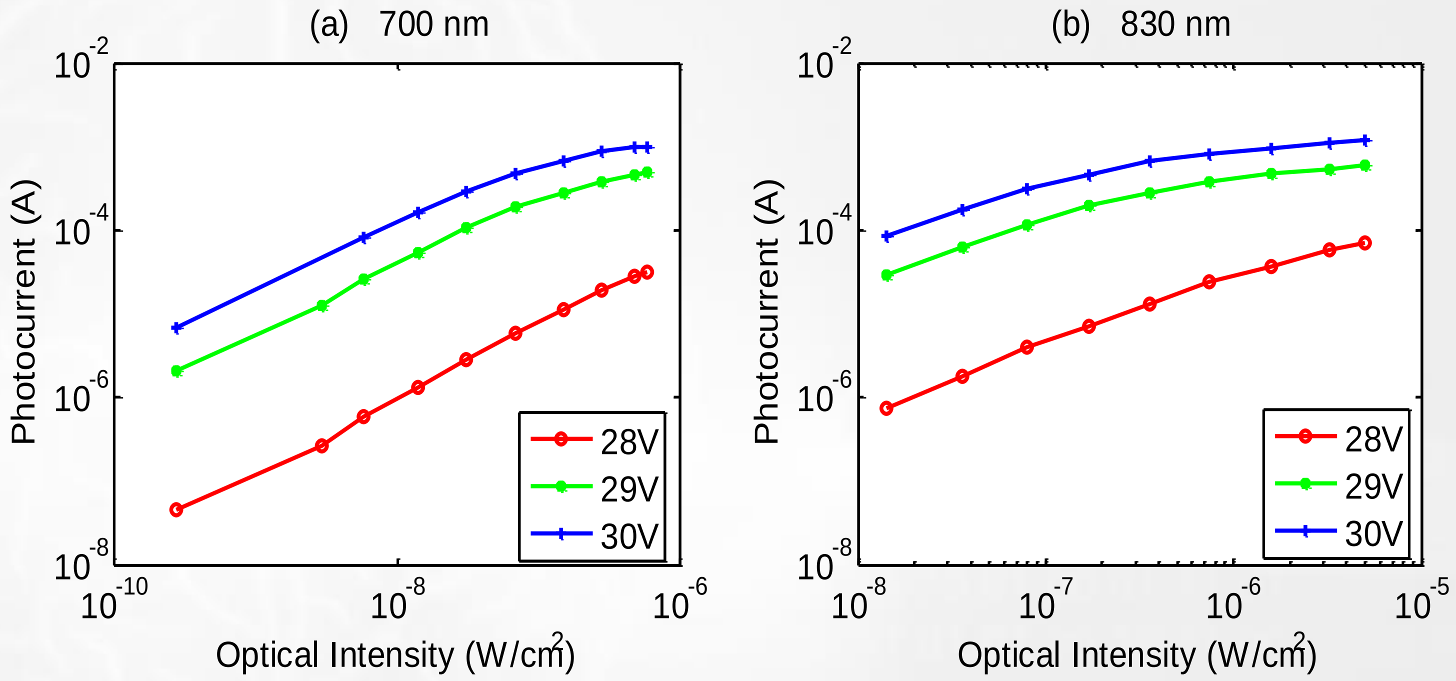
SiPM characterization: Linear Range

$$MAX = N_{pixel}/(EQE \cdot T_{quench}) \qquad MIN = 3dB + N_{pixel} / t_{dark}$$

Device



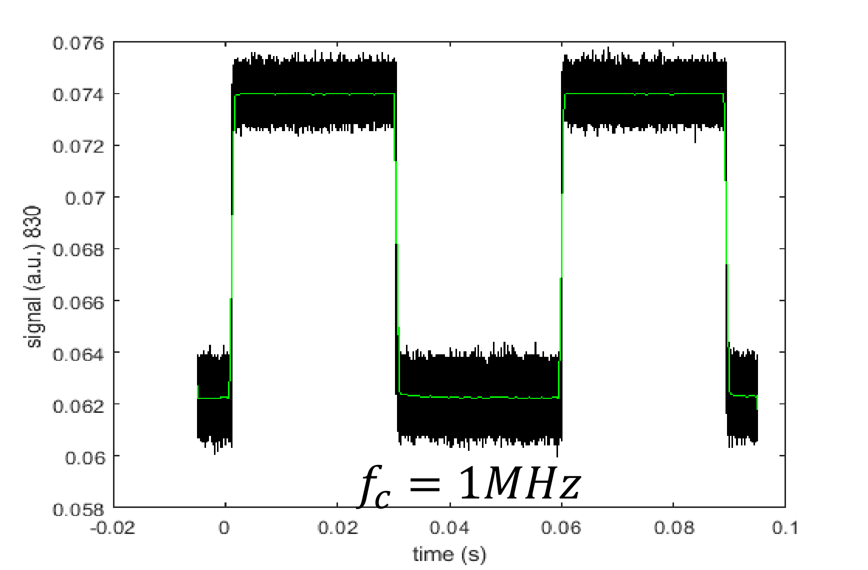
System channel

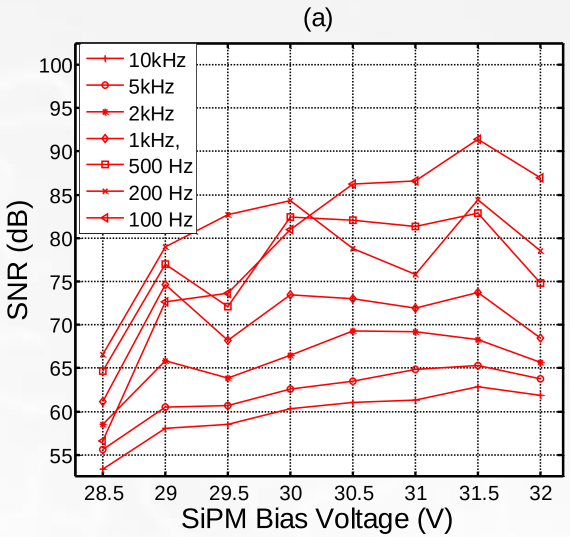


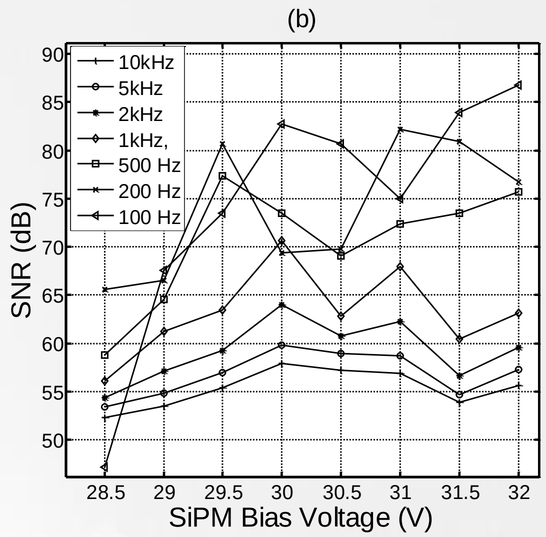
<u>Patent Application</u> of CNR and Ud'A, Authors list: **Giovanni A. Maira**, Salvatore A. Lombardo, Sebania Libertino, Arcangelo Merla, Antonio M. Chiarelli.

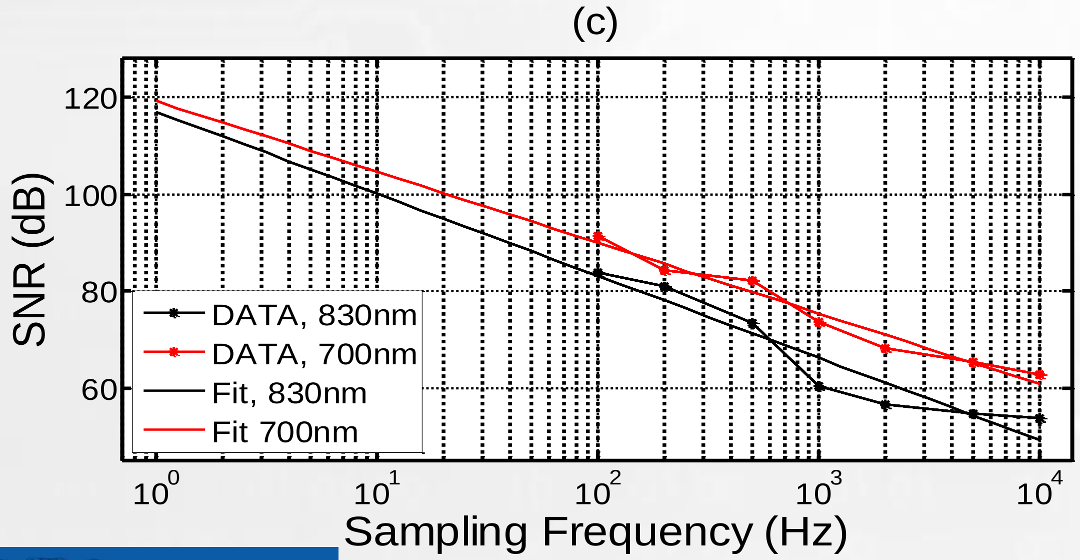
G. Maira, A.M. Chiarelli, S. Brafa, S. Libertino, G. Fallica, A. Merla, S. Lombardo «Imaging system based on Silicon Photomultipliers and Light Emitting diodes for functiona Near Infrared Spectroscopy», Applied Sciences (**2020**)

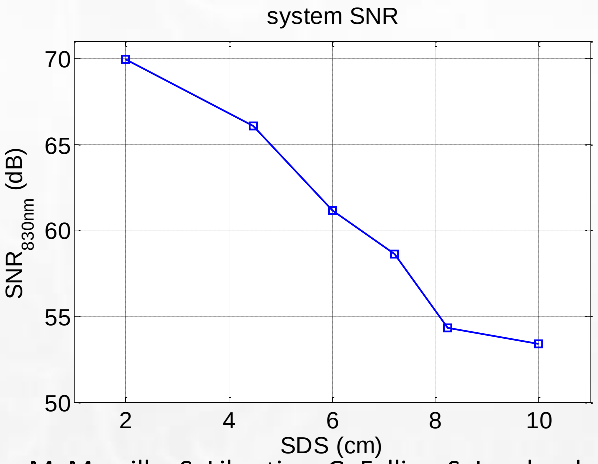
fNIRS System Signal to Noise Ratio











70 dB

G. Maira, M. Mazzillo, S. Libertino, G. Fallica, S. Lombardo, «Crucial Aspects for the use of Silicon Photomultiplier devices in continuous wave functional near-infrared Spectroscopy», Biomedical Optics Express (**2018**)

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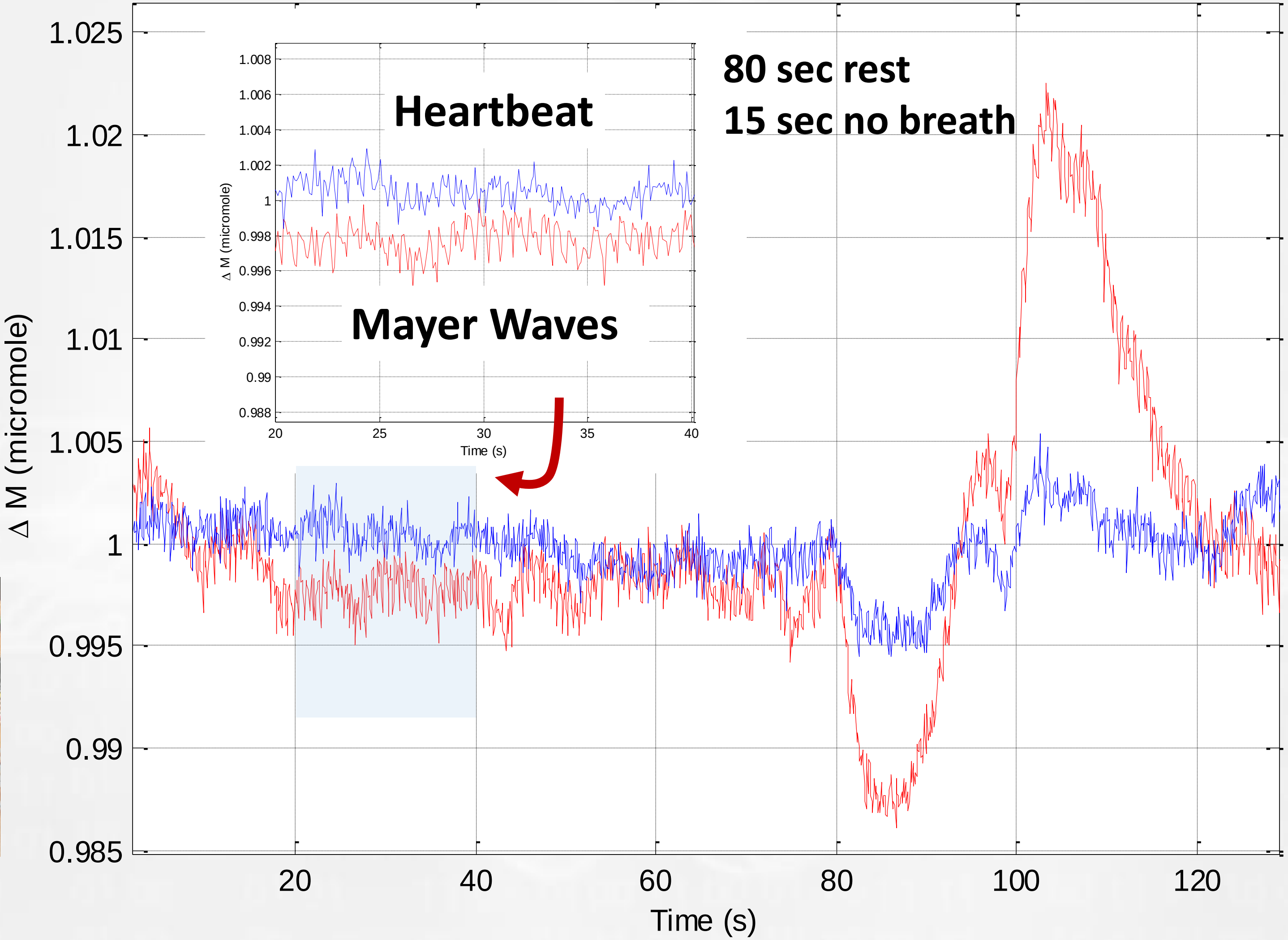
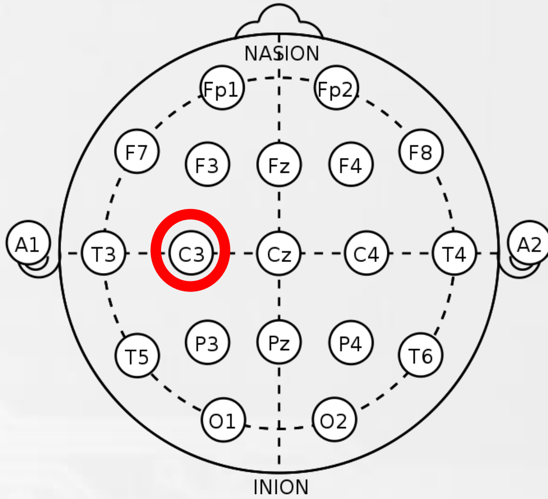
1 fNIRS channel: breath test

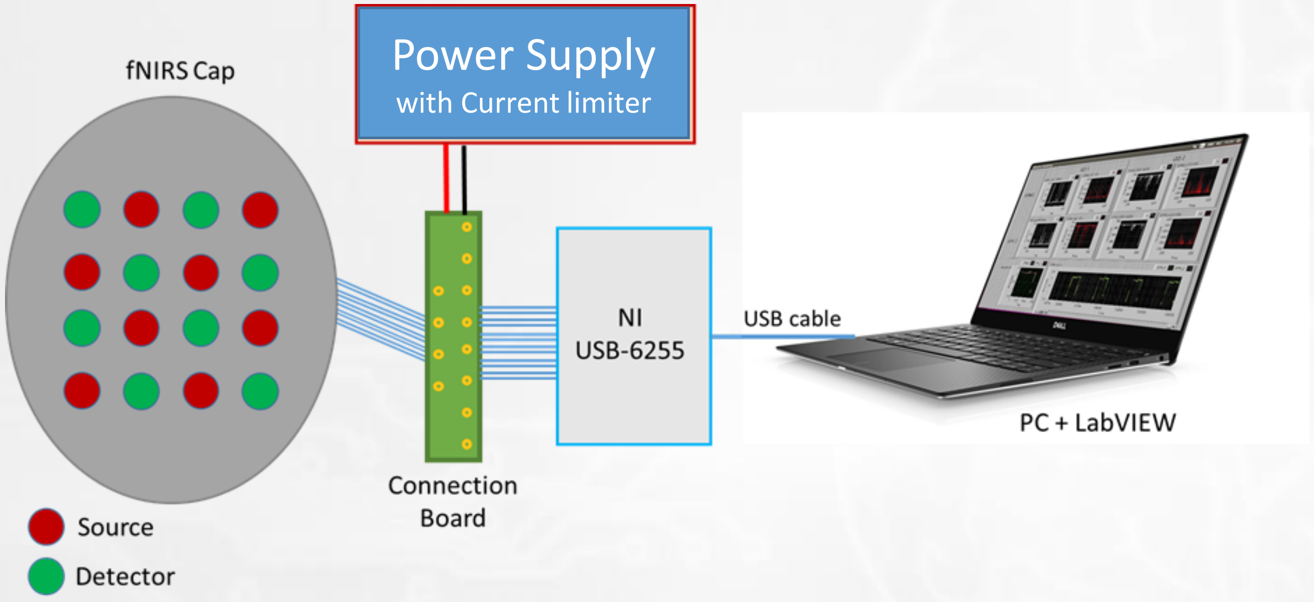


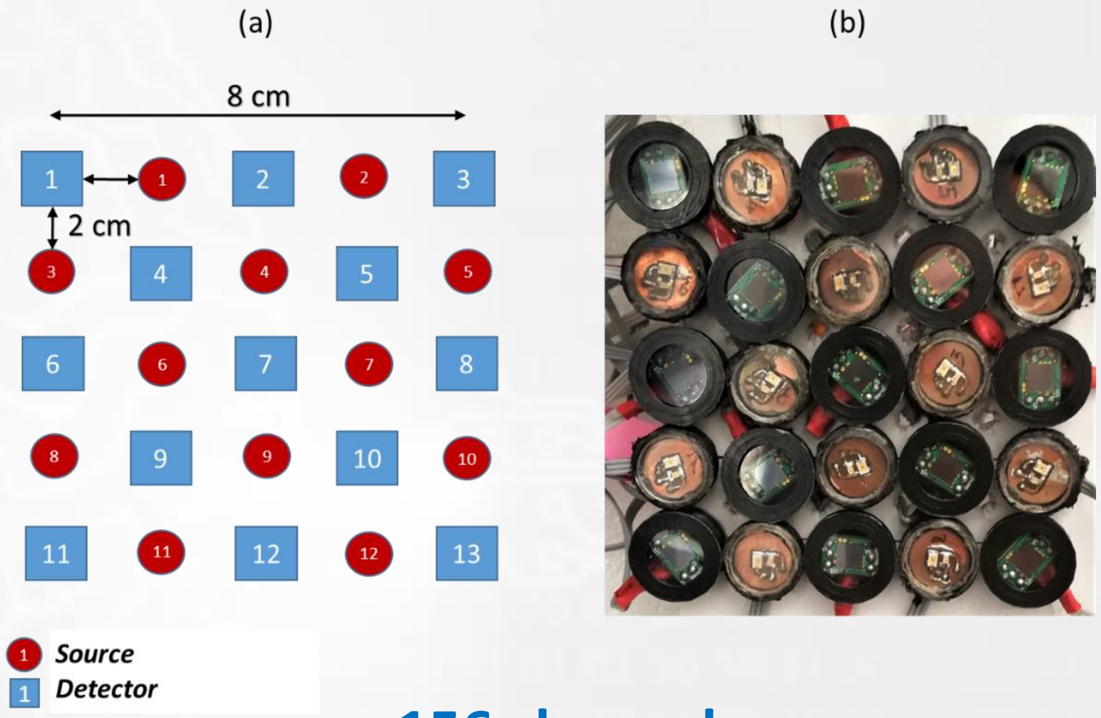
10-20 system for EEG



SDS = 3cm

fNIRS / DOT (Diffuse Optical Tomography) multichannel prototype system





156 channels,
2 wavelenghts

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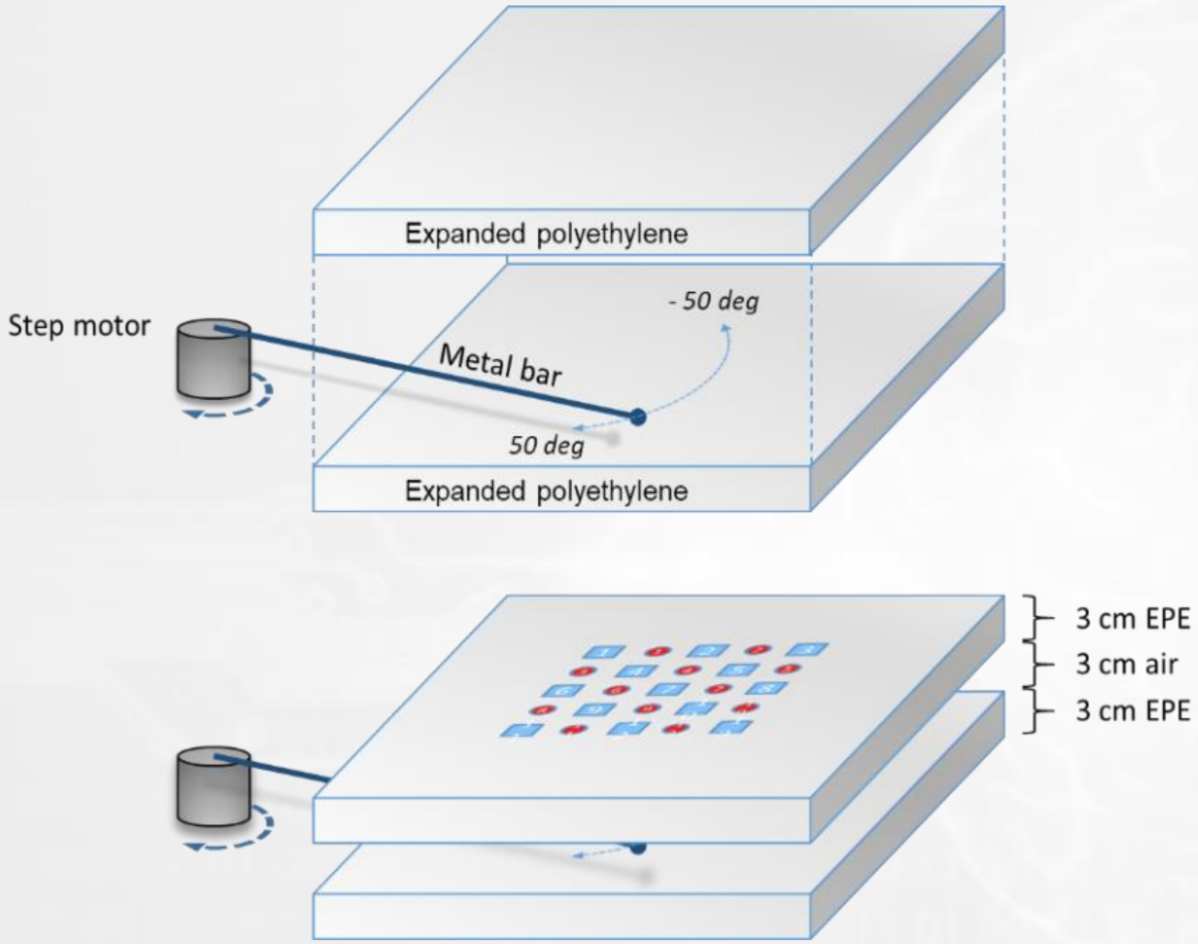
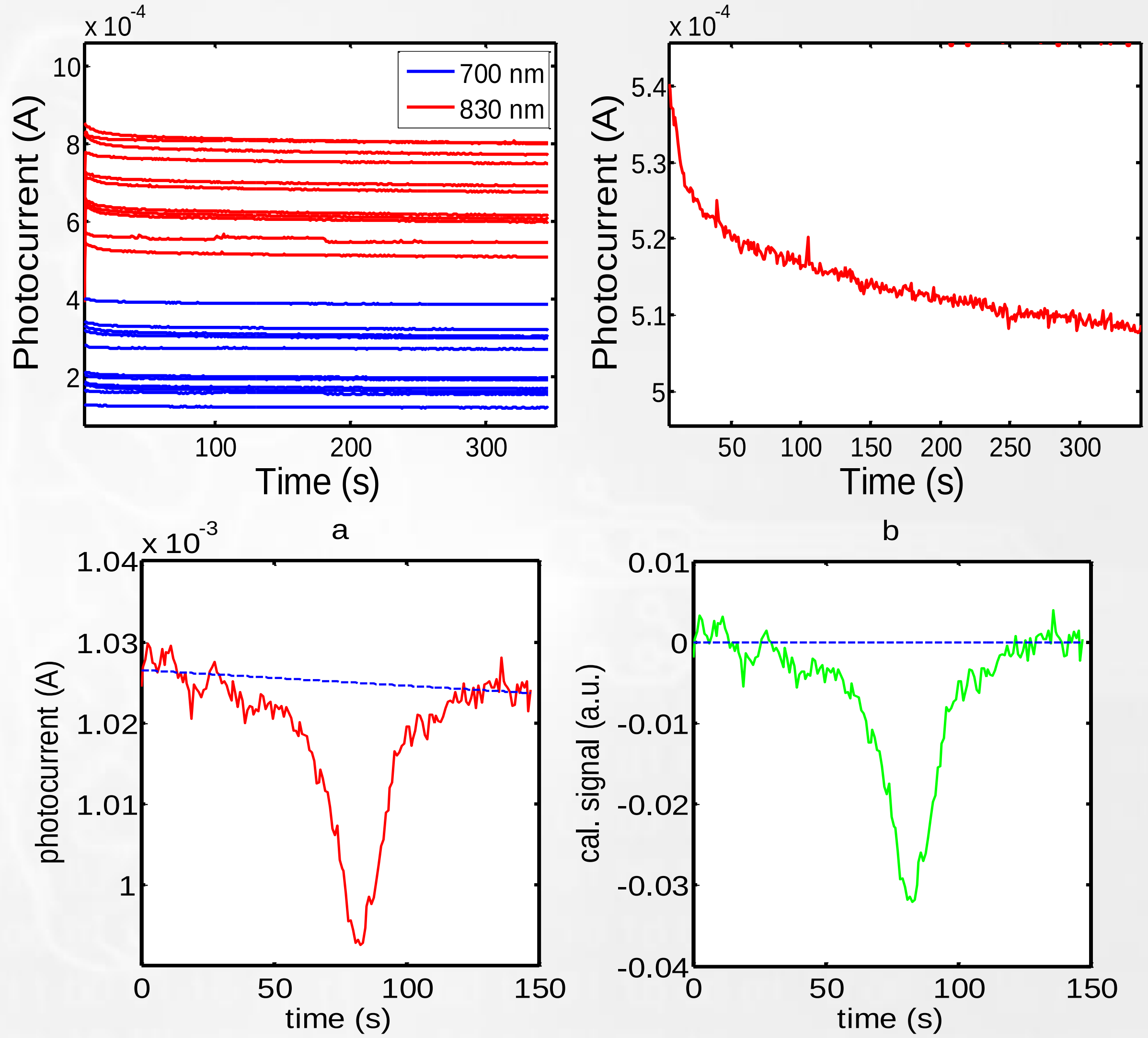
Dynamic Phantom and calibration algorithm





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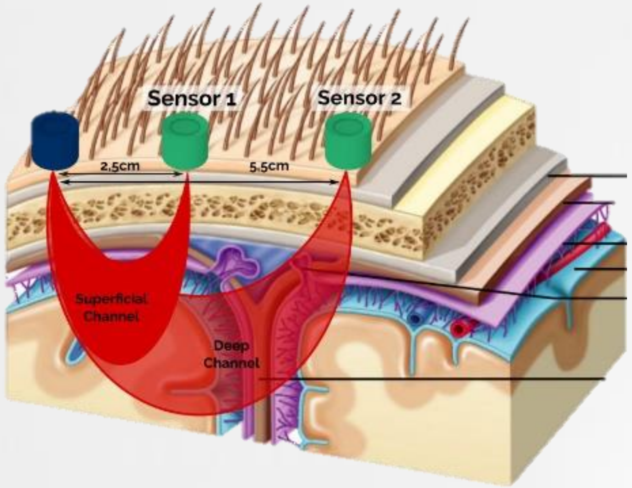
The Phantom



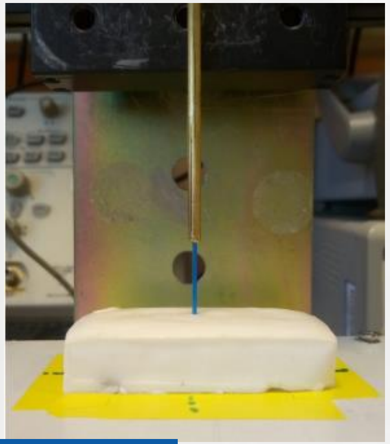
850 nm		
Tissue Type	μ_a (mm^{-1})	μ_s' (mm^{-1})
Scalp	0.012	1.8
Skull	0.025	1.6
Modified CSF	0.009	0.8
Gray Matter	0.036	0.9
White Matter	0.014	1.1

Jacques, S.L., Optical properties of biological tissues: a review. Phys Med Biol, 2013. 58(11):

$$\mu_s' = 10\ \text{cm}^{-1}$$
$$\mu_a = 0.1\ \text{cm}^{-1}$$

$$\sqrt{\mu_a \cdot \mu_s'} = 1\ \text{cm}^{-1}$$

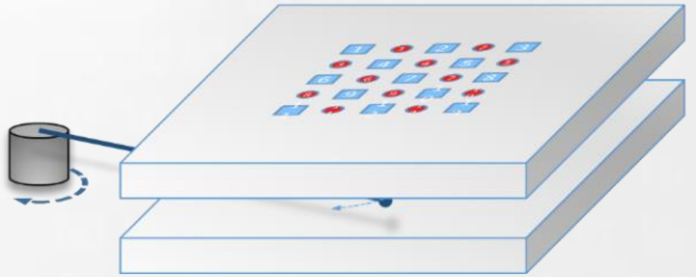
Intralipid® + india ink



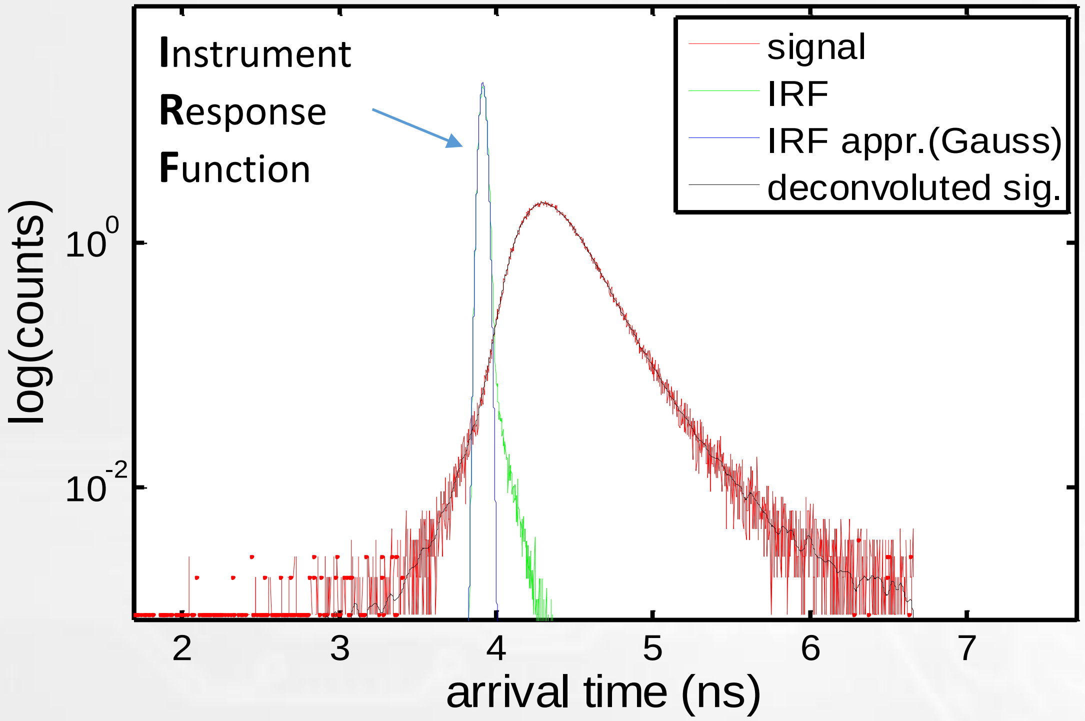
Agar + india ink

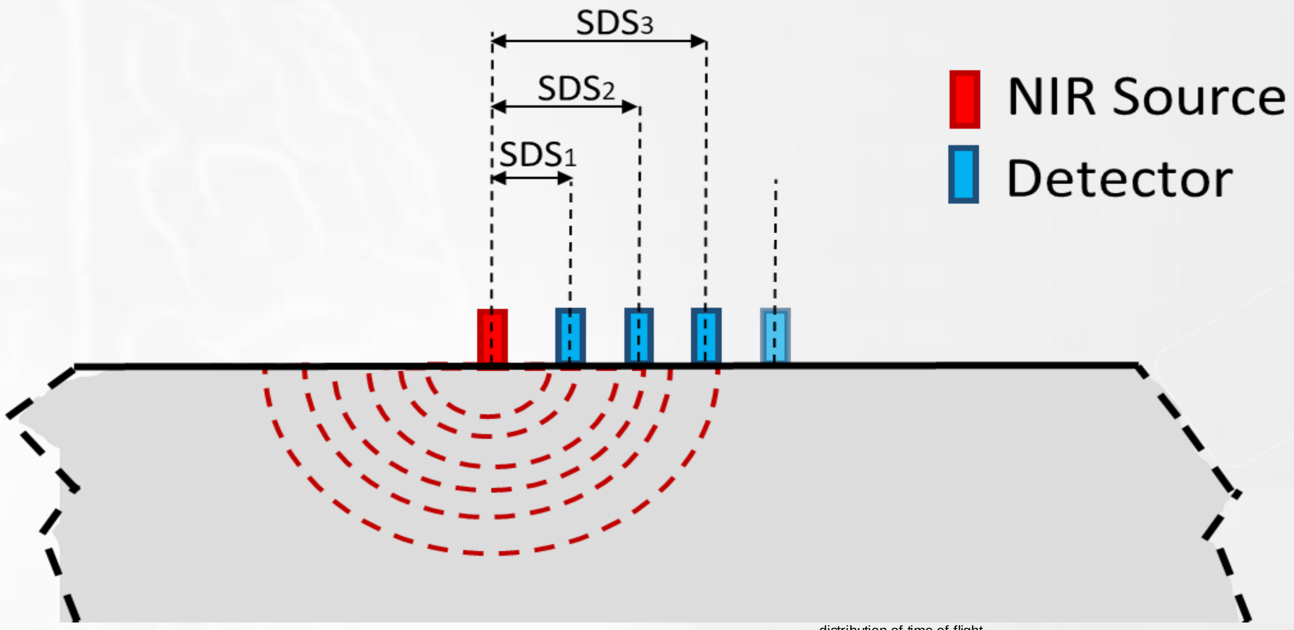
Milk + india ink

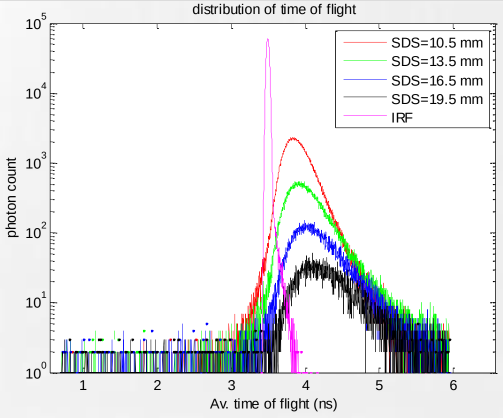
Expanded Polyethylene



Material optical characterization:
Time correlated single photon counting (TCSPC)

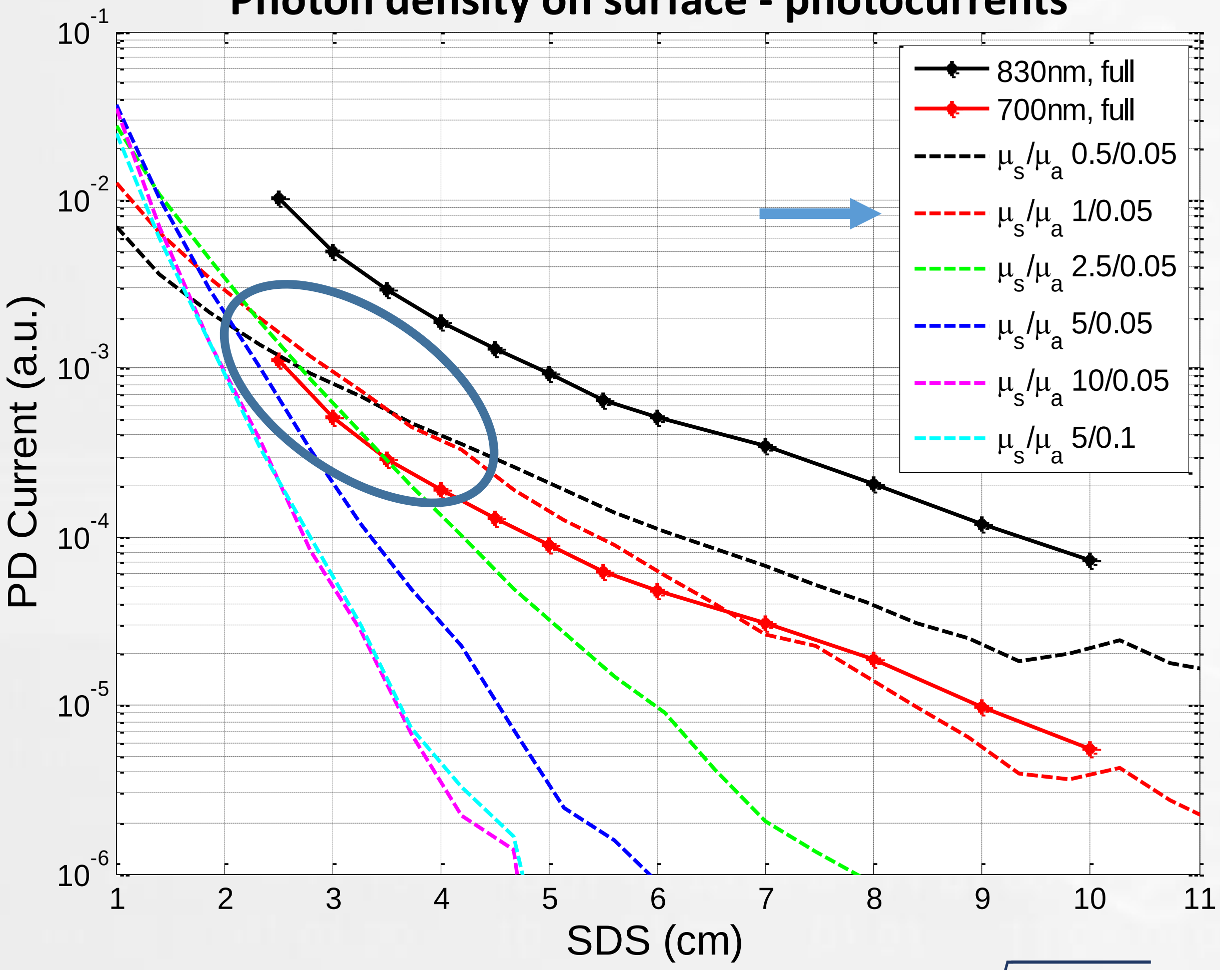


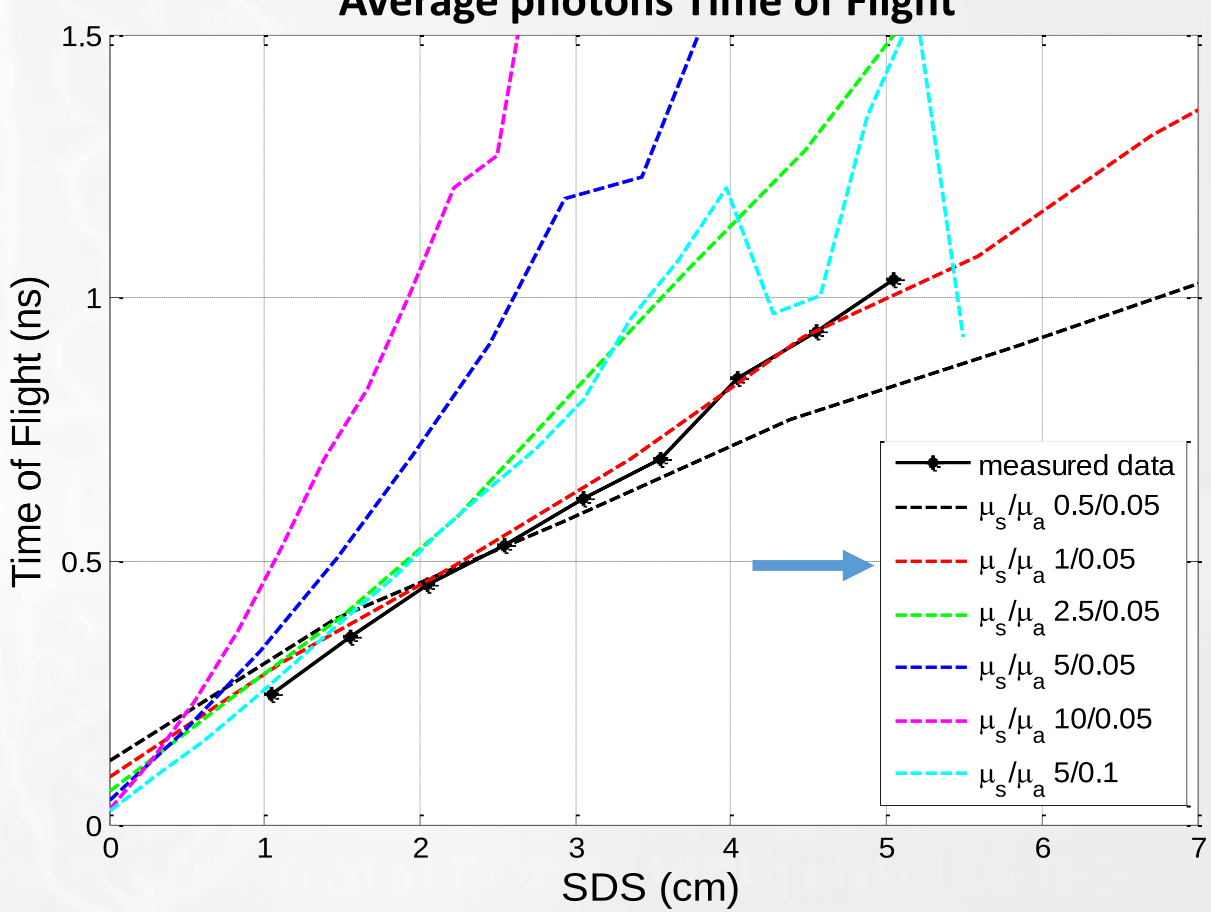




Materials optical characterization:
Photocurrents + TCSPC + Montecarlo Simulation

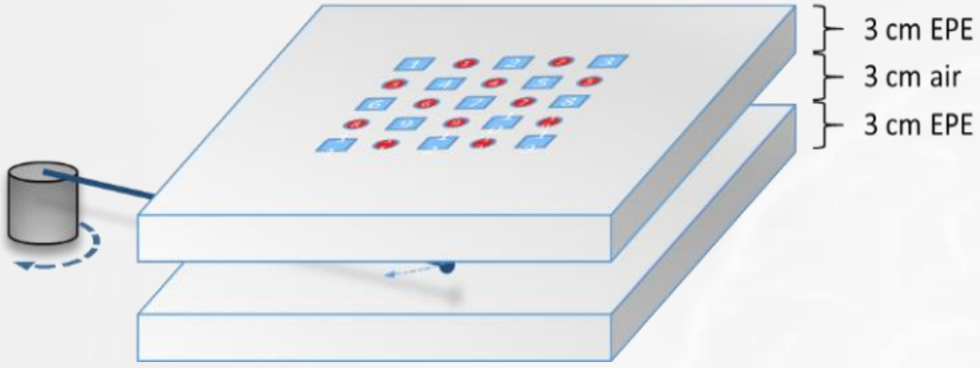
Materials optical characterization: photocurrents + TCSPC + Montecarlo Simulation

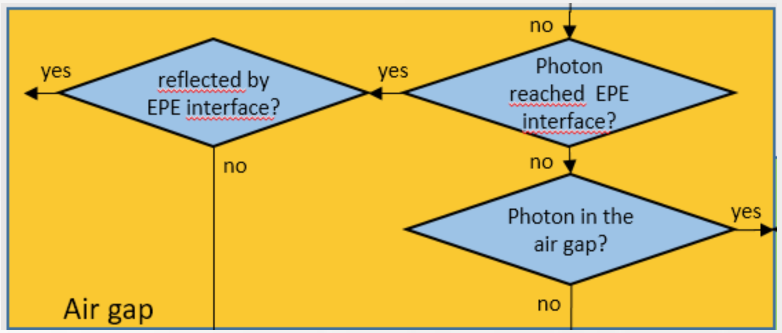




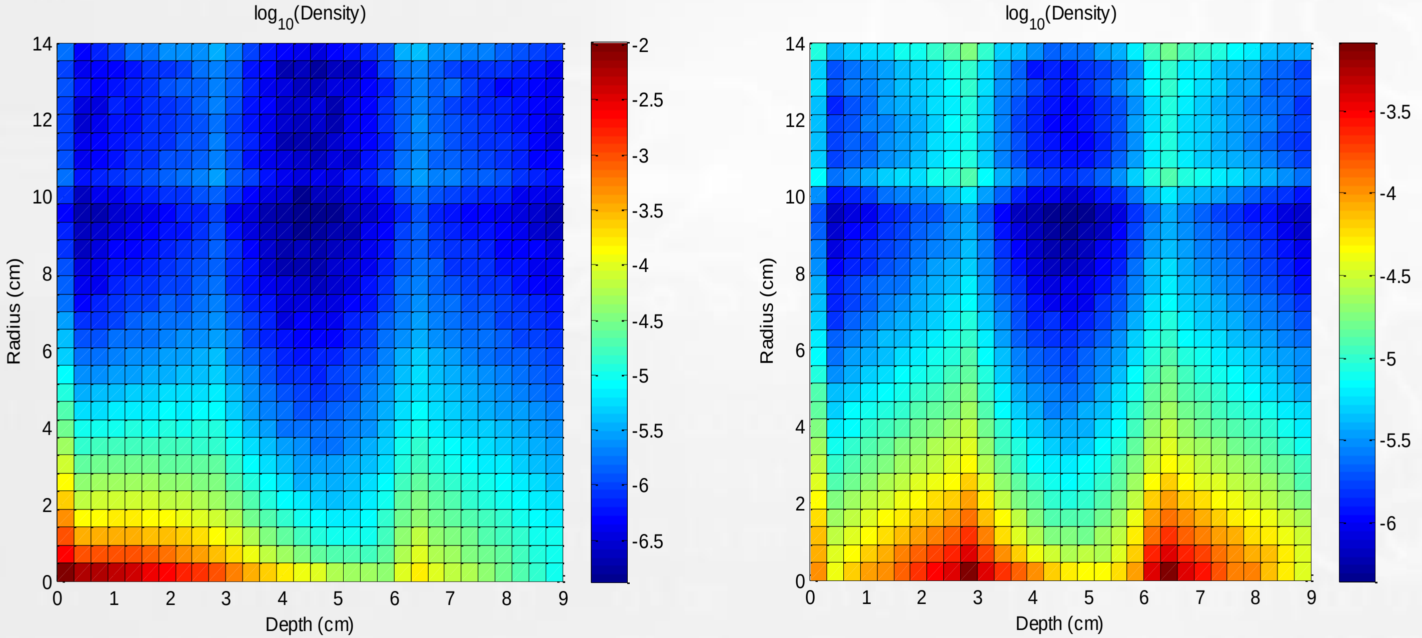
$$\sqrt{\mu_a \cdot \mu_s'} = \sqrt{0.05 \cdot 1} = 0.2\ \mathrm{cm}^{-1}$$

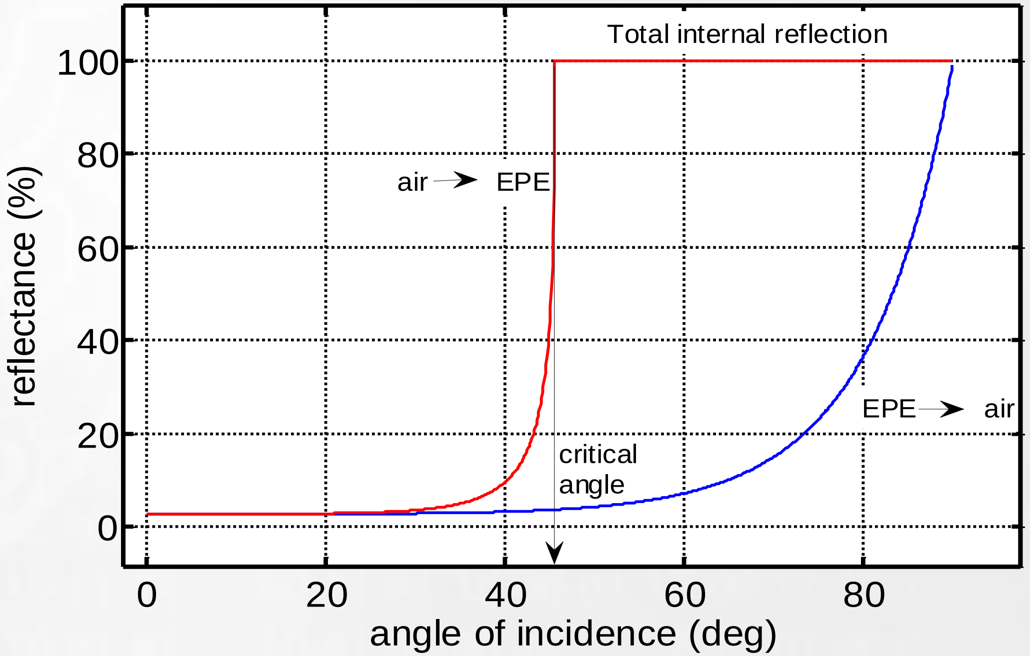
Signals Prediction: Montecarlo Simulation





Montecarlo output





Signals prediction: Montecarlo Simulation

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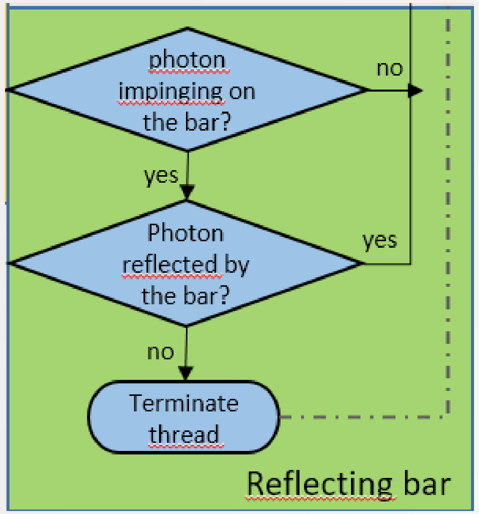

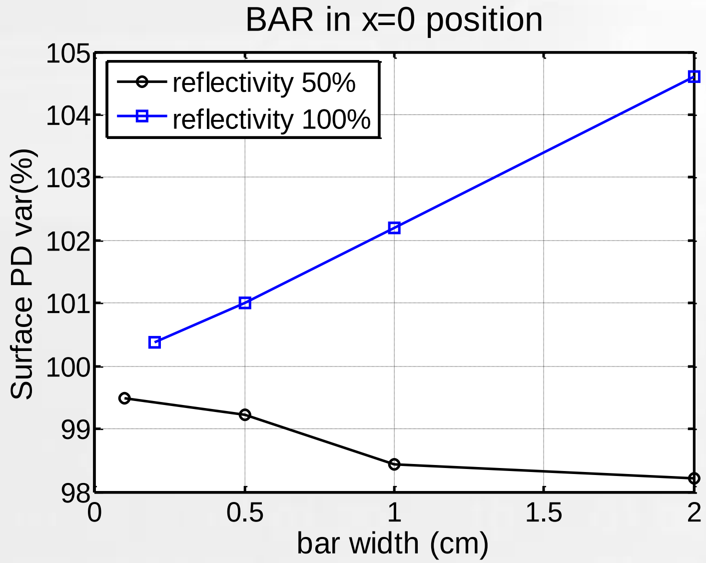

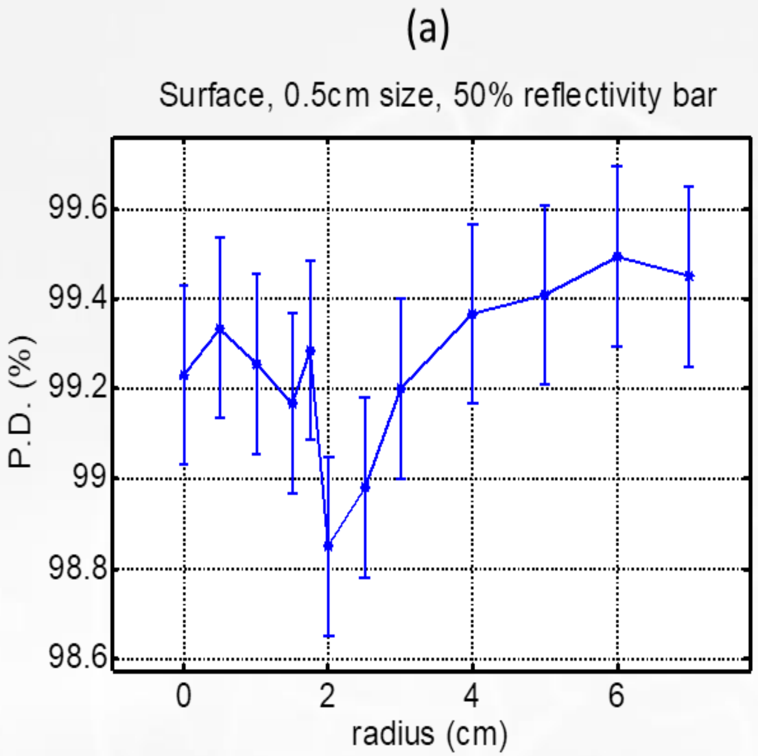

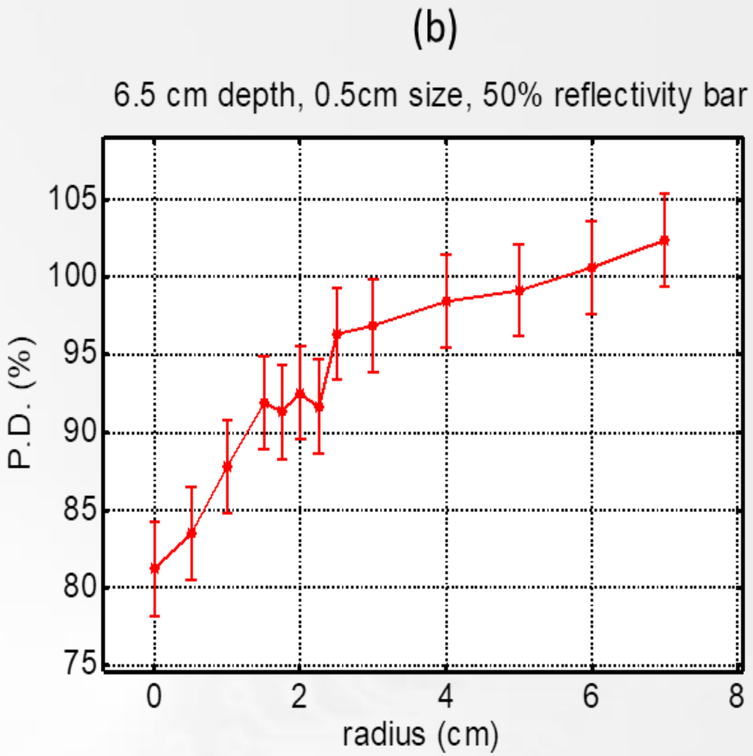

1. **Photon density on surface decreases with the bar width (50% reflecting bar in x = 0)**
2. **Photon density on surface has a minimum along the radius**

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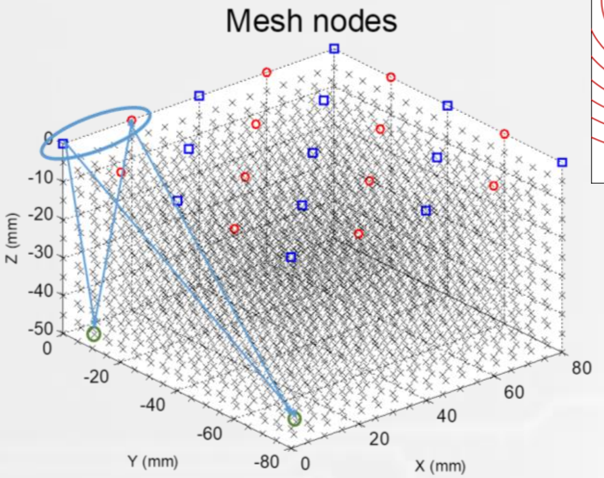
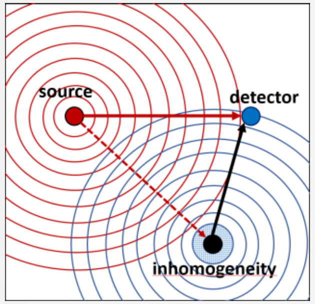
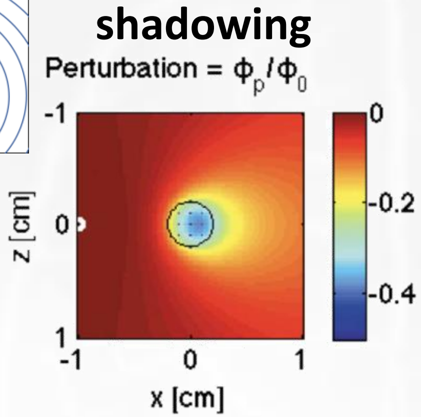
Signals prediction: Montecarlo Simulation

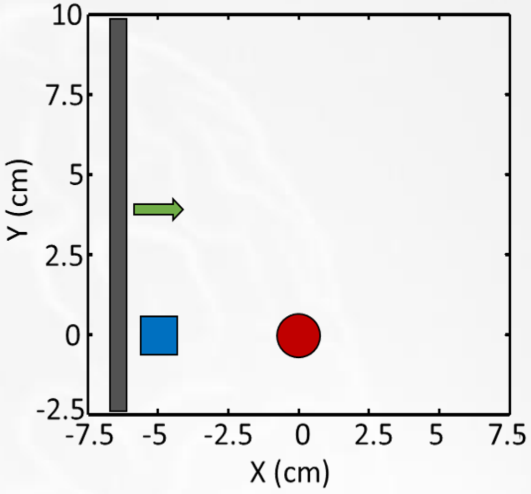
$$y_{sd}(t) \propto \sum_{p=1}^{N} T_{s\to v_p}(t) \cdot T_{v_p\to d}(t)$$



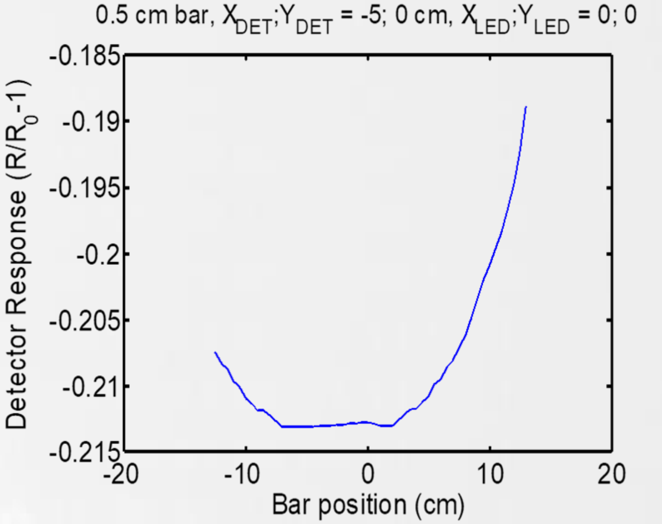


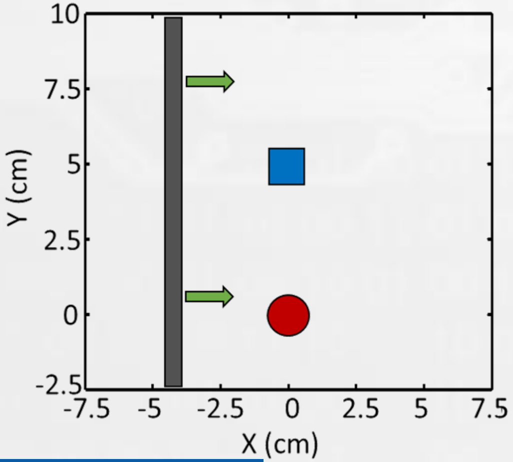


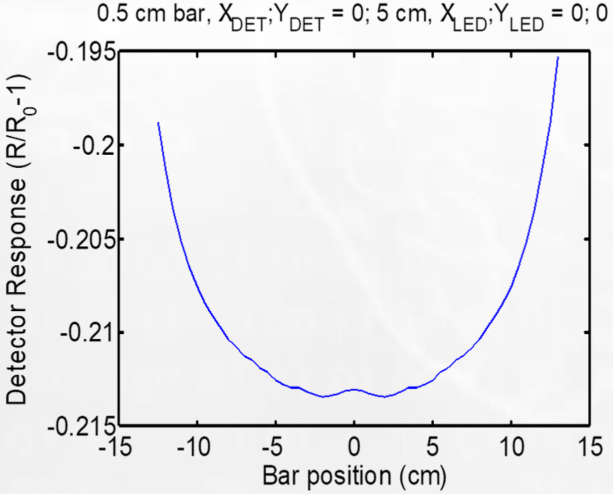
(a)

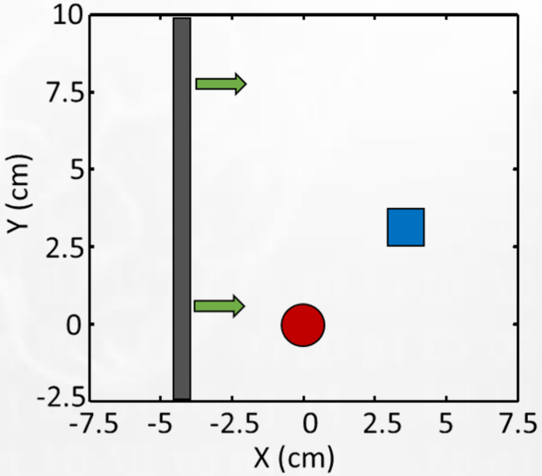


(b)

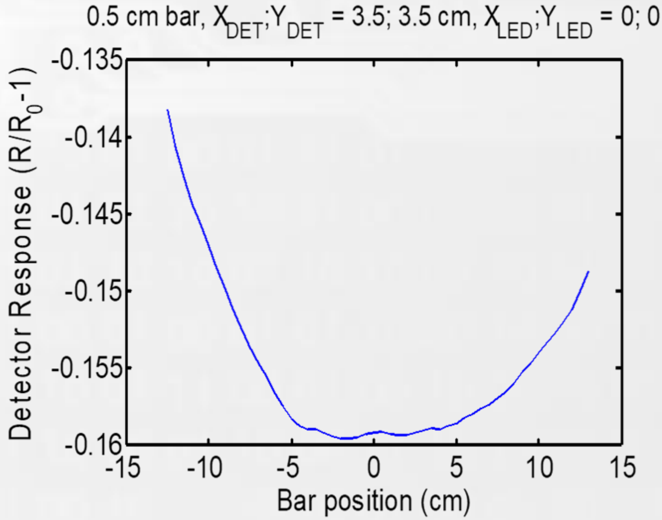




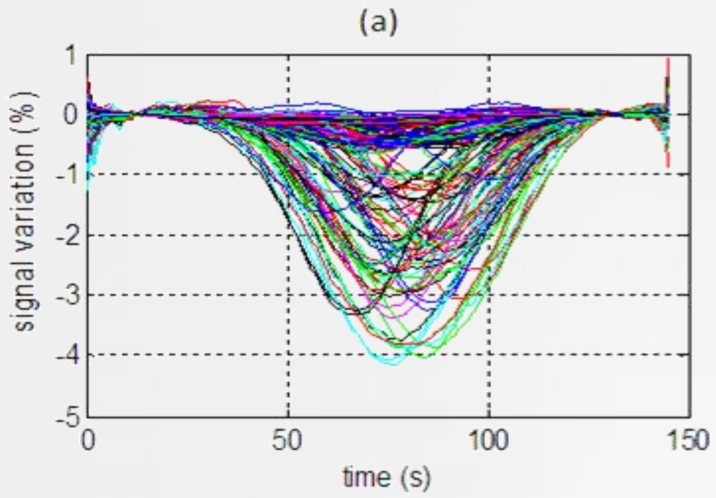


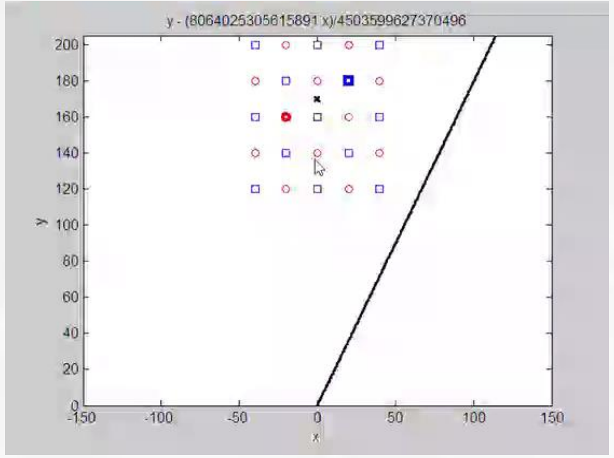


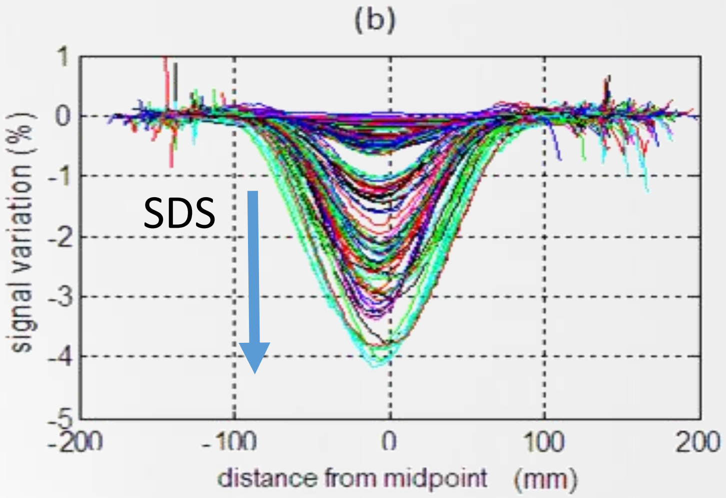
(c)

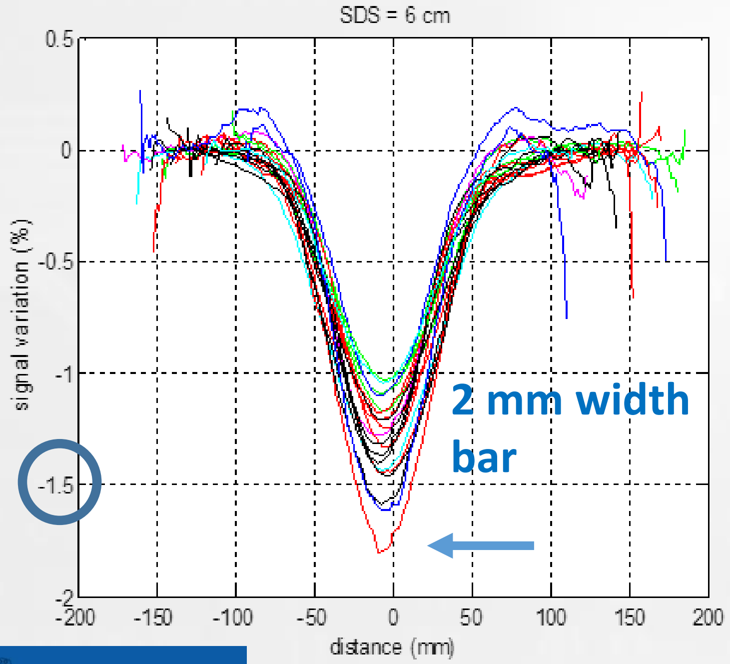


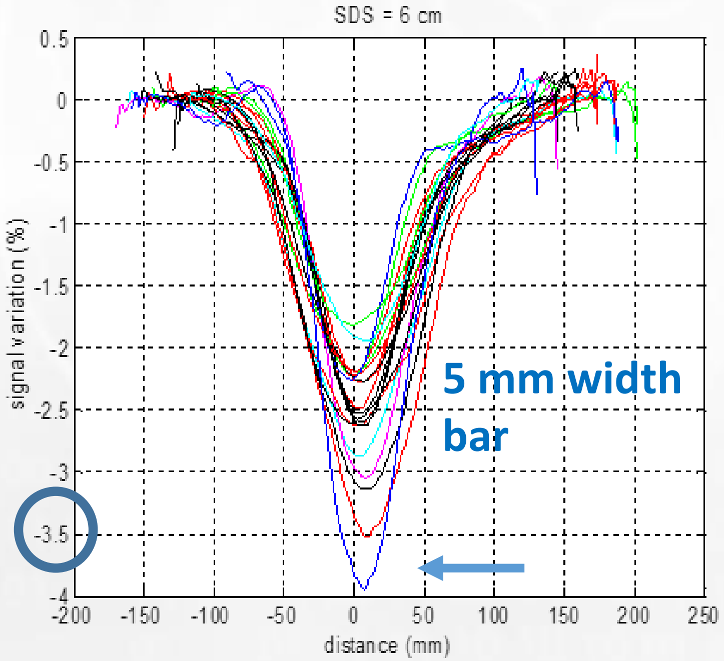
Signals prediction: Comparison

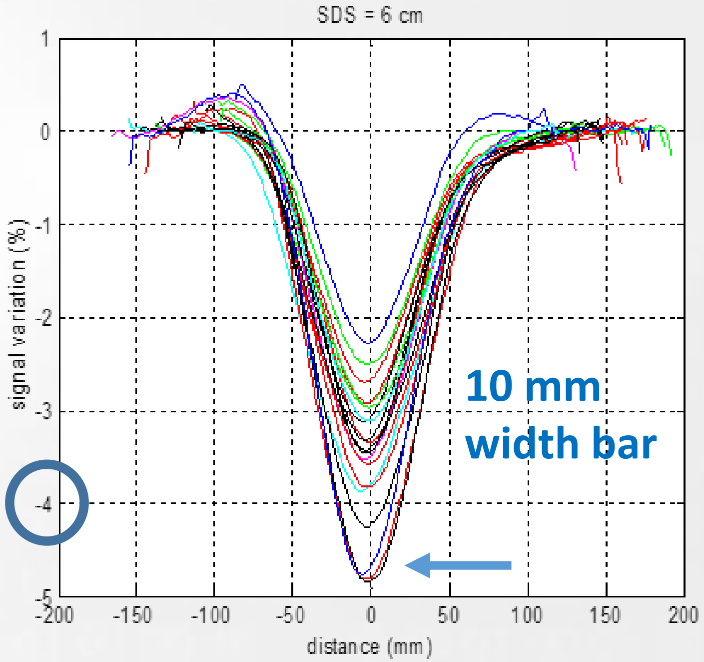












Imaging algorithm for DOT measurements

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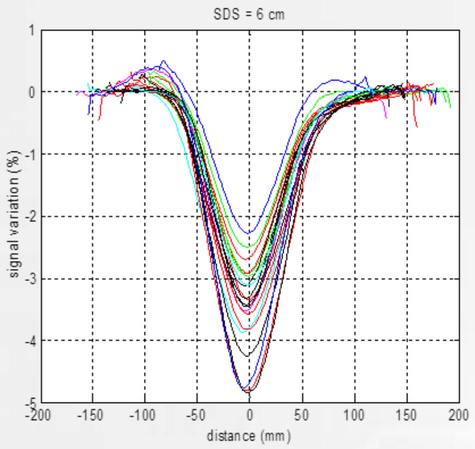

$D = \sim SDS/2$

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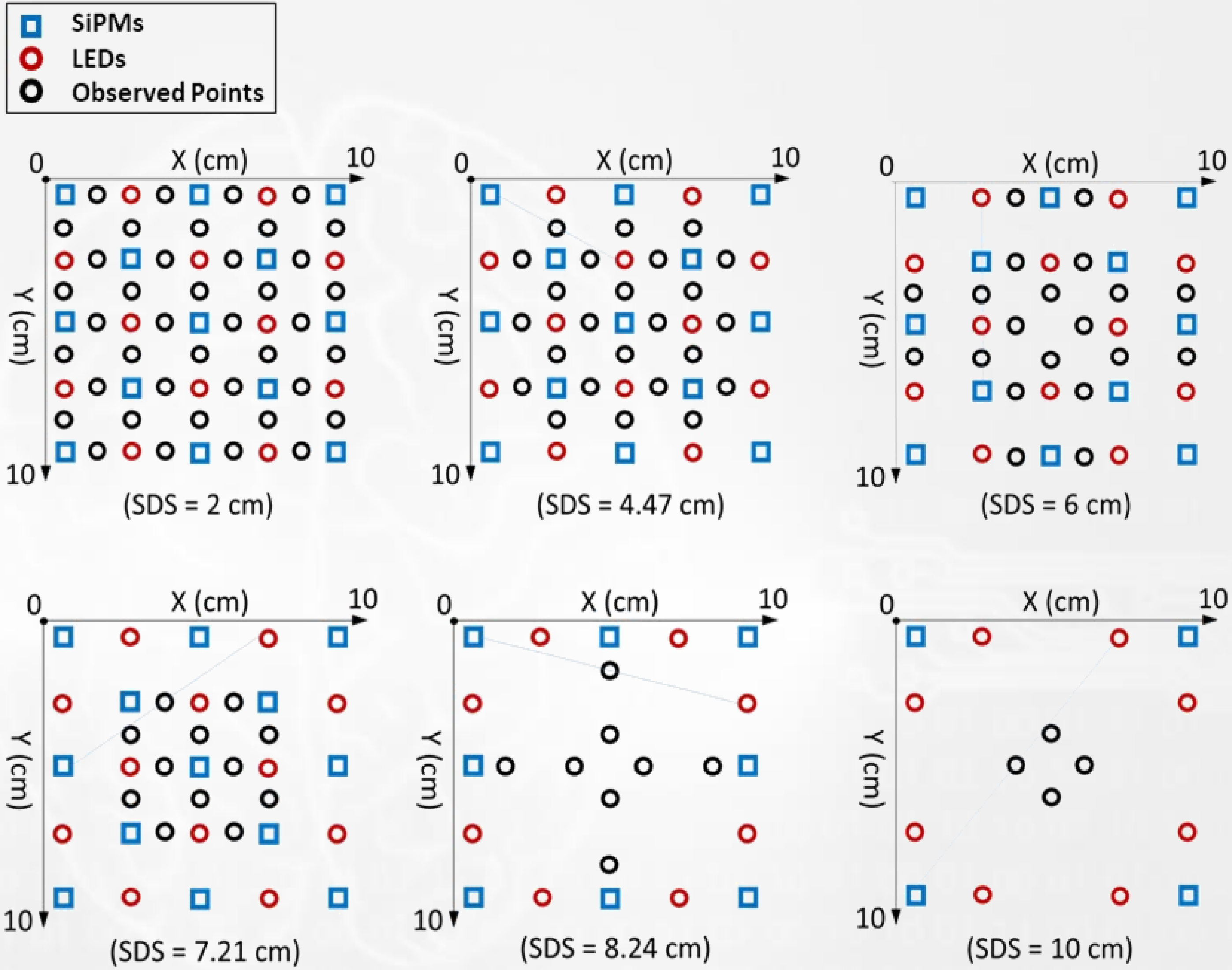
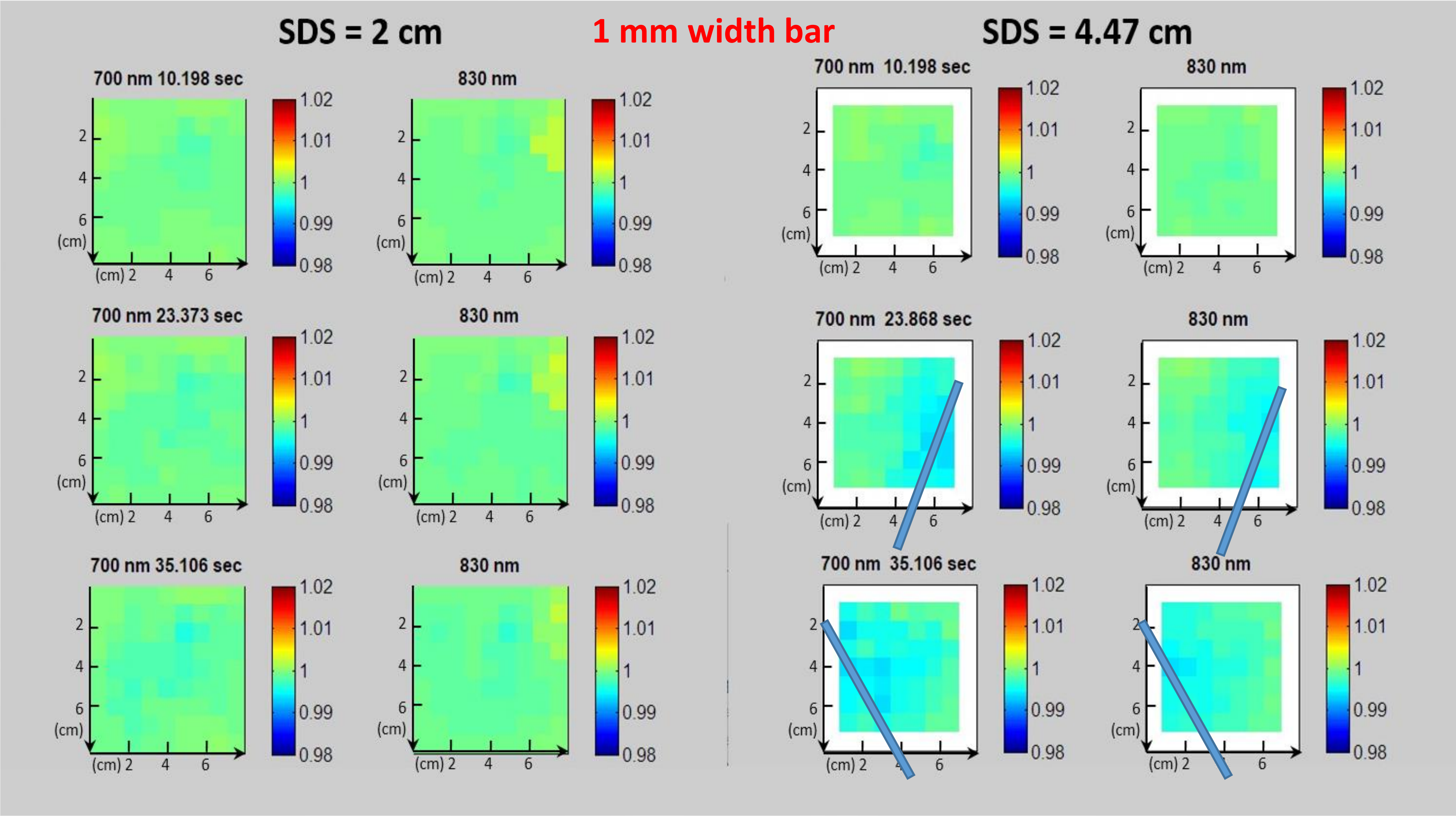


Imaging algorithm for DOT measurements



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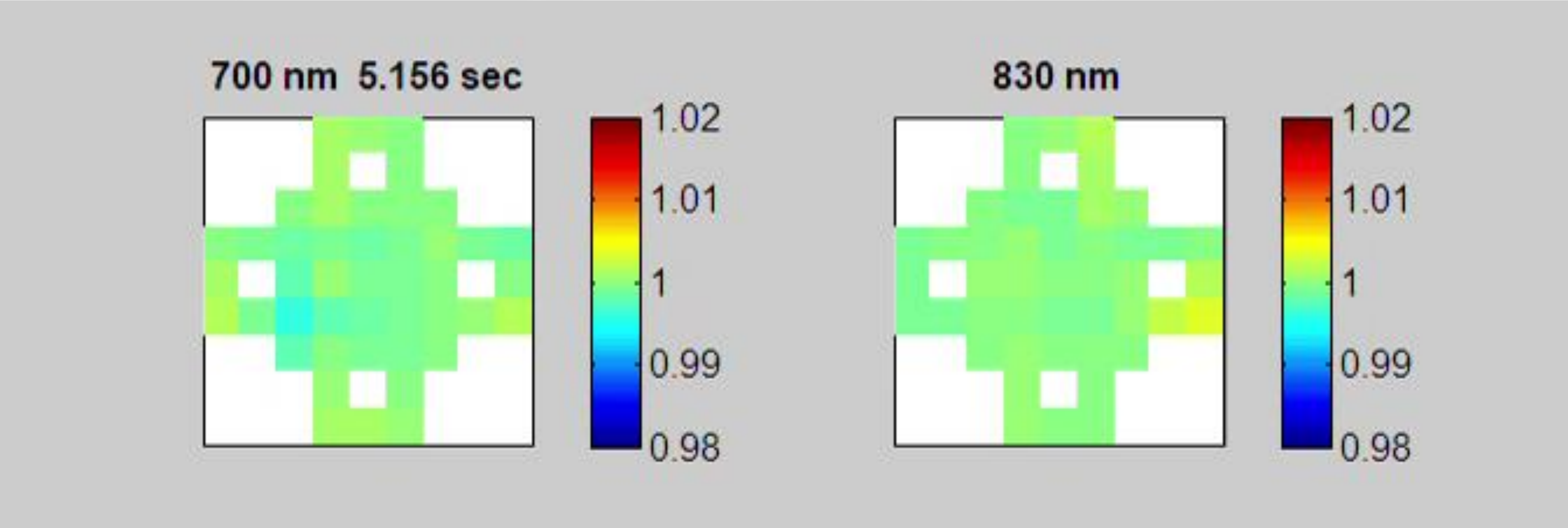
SDS = 6 cm , 1 mm width bar



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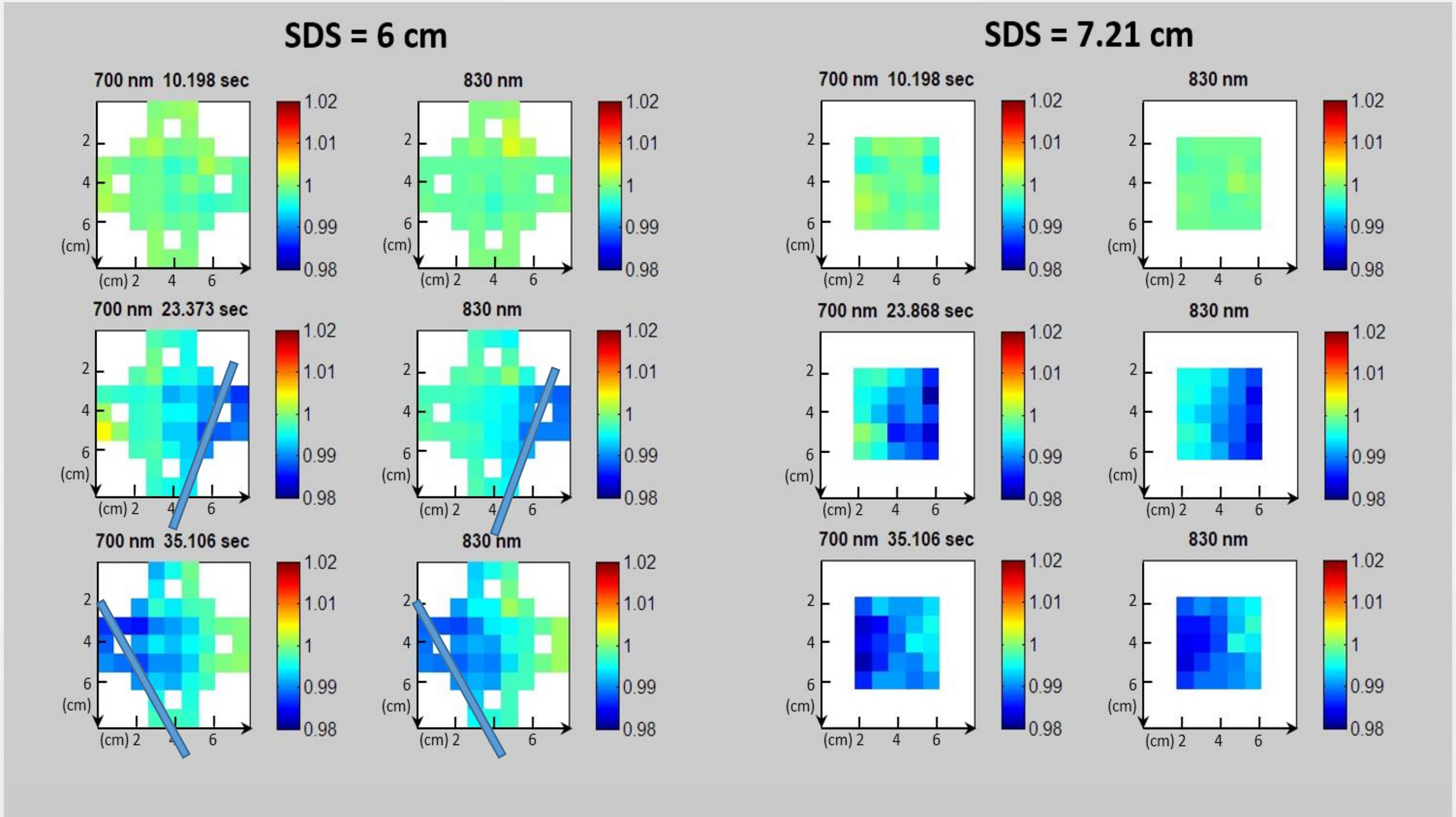

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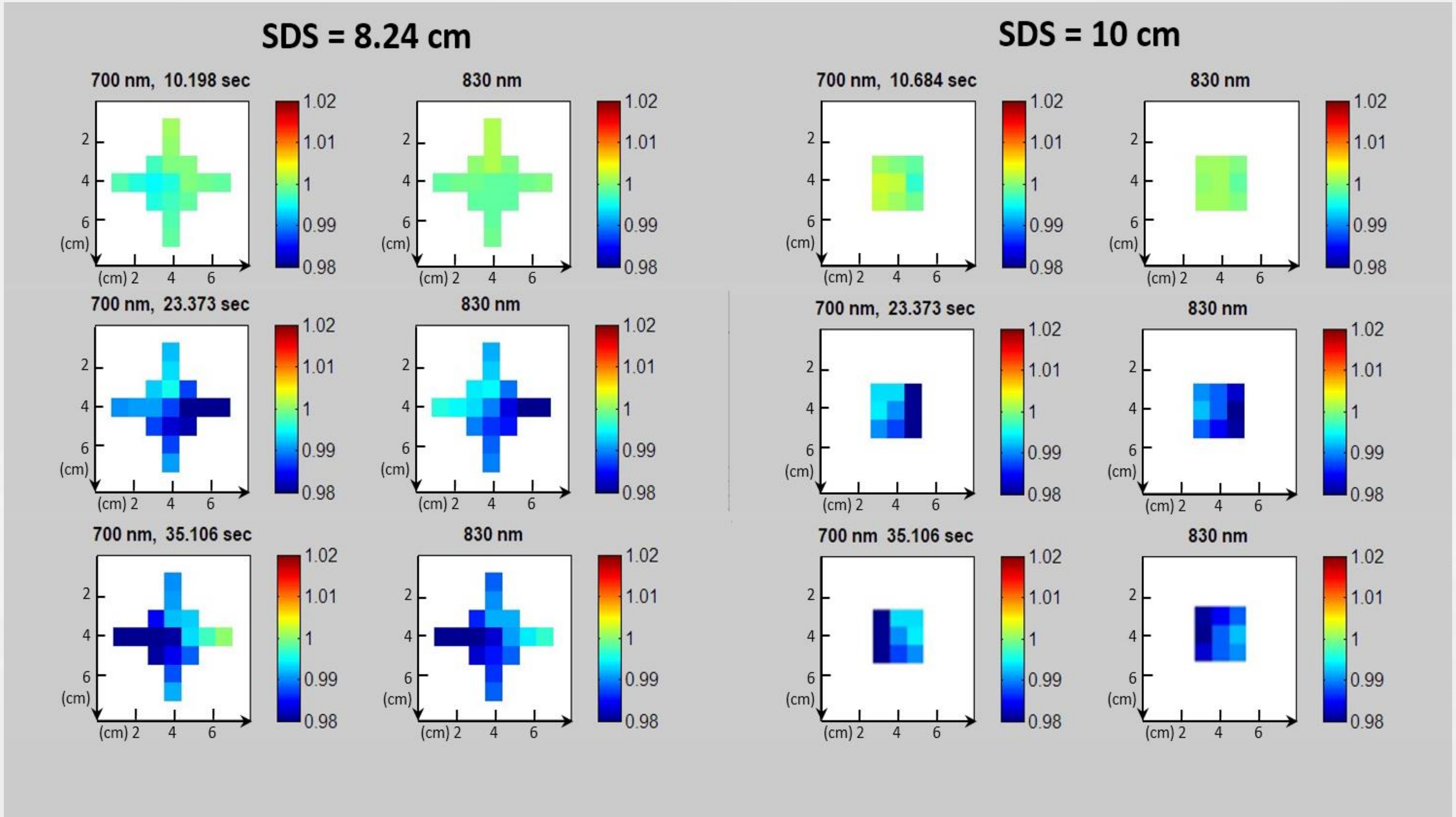

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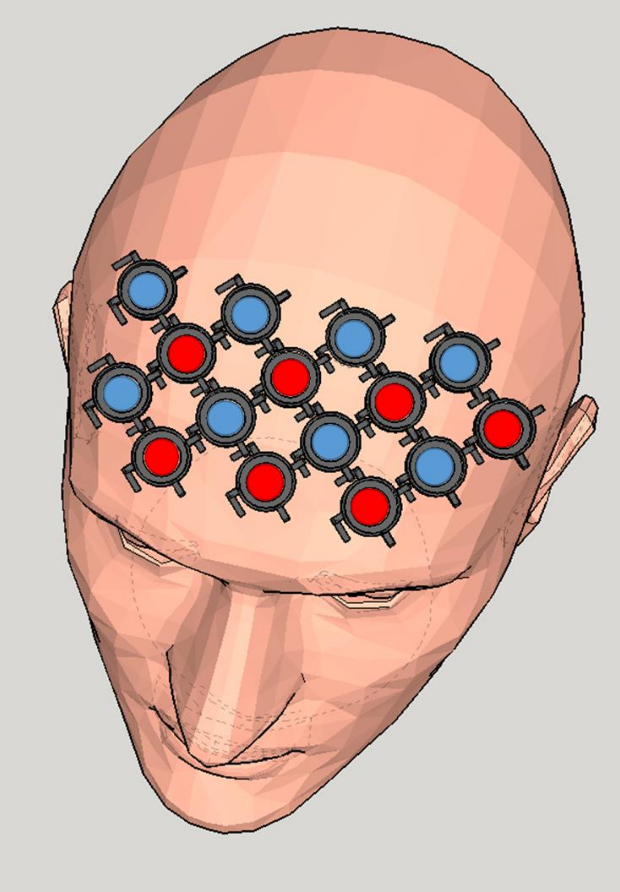
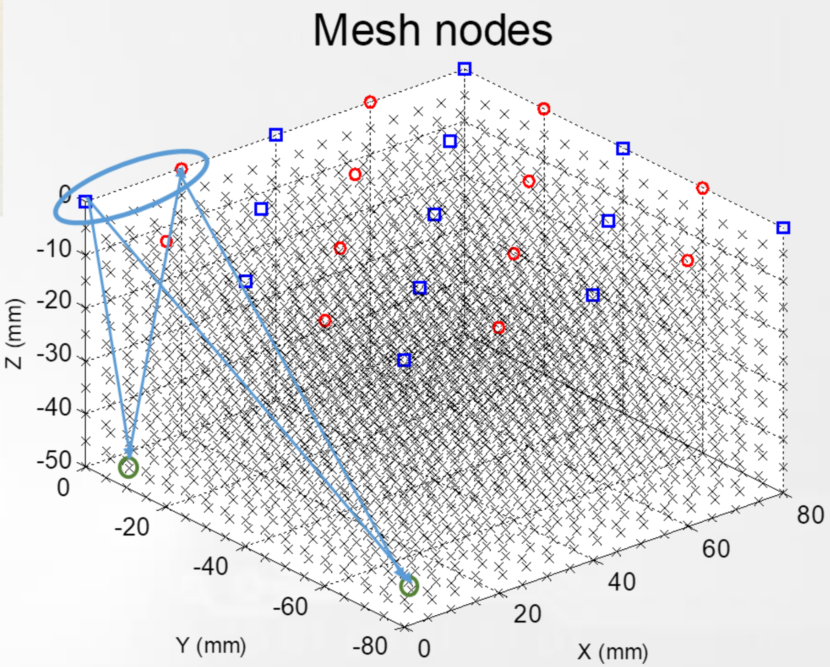
Future Work





Imaging algorithm for DOT measurements

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TOMOGRAPHY

Direct problem:

$\mathbf{y} = \mathbf{A}\mathbf{x}$

Inverse problem:

$\hat{\mathbf{x}} = \mathbf{A}^T(\mathbf{A}\mathbf{A}^T + \alpha s_{\max}\mathbf{I})^{-1}\mathbf{y}$

In homogeneous media:

$$a_{i,j} = \frac{\partial}{\partial \mu_{ai}} I_j$$

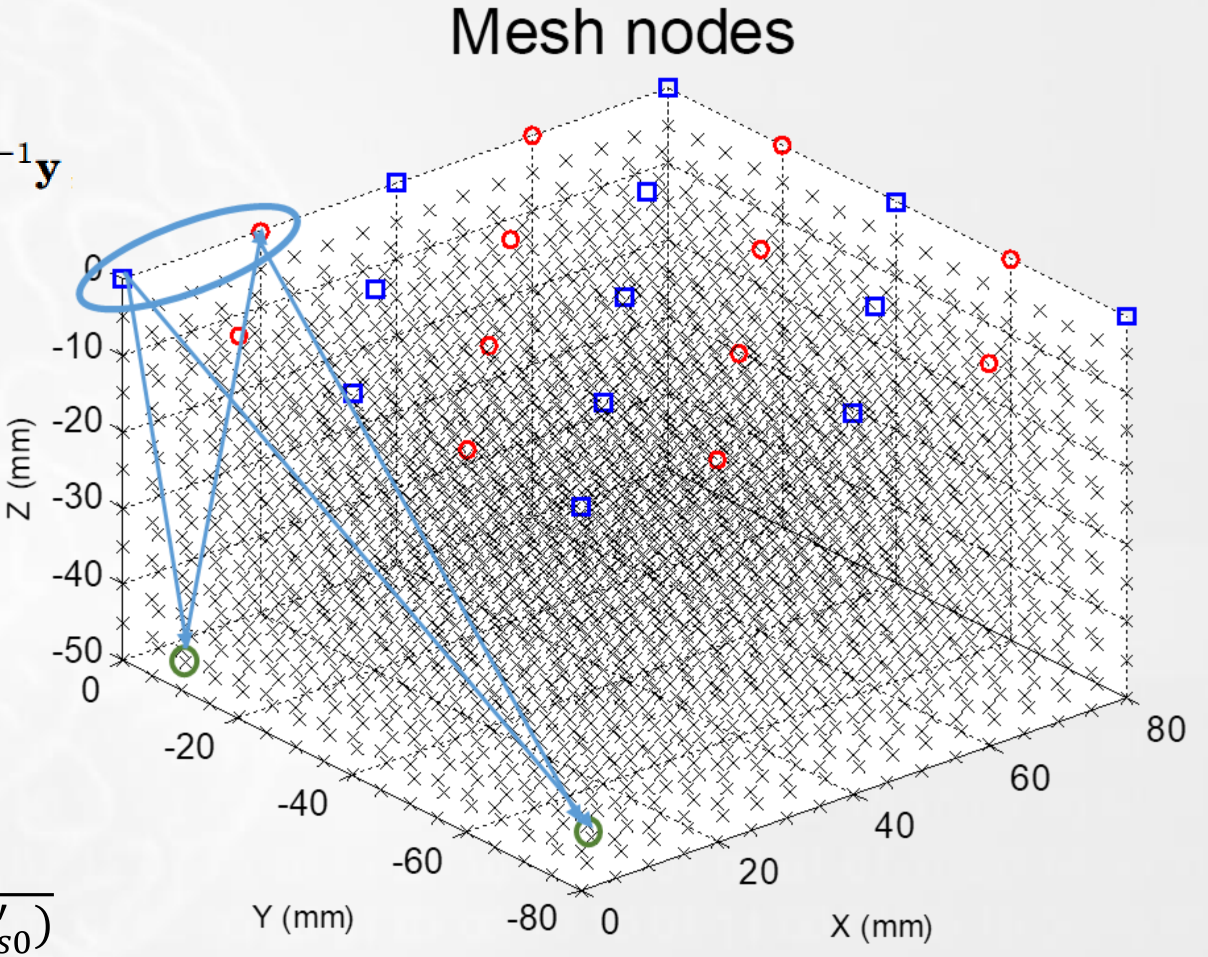
Evaluable with the adjoint method:

$$a_{i,j} = -T_{s\to p}T_{p\to d}$$

$$T_{s\to p} = \frac{\exp(-r_{s\to p}/\delta)}{4\pi D r_{s\to p}}$$

$$D = \frac{1}{3(\mu_{a0} + \mu'_{s0})}$$

$$\delta = \sqrt{D/\mu_{a0}}.$$



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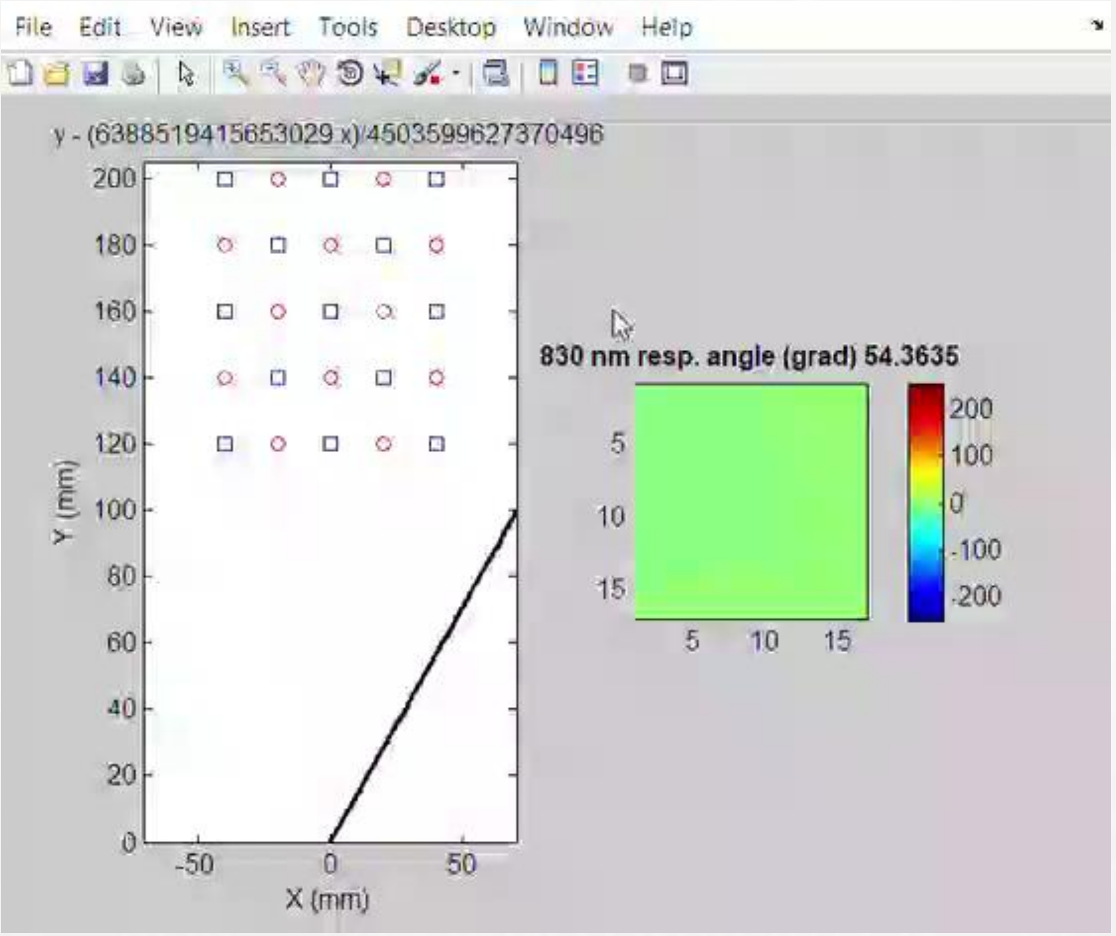

Conclusions

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- Optimized use of Silicon Photomultiplier devices in fNIRS: Electrical - Physical – Optical Characterization:

  - After-pulsing
  - Defects
  - Thermal Transients
  - Signal to Noise Ratio optimization
  - Linear range → intellectual property production

- Realization of an optimized dynamic phantom with light diffusion properties close to human tissues
- Baseline optical characterization of materials by Time of flight measurements – Montecarlo simulations
- Realization of 156 channels/2 wavelenghts fNIRS/DOT system with optimal use of Si Photomultipliers
- Experimental results in excellent agreement with Monte Carlo light diffusion modeling
- Imaging algorithm based on back-projection approach

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Thank you!

Gaetano Santoro
Alfredo Ferro

Salvatore Lombardo
Sebania Libertino

IMM Institute for Microelectronics and Microsystems

Giorgio Fallica
Vincenzo Vinciguerra
Delfo Sanfilippo
Massimo Mazzillo

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