

DVN LiDAR Conference 2022, Wiesbaden

Data reduction in SPAD-based LiDAR systems

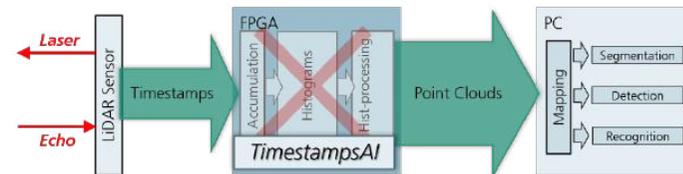
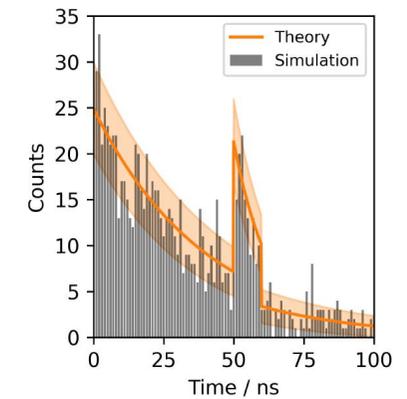
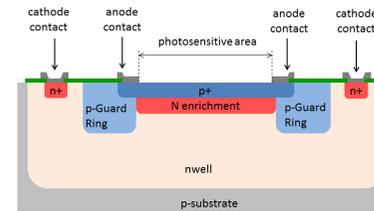
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Data reduction in SPAD-based LiDAR Systems

Outline

- A brief review on single-photon avalanche diodes (SPAD)
- SPAD and direct time-of-flight LiDAR
- TimestampsAI: AI-based LiDAR data processing
- Case-example in human-robot-interaction:
Fraunhofer Lighthouse Project “NeurOSmart”

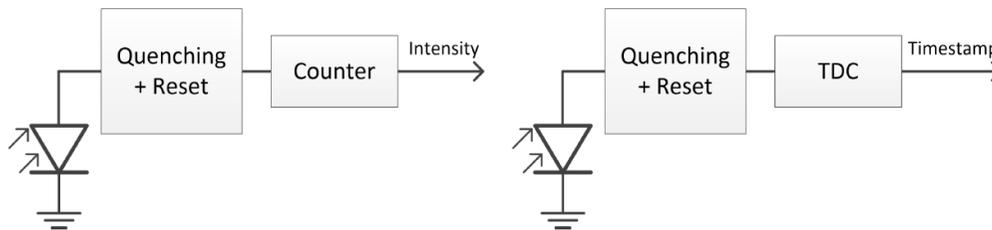


NeurOSmart

Core Technology

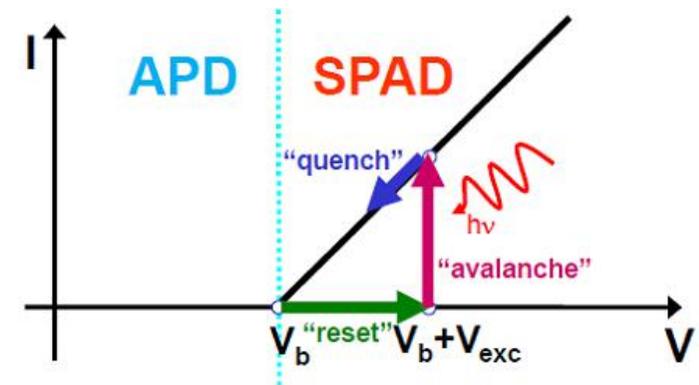
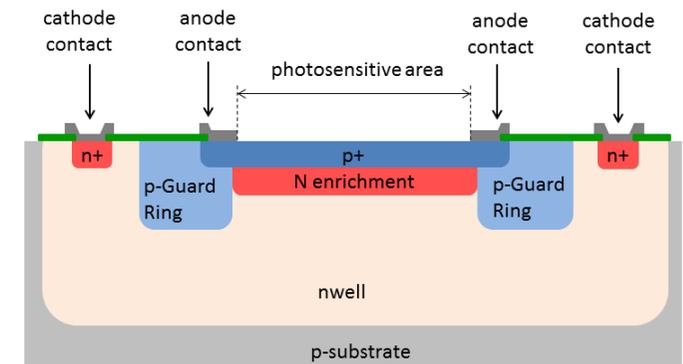
Single-Photon Avalanche Diodes (SPAD's)

- Diode operates in Geiger (Breakdown-) regime
- Events can be recognized and passed to counting or timing (TDC) structures
- Current needs to be quenched to reset the device



- CMOS compatible process
- High sensitivity with world-record dark-count-rate ($<0.1\text{Hz}/\mu\text{m}^2$)

C. Accarino *et al.*, *IEEE Sensors* 19(17), 7319 (2019)



Core Technology

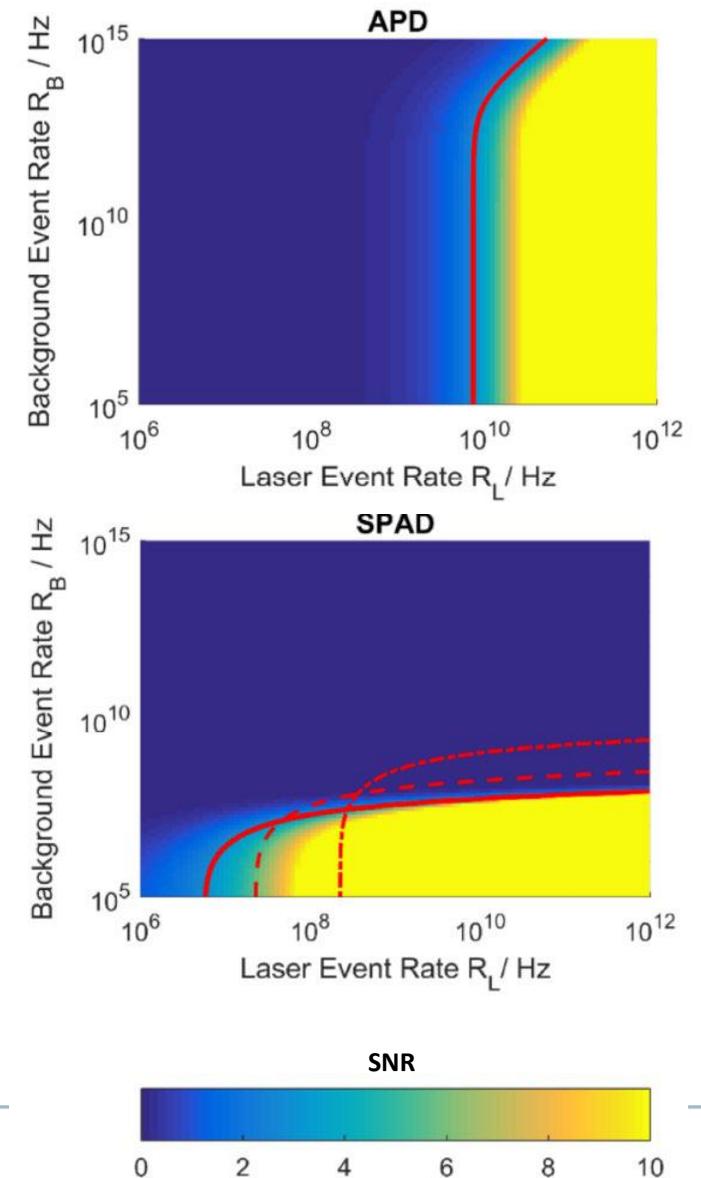
APD's vs. SPAD's

source: forschungsfabrik-mikroelektronik.de

	PIN-PD	APD	SiPM	SPAD
Gain	1	10^3	10^6	10^6
Single photon detection	No	No	Yes	Yes
Operational Bias	Low	Medium	Medium	Medium
Temperature Sensitivity	Low	High	Low	Low
Array possible	Limited	Limited	Limited	Yes
Readout / Electronics	Complex	Complex	Medium	Simple
Rise time	Medium	Slow	Fast	Fast

- **SNR (Signal-to-Noise)=3 analysis for target distance of 100 m**
- **Taking into account read-out and amplification noise of APD**
- **SPAD perform better in low-light scenarios, but fail at high background rates ...**
- **SPADs are n particular suited for FLASH LiDAR**

A. Buchner *et al.*, *MDPI Sensors* **21**(8), 2887 (2021)



SPAD and direct time-of-flight (dTOF) LiDAR Measurement Principle

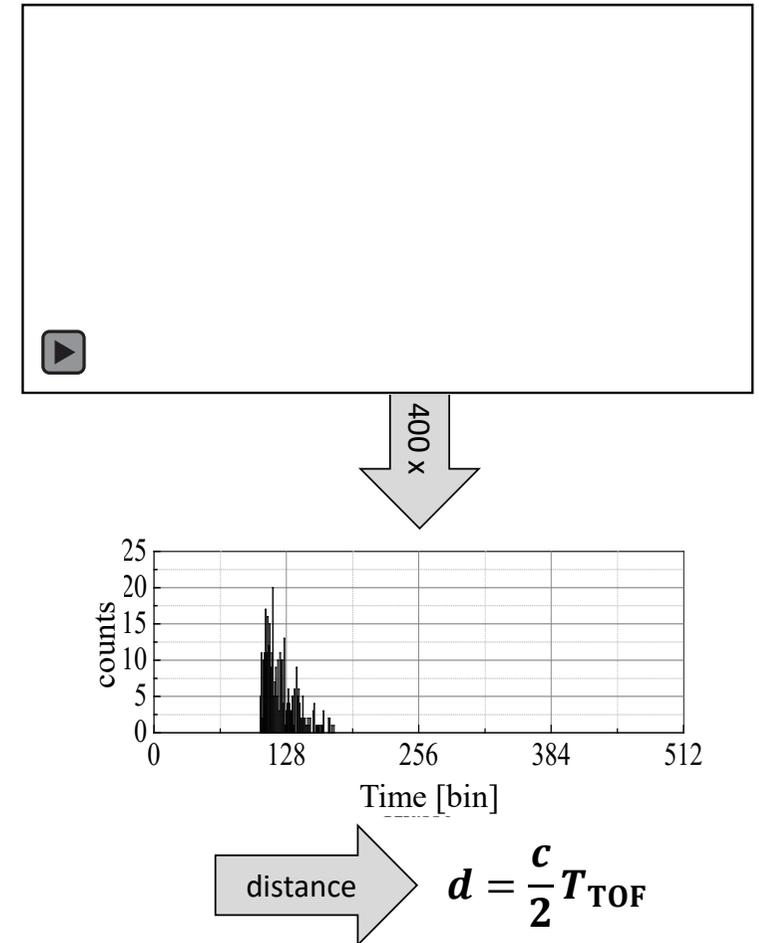
- Exemplary values:

- $d_{\text{MAX}}=200 \text{ m} \Rightarrow t_{\text{MAX}}=1.3 \mu\text{s}$
- $R_{\text{laser}}=10 \text{ kHz}, 25 \text{ fps} \Rightarrow 400 \text{ timestamps per histogram}$
- $\Delta d=5 \text{ cm} \Rightarrow \Delta t=334 \text{ ps}$

120 kBit/s/px data stream
1.9 Mbit/frame/px histogram memory

- Full imager (e.g. 100x100 px array):

- 150 MB/s data stream
- 2.3 GB/frame histogram memory



SPAD and direct time-of-flight (dTOF) LiDAR

Counting Statistics

- Device is “blind” for a “dead-time” after detection of the first photon and cannot distinguish between laser r_L and background light r_B photons
- Detection probability of photons is exponentially decreasing with time of flight

$$p(t) = r(t) \cdot \exp\left(-\int_0^t r(\tau) d\tau\right)$$

- Distant objects become harder to detect when background light r_B is present

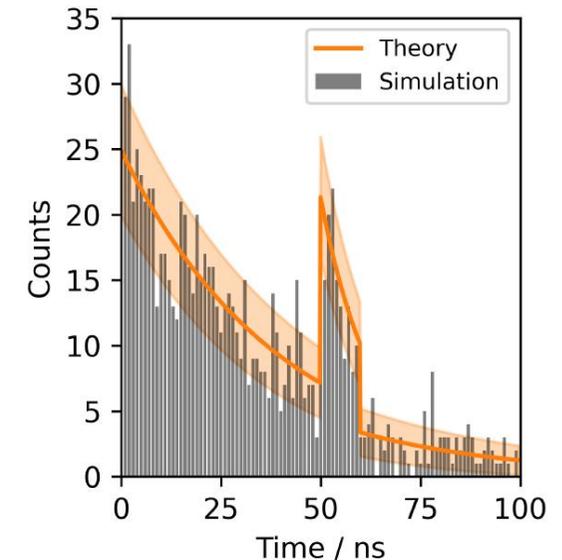
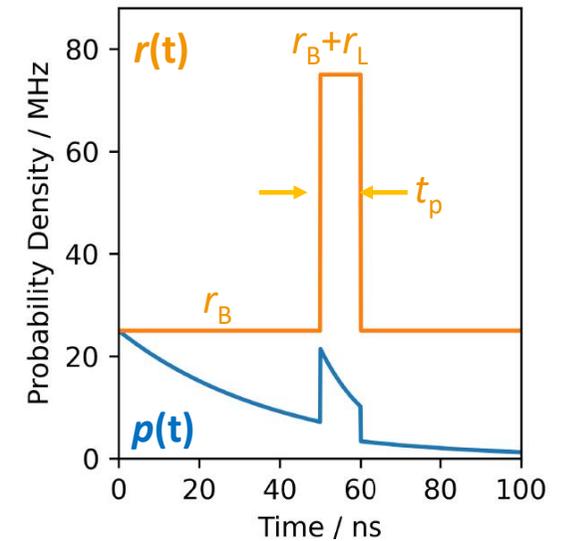
$$SNR = \sqrt{N t_p \exp(-r_B T_{TOF})} \frac{r_L}{\sqrt{r_B + r_L}}$$

- Pile-up and range-walk effects

in-depth data analysis required

A. Buchner *et al.*, *MDPI Sensors* **21**(8), 2887 (2021)

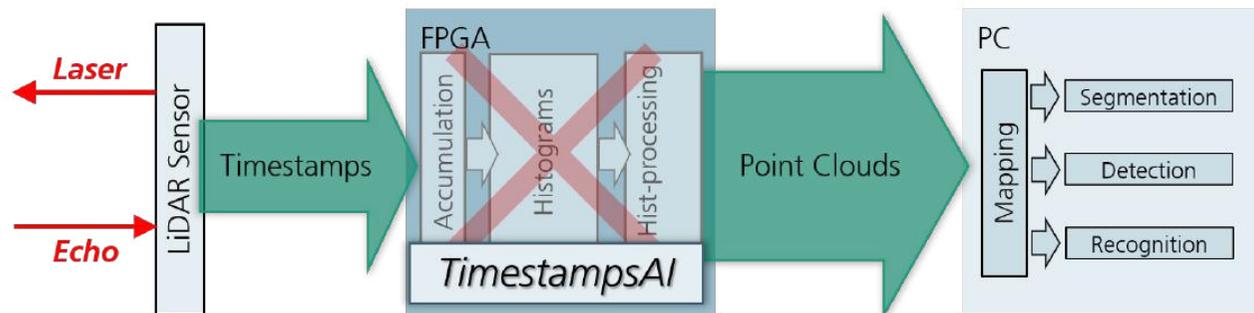
A. Henschke, Dissertation Univ. DUE (submitted)



TimestampsAI

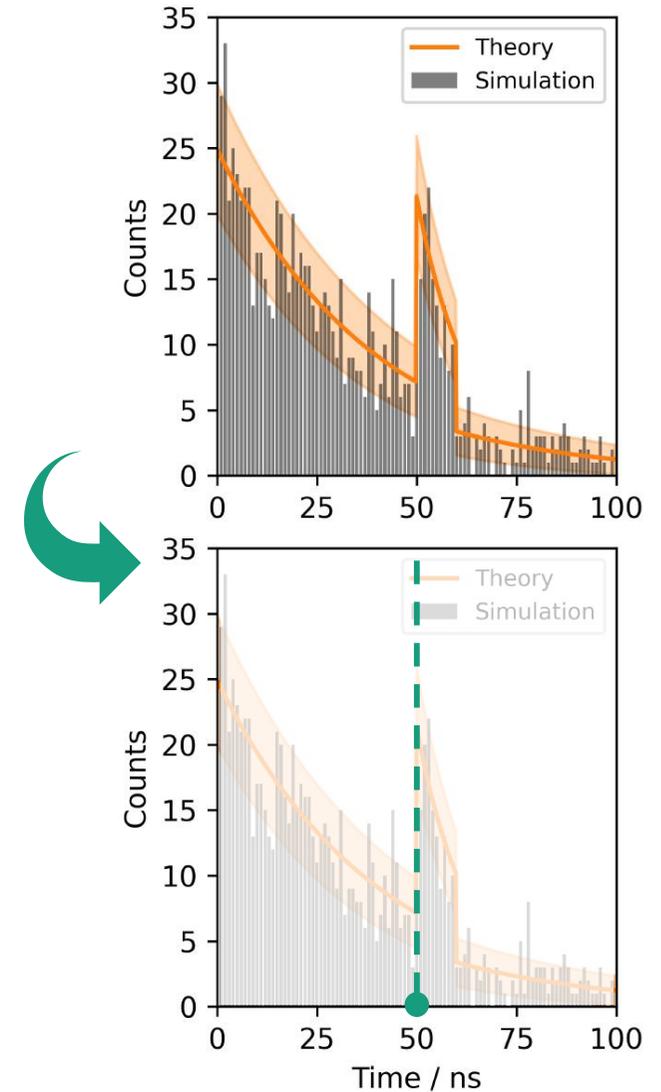
LiDAR data processing

- Floating data analysis by pre-trained (“gray-box”) neural network
- Processing on FPGA



Fraunhofer IMS patent in preparation

bypass histogram storage
confidence level analysis

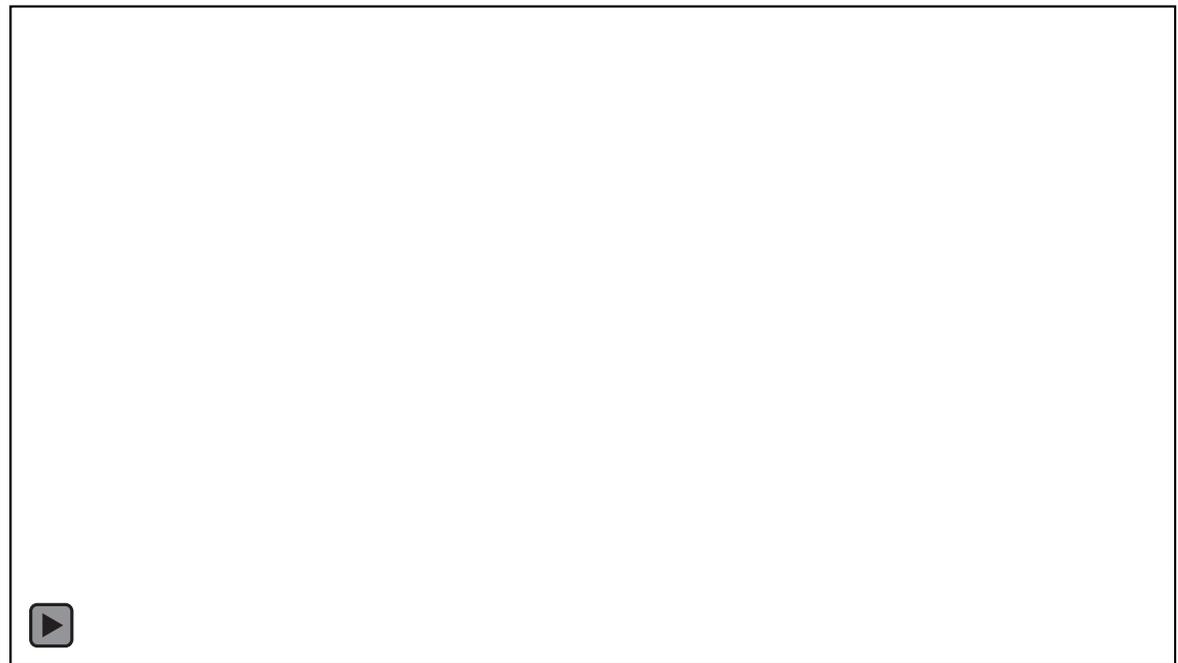


Fraunhofer Lighthouse Project NeuroSmart

Analog neuromorphic accelerators enabling efficient and smart sensors



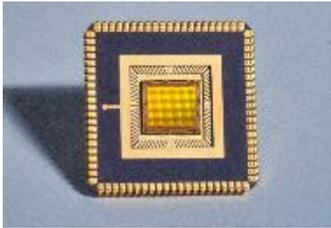
- **Use-case: human-robot-collaboration**
- **Reconfigurable LiDAR system**
- **AI-based raw data reduction and Region-of-Interest selection**
- **Optimized energy efficiency of AI processes through analog neuromorphic in-memory accelerator**
- **Application-specific, compact neural networks**



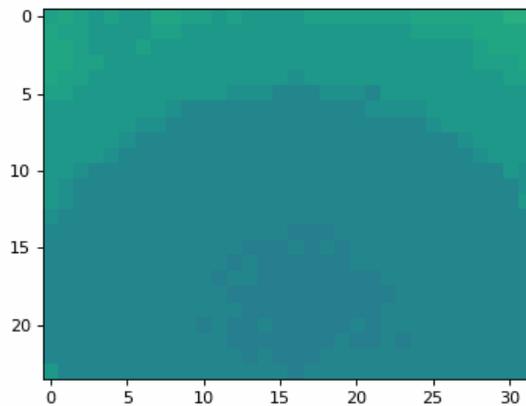
initial deployment in a human-robot-collaboration environment

Fraunhofer Lighthouse Project NeurOSmart

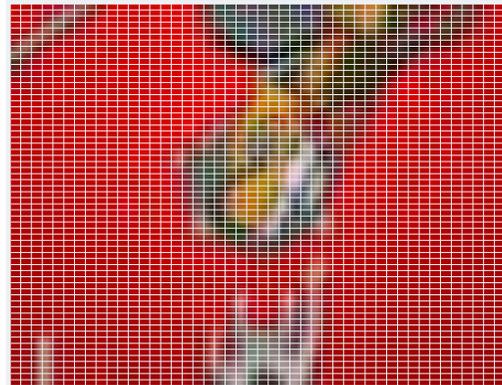
IMS CSPAD Sensor Family



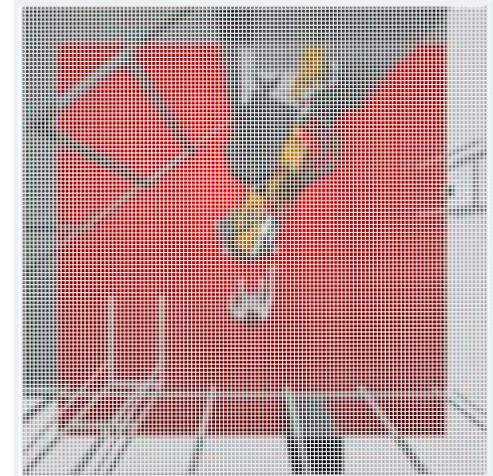
- **CSPAD α**
- **32x24 pxs**
- **FOV 30°x40° FLASH**
- **34 MB/s data stream**



- **CSPAD3K**
- **64x48 pxs**
- **FOV 30°x40° FLASH**
- **134 MB/s data stream**



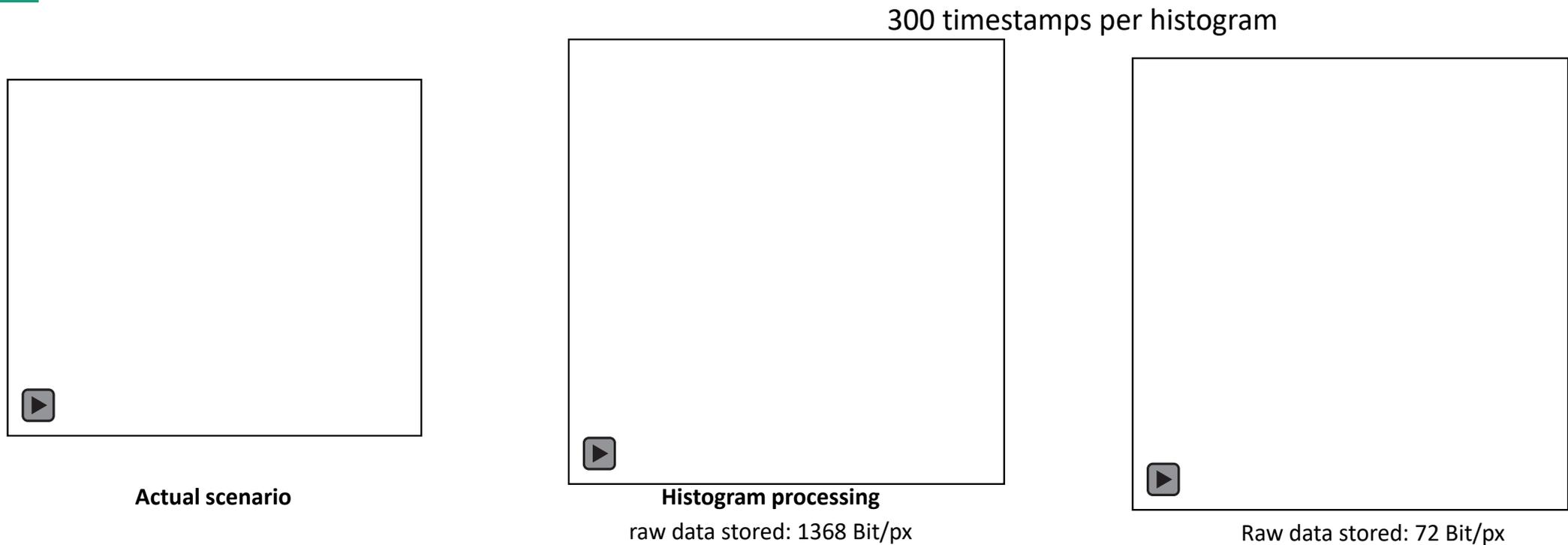
- **CSPAD12K**
- **112x112 pxs**
- **FOV 90°x90° sq. FLASH**
- **724 MB/s data stream**



see, e.g. S. Grosse *et al.*, *SMSI2021*, doi:10.5162/SMSI2021/B10.1 (2021)

TimestampsAI

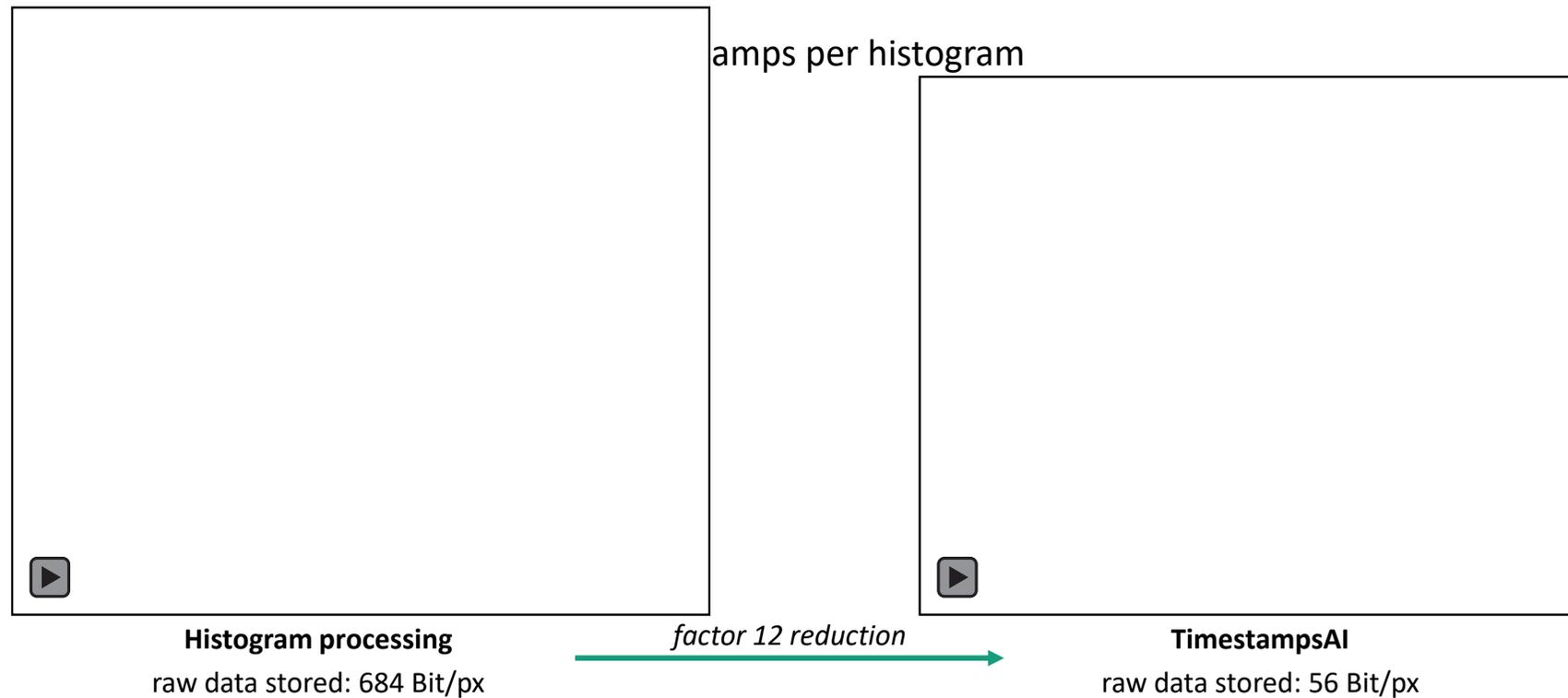
Results: TimestampsAI vs. histogram processing



- AI was trained on box, ground and stationary dummy distance
- Reduced keystone distortion

TimestampsAI

Results: TimestampsAI vs. histogram processing

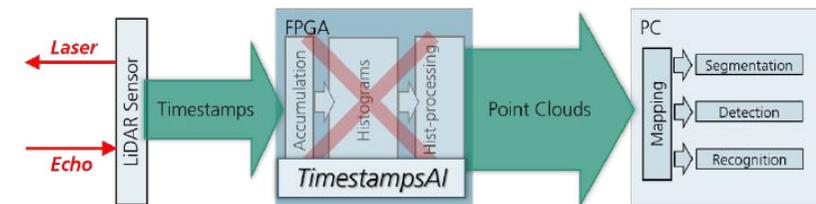
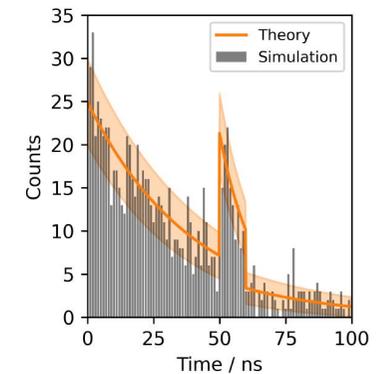
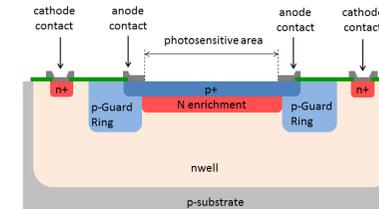


Successful negligence of dominating background events in AI approach

Data reduction in SPAD-based LiDAR systems

Summary

- SPAD arrays are a key player in FLASH LiDAR systems, but provide huge amount of data
- Presence of background photons requires histogram formation and, thus, provisioning of sufficient memory
- Complex histogram analysis required
- Data processing using TimestampsAI results in stable point-cloud
- Limited amount of training data required
- Raw data reduction of at least 90%



Data reduction in SPAD-based LiDAR systems

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NeuroSmart

Fraunhofer ISIT
Fraunhofer IPMS
Fraunhofer IWU
Fraunhofer IAIS

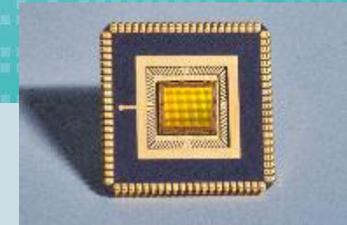
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