On-chip and off-chip processing for high-speed, super-resolution LIDAR

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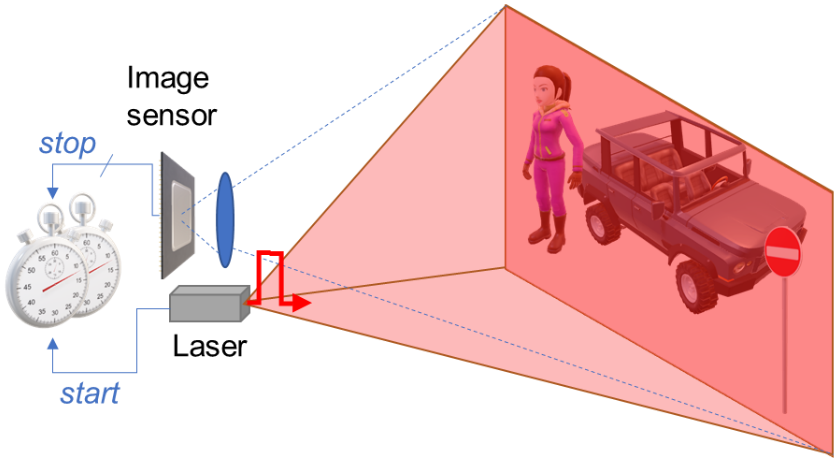
Contents

- Solid-state LIDAR
- SPAD sensor architectures for LIDAR
- Depth map enhancement and scene interpretation

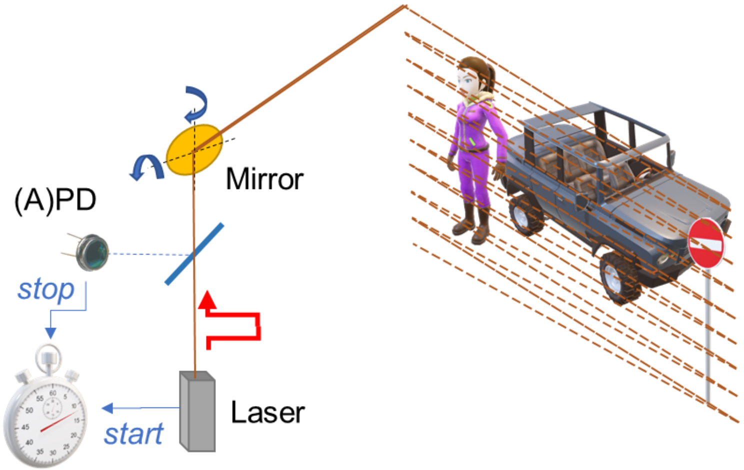
LIDAR

Solid-state



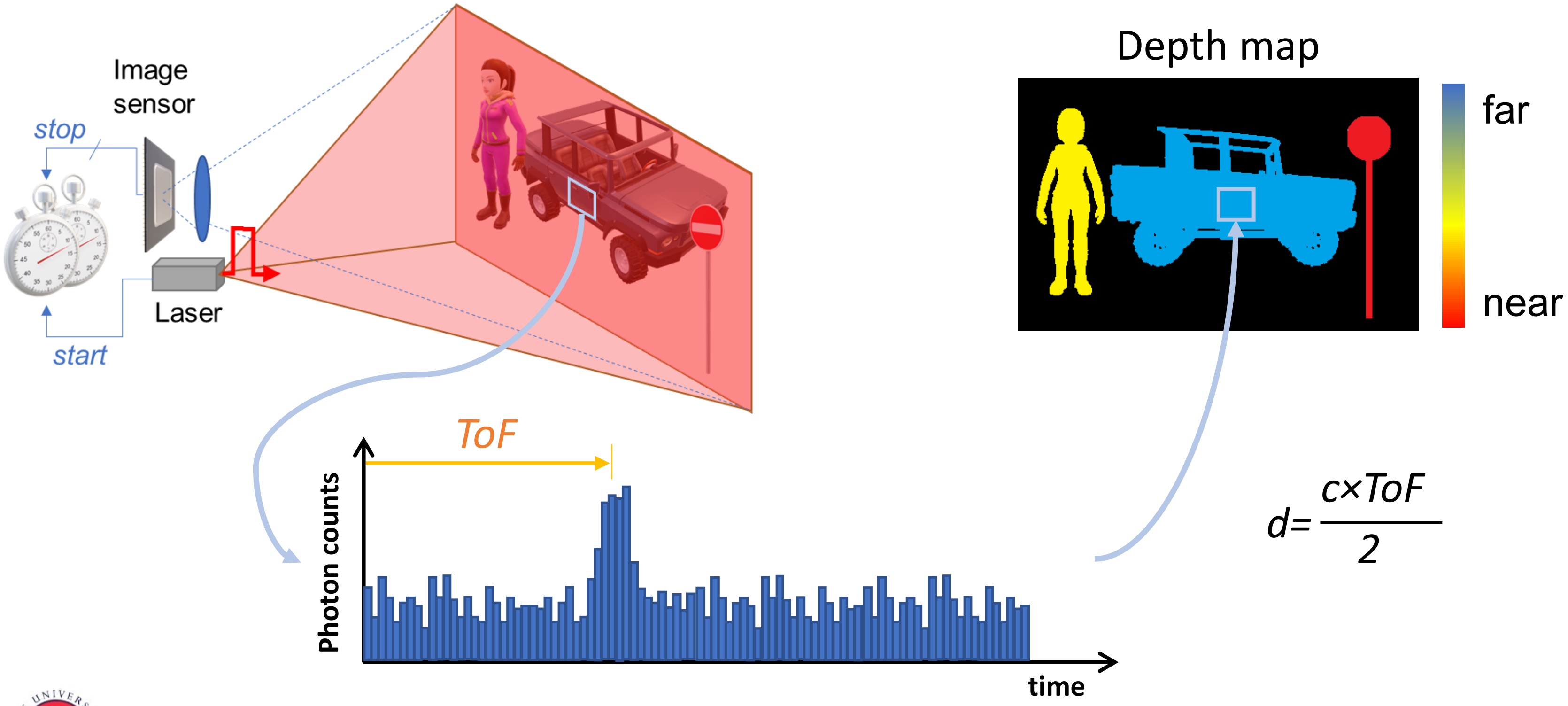
- Compact, robust system ✓
- Lower cost ✓
- Reduced motion artefacts ✓

Mechanical scanning



- Simpler receiver architecture ✓
- Higher SNR ✓

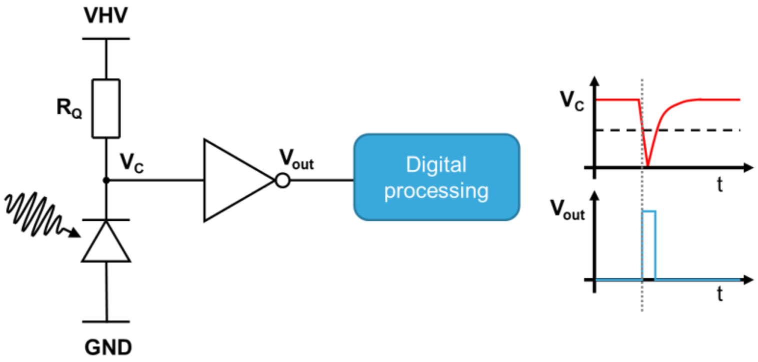
Time-correlated single-photon counting (TCSPC)



$$d = \frac{c \times ToF}{2}$$

Advantages of SPADs

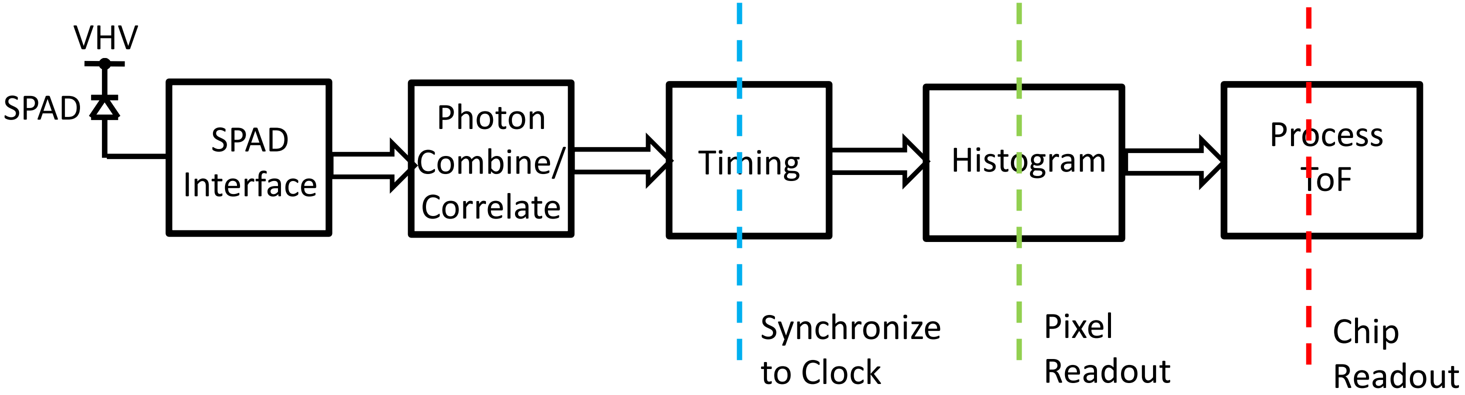
- CMOS-compatible → arrays with integrated processing
- Output is digital → all-digital receiver
- Low jitter (<100ps) → high resolution in z
- Low noise, even at room temp. and above→ no need for cooling



Challenges

- High photon detection efficiency (PDE) (NIR)→ long range (250m)
- High photon throughput → high frame rates even under high ambient levels (100klux)
- Scalable architecture→ large FOV with high angular resolution ($120^{\circ} \times 30^{\circ}$, $<0.1^{\circ}$)
- Low power consumption (class 1 laser source)

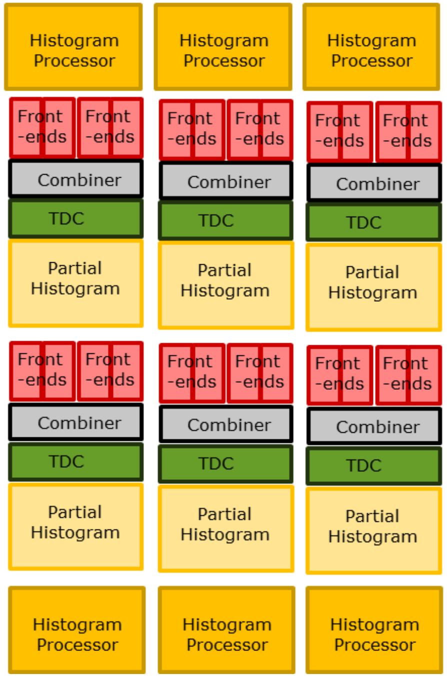
SPAD ToF Imagers



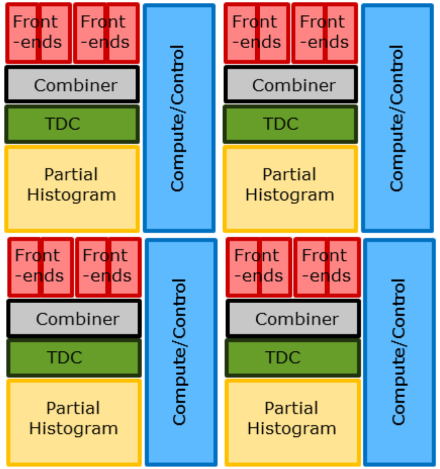
Aim: High resolution, solid-state, scanning/flash imagers for LIDAR

- SPAD Interface (front-end) : quench, buffer, level shift
- Photon Combine : combine or correlate multiple SPADs
- Timing : measure the arrival time of photons
- Histogram : assemble photon event times into a histogram
- Process ToF : Background removal, time of flight fitting, pile-up correction, compress data

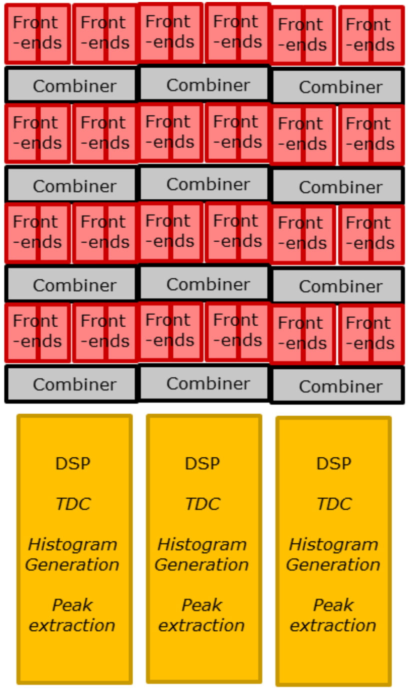
3D-Stacked Architectures



Partial Histogram ToF



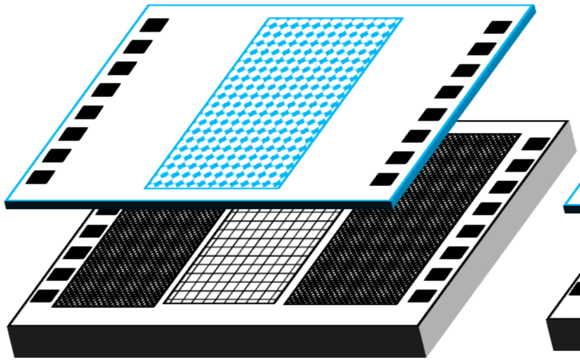
Adaptive Histogram ToF



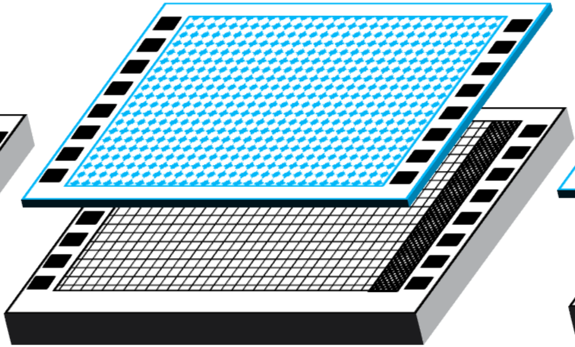
Full histogram ToF

Top and Bottom Tier Usage

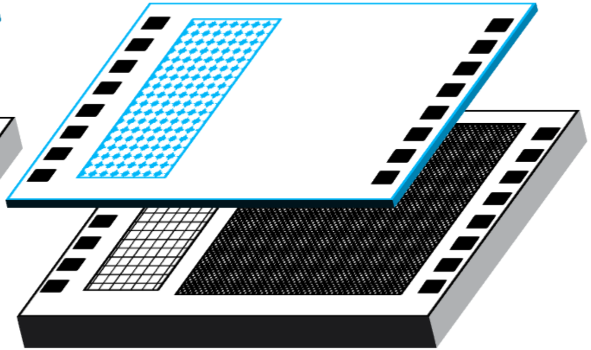
Partial Histogram ToF

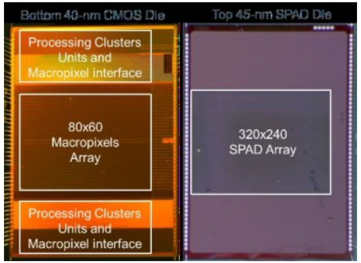


Adaptive Histogram ToF

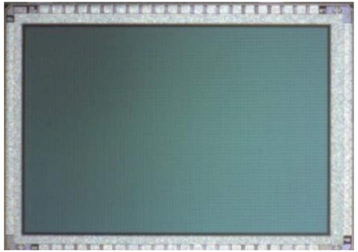


Full histogram ToF

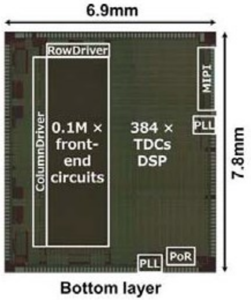




Stoppa, IISW 2021



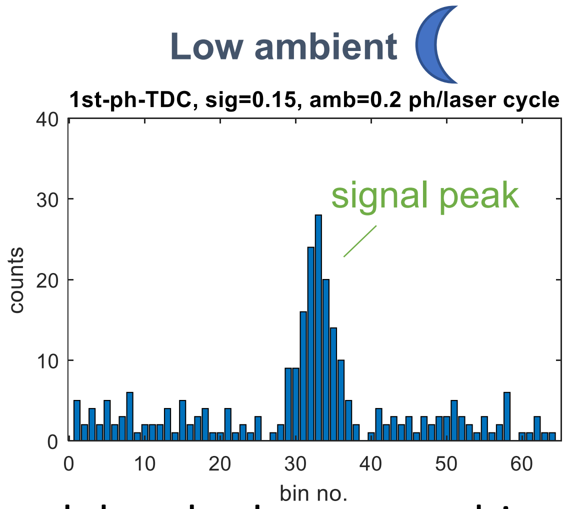
Zhang, OJSSCS 2021

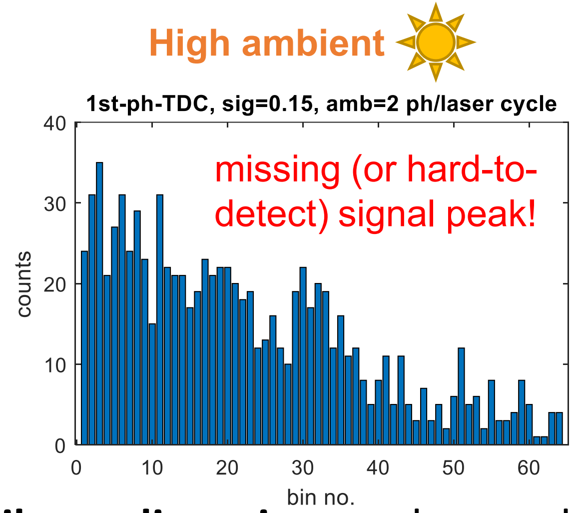


Kumagai, ISSCC 2021

First photon TDC

- Traditional single-photon LIDAR systems use “first-photon” time-to-digital converters (TDCs) which register only the first photon event per laser cycle and frame





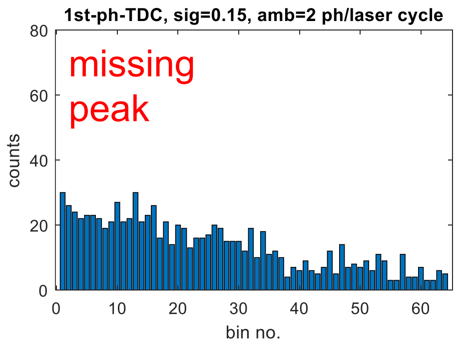
- The approach breaks downs, resulting in **pile-up distortion**, as the number of photon detections/TDC channel/laser cycle approaches 1

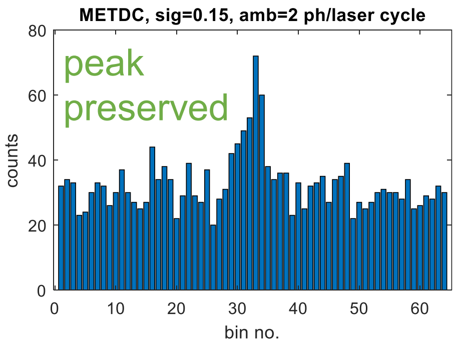
Mitigating TDC pile-up

- **Coincidence detection** (e.g. [Beer, 2018]) which filters photon events in an attempt to ensure that only “signal” events are processed by the first-photon TDC

- **Time gating** (e.g. [Padmanabhan, 2021])

- **Multi-event histogramming TDC** (e.g. [Hutchings, 2019]) which registers multiple events per laser cycle and builds a histogram over multiple cycles





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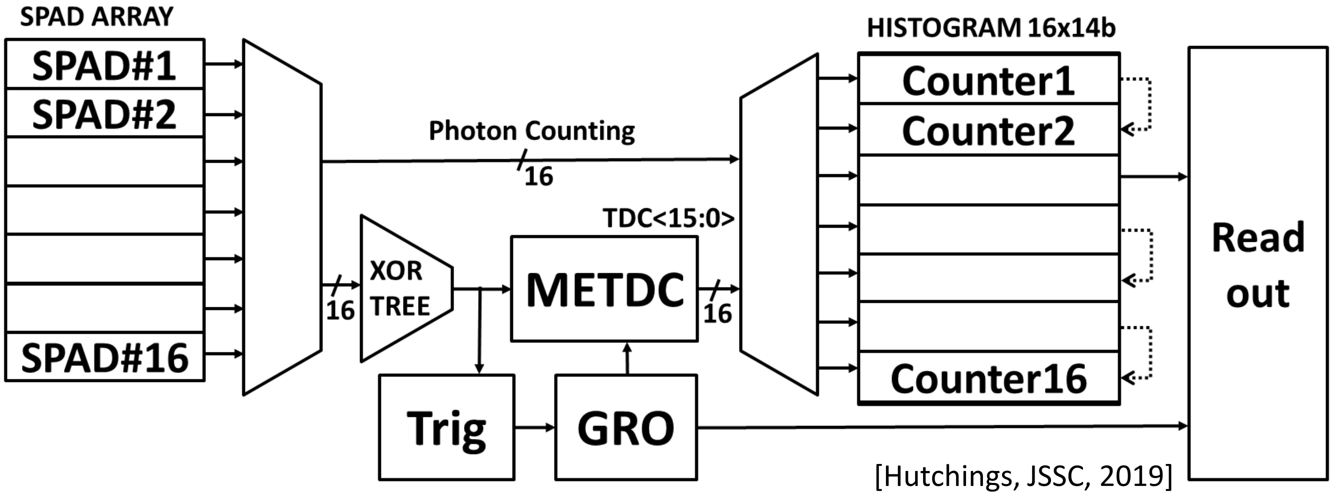
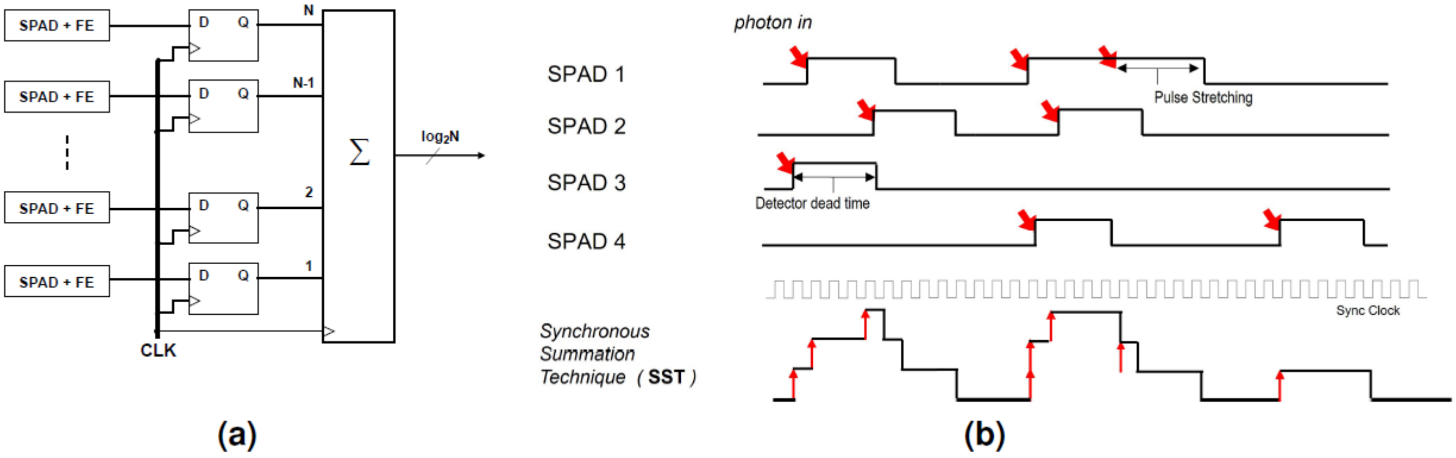
Multi-event Histogramming (Quantic4x4)



[Hutchings, JSSC, 2019]

- 4x4 sharing of shift register-based Multi event TDC
- 16x14b bins, 560ps/bin
- Good background tolerance
- Other implementations:
  [Van Blerkom, ISSW, 2020], [Seo, JSSC 2021], [Srowig, ISE, 2022]

Synchronous Summation Technique (SST)

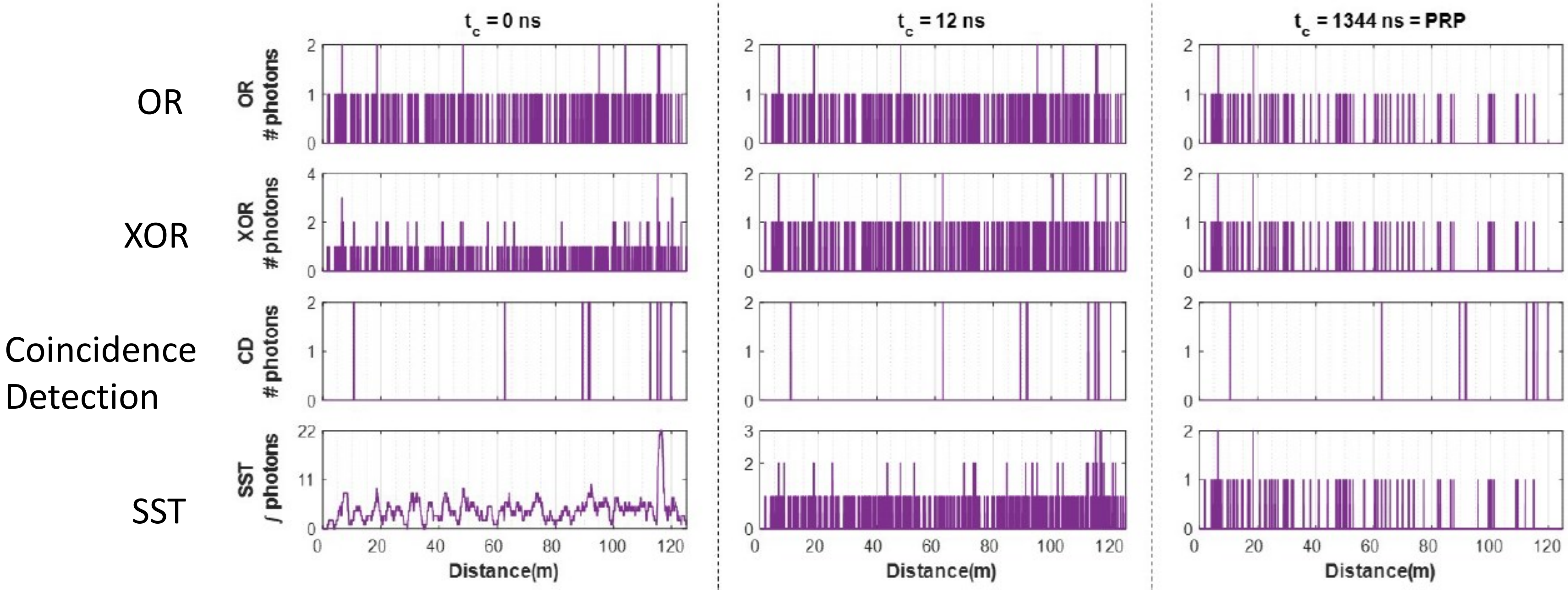


[Patanwala, PhD Thesis, U. Edinburgh, 2021]

- SST combines readily with a multi-event TDC operating on CLK
- Pipelined TDC operation required for faster clock rates
- Modelling/emulated comparison with OR, XOR and coincidence combining

Synchronous Summation Technique (SST)

Simulated histograms: 115m range, 100kLux ambient, 10% reflectivity target



[Patanwala, PhD Thesis, U. Edinburgh, 2021]

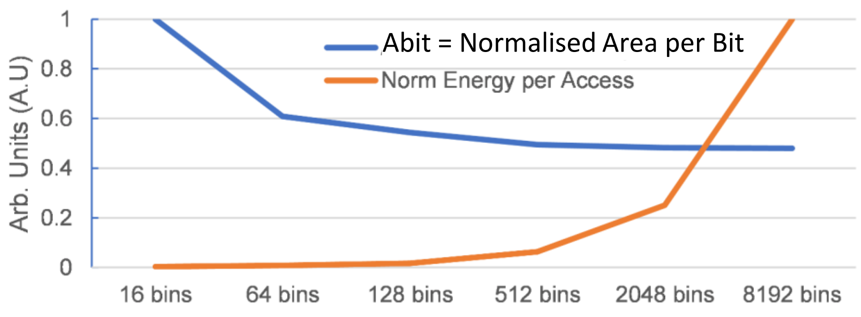
- Only SST + short conversion time t_c able to recover target

How many histogram bins?

$$\delta = \frac{\sigma}{\sqrt{N}}\sqrt{1 + \frac{1}{12}\left(\frac{a}{\sigma}\right)^2 + 4\sqrt{\pi}\left(\frac{\sigma}{a}\right)\left(\frac{b}{N}\right)}$$

Symbol	Description
N	signal photons
b	background/bin
a	bin width
σ	timing jitter
δ	precision

[Koerner, ISSW, 2022]



[Gyongy, TED, 2022]

- Choose bin width *a* to be around laser IRF FWHM
- Few 100ps and 100’s bin for short range (0-10m) flash LIDAR
- Few ns and 1000’s bins for long range scanning/flash (50-300m) LIDAR
- Large SRAM histogram has energy overhead
- Smaller SRAM histogram has high access logic overhead – counters better

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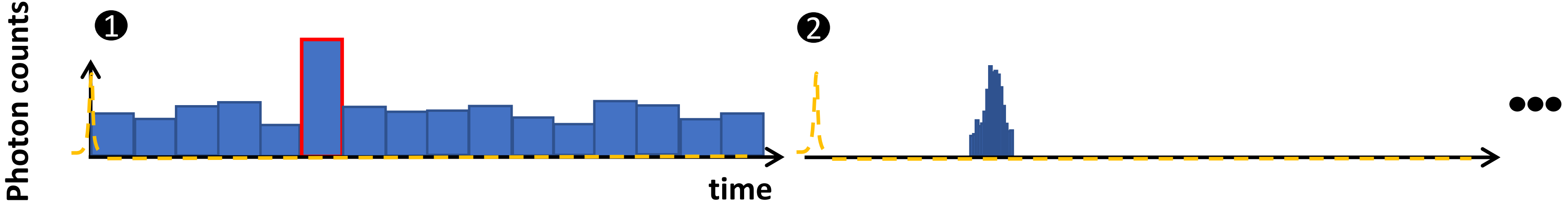
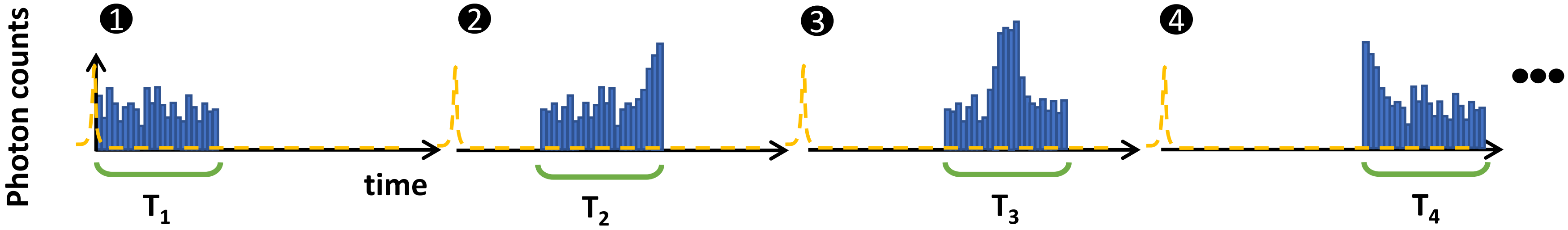
Partial Histogramming

Zooming



e.g. Lindner (2018), Zhang (2021), Park (2022)

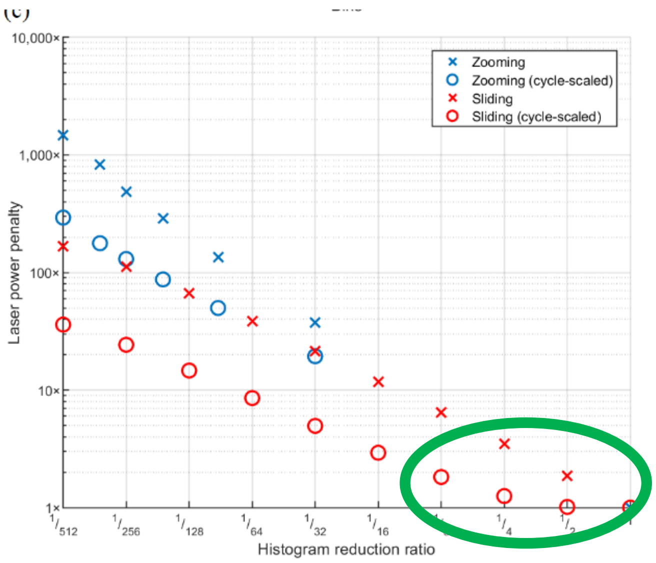
Sliding

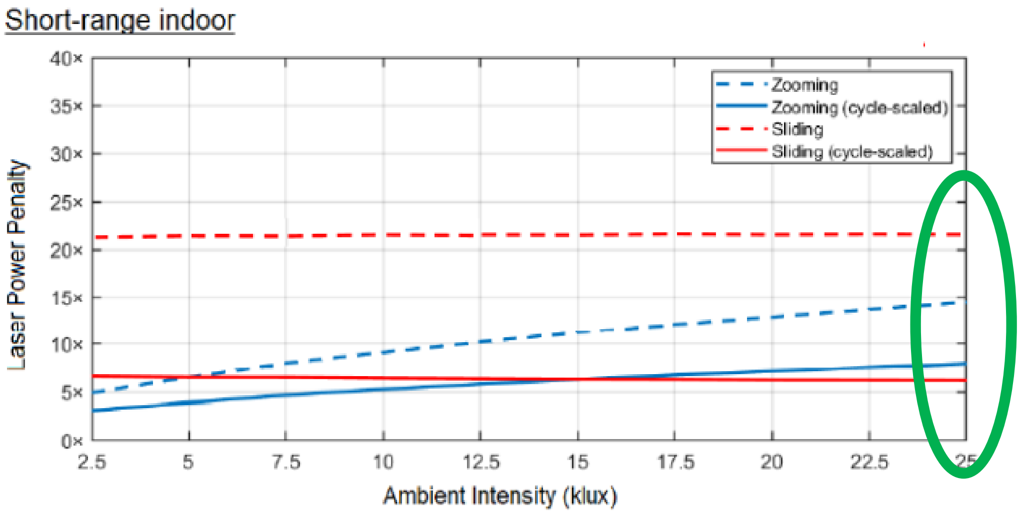


e.g. Stoppa (2021)

- Only subrange of full depth held in pixel

Partial Histogram – Power Penalty





[Taneski, JLT, 2022]

- Histograms of 1/4-1/8th full scale depth range provide acceptable compromise
- Scaling laser cycles with sub-range can save significant emitter power

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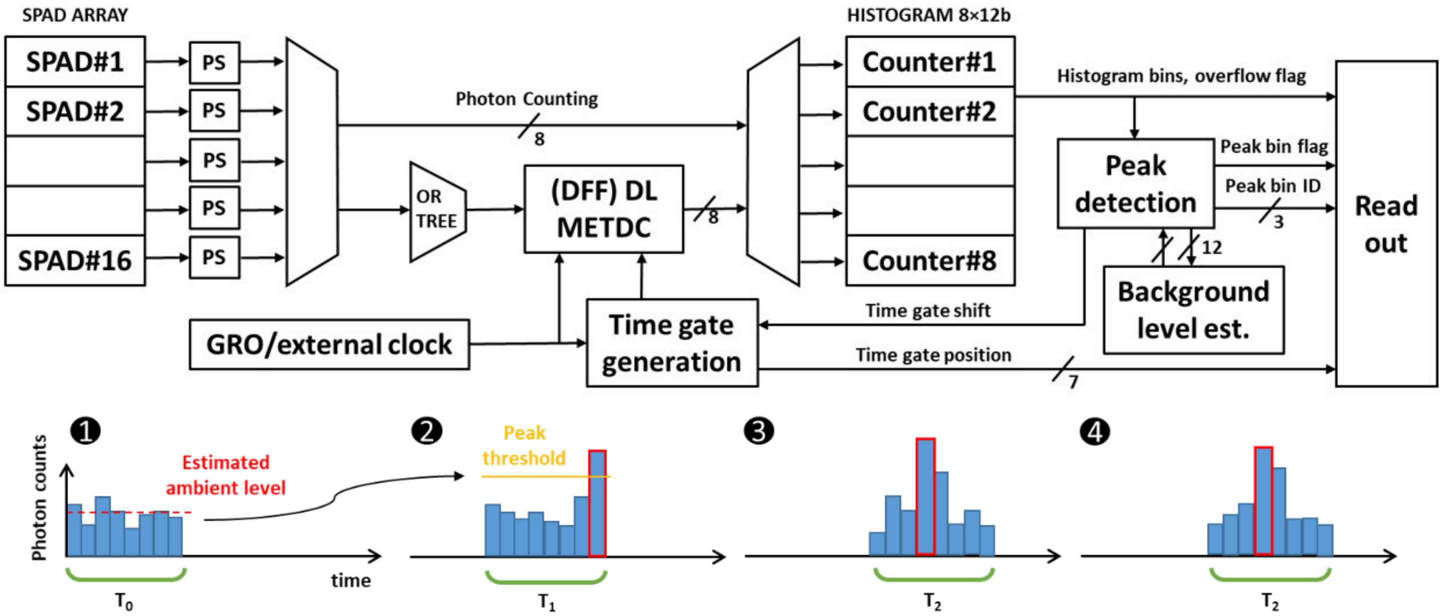
Partial Histogram – peak tracking (HSLIDAR)



[Gyongy, ISSW 2022]

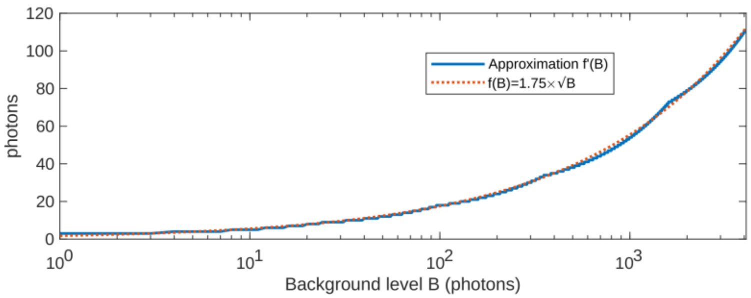
- Pixels with multi-event histogramming
- Peak tracking in pixel with in-pixel background estimator
- Dynamic vision mode outputs only pixels with change in depth

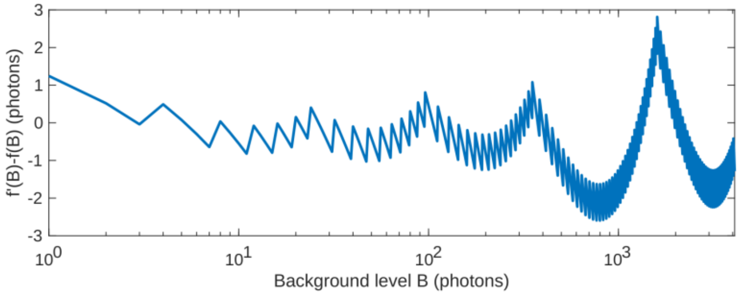
HSLIDAR – peak tracking

- Peak detection threshold is calculated as

$$h_{thresh} = B + 1.75\alpha\sqrt{B}$$

where B is the estimated background level and α = 1 or 2.

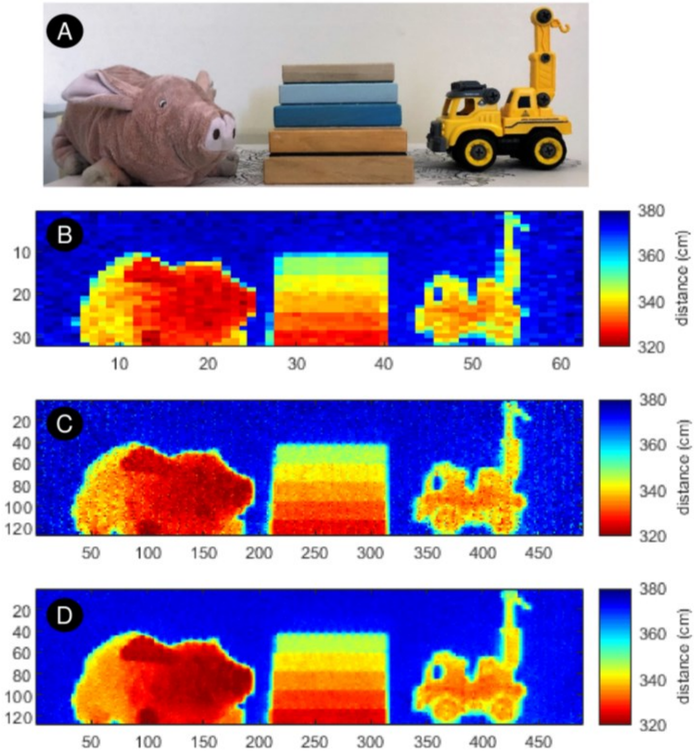




A direct time-of-flight image sensor with in-pixel surface detection and dynamic vision

Istvan Gyongy, Ahmet T. Erdogan, Neale A.W. Dutton, *Member, IEEE* Germán Mora Martín, Alistair Gorman, Hanning Mai, Francesco Mattioli Della Rocca, *Member, IEEE* and Robert K. Henderson, *Fellow, IEEE*

HSLIDAR – short range



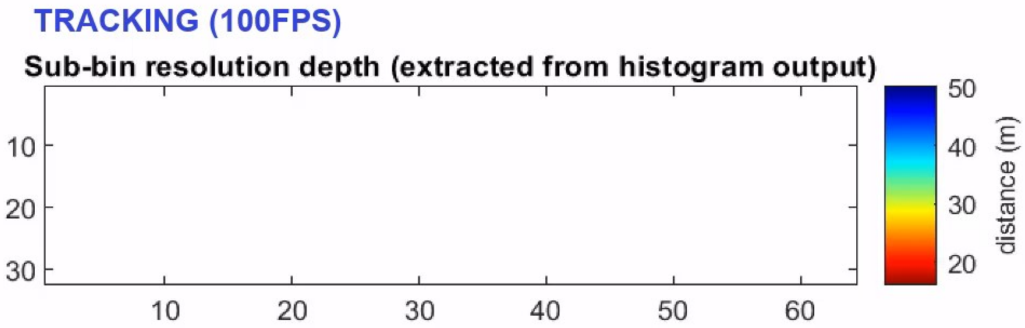
Single frame (1kFPS)
(bin width = 8 ns)

HR: Combination of
16 frames (20FPS)

Average of 20 HR
images

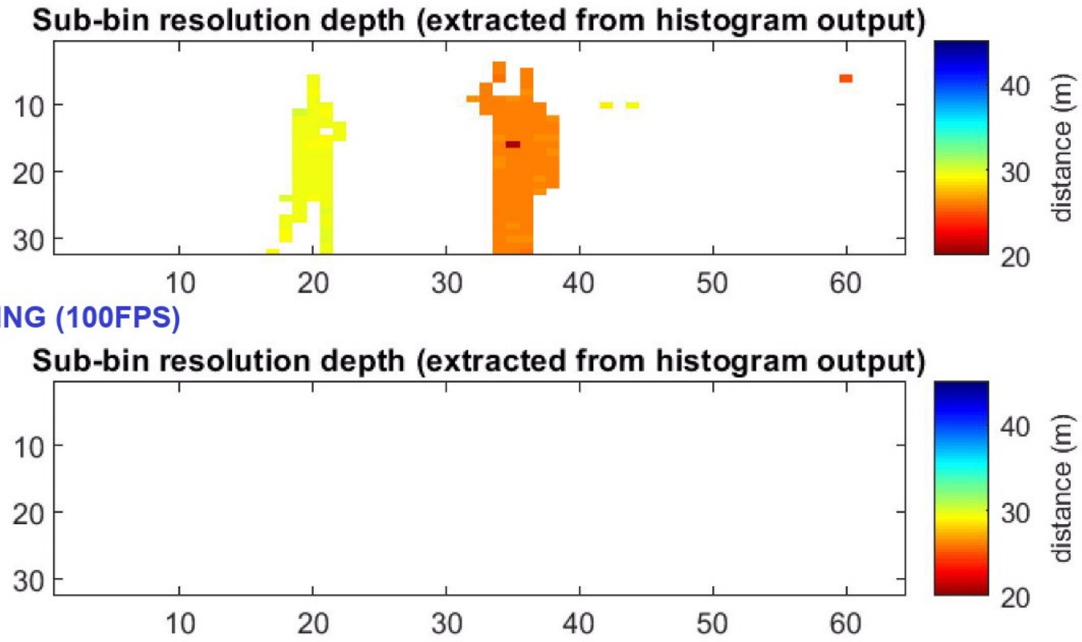
Partial Histogram – peak tracking

Partial Histogram – peak tracking

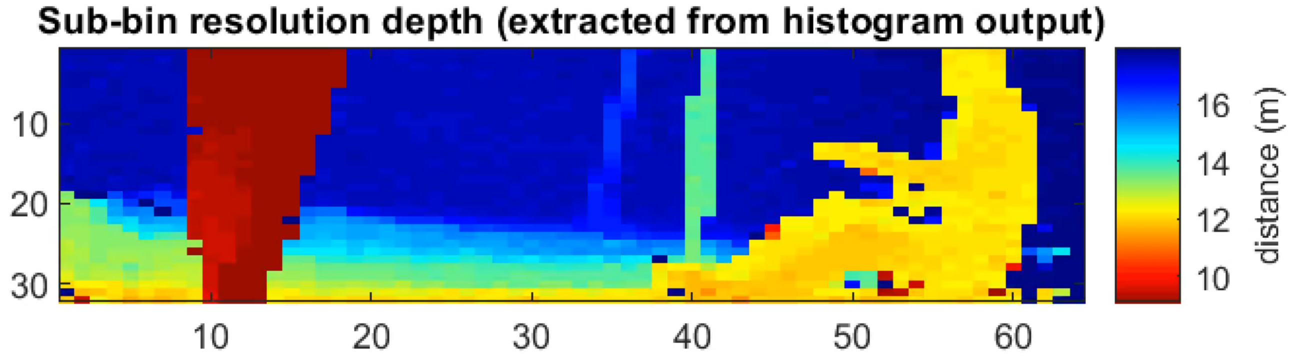


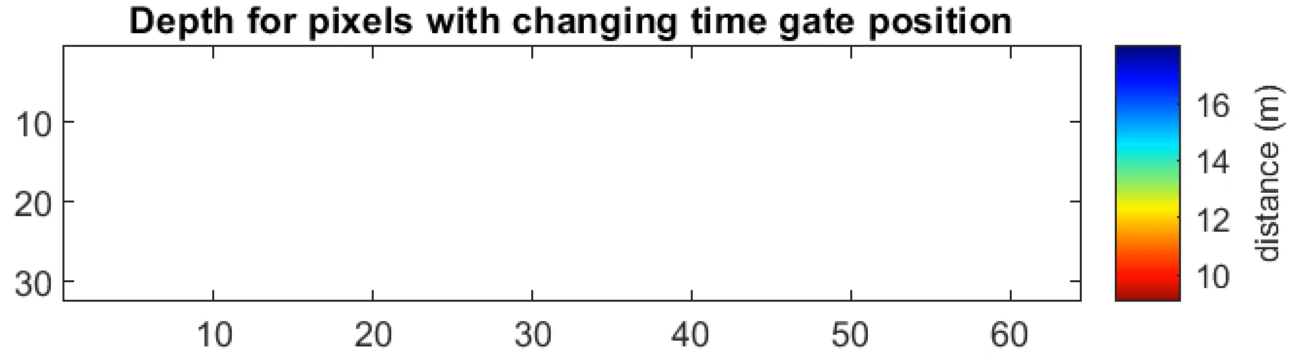
Sliding vs peak tracking

SLIDING (6.25FPS)

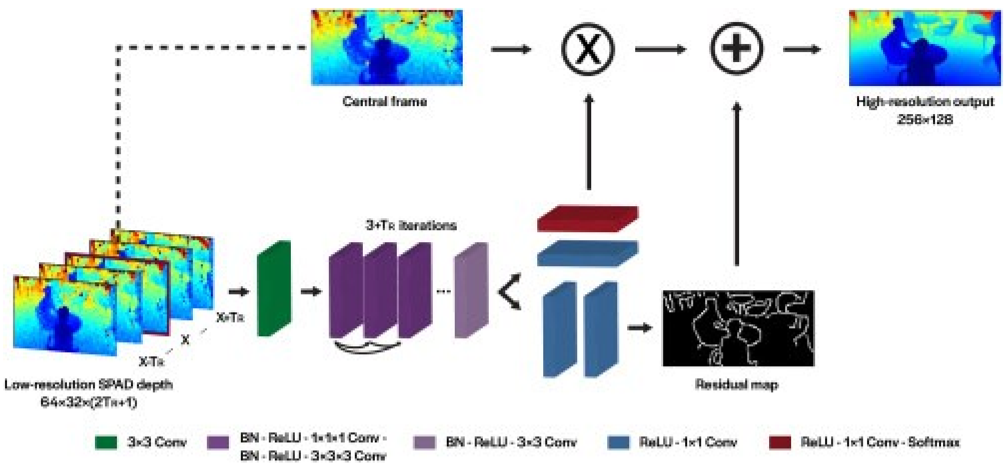


Dynamic vision using peak tracking





Depth upscaling

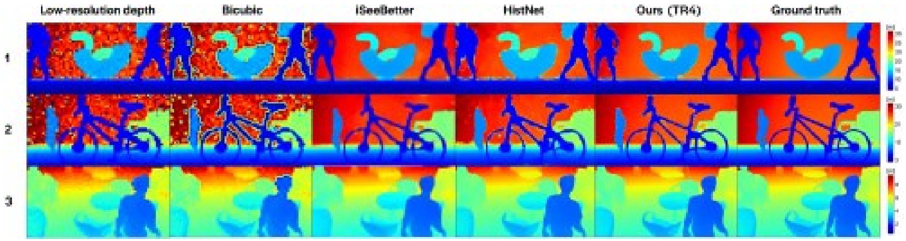


Research Article Vol. 31, No. 5 / 27 Feb 2023 / *Optics Express* 7060

Optics EXPRESS

Video super-resolution for single-photon LIDAR

GERMÁN MORA-MARTÍN,[1,*] STIRLING SCHOLES,[2] ALICE RUGET,[2] ROBERT HENDERSON,[1] JONATHAN LEACH,[2] AND ISTVAN GYONGY[1]



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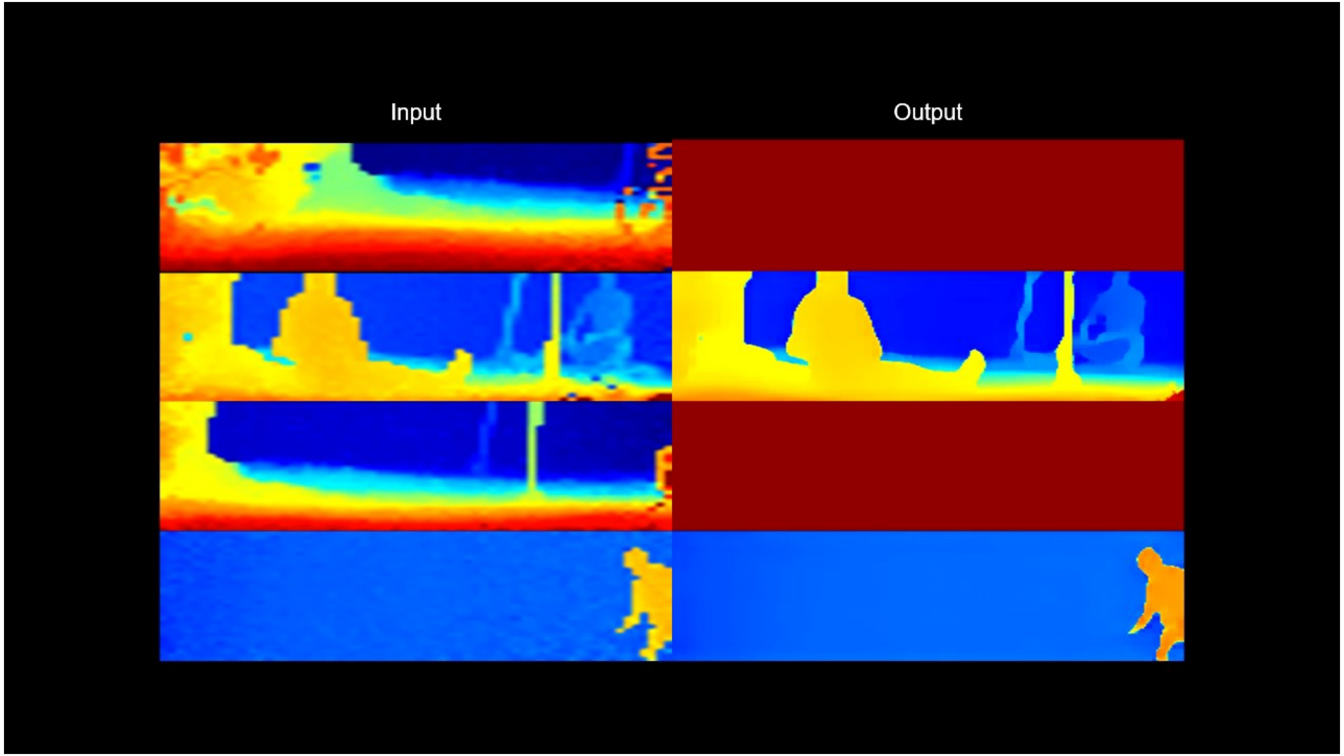
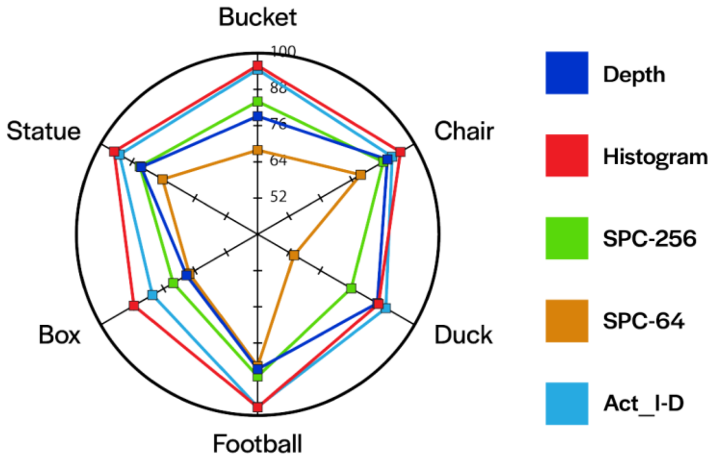
Depth upscaling (cont.)



High-speed object detection

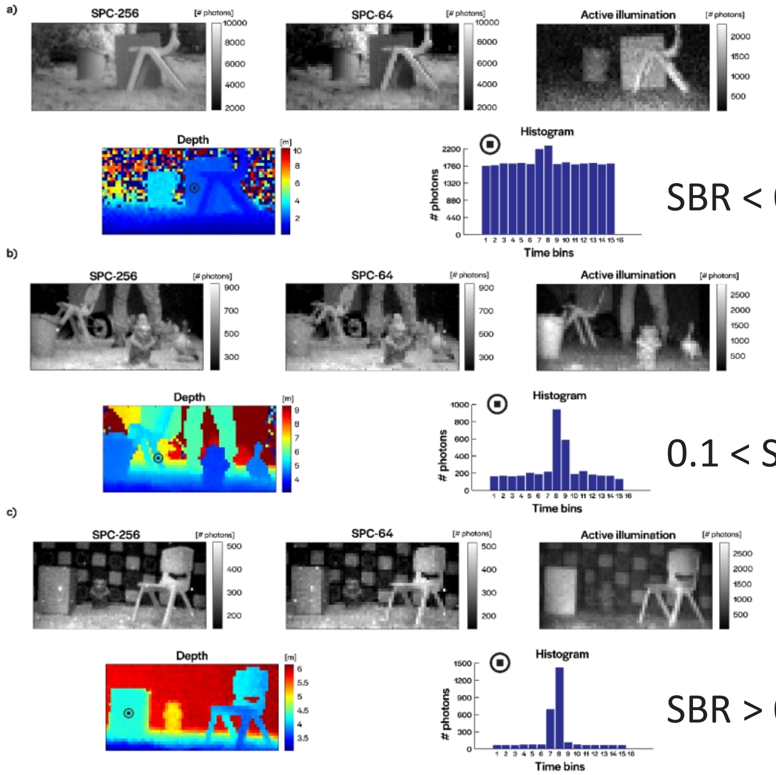
F1 score



Research Article Vol. 29, No. 21 / 11 Oct 2021 / *Optics Express* 33184
Optics EXPRESS

High-speed object detection with a single-photon time-of-flight image sensor

GERMÁN MORA-MARTÍN,[1,*] ALEX TURPIN,[2,3] ALICE RUGET,[4] ABDERRAHIM HALIMI,[4] ROBERT HENDERSON,[1] JONATHAN LEACH,[4] AND ISTVAN GYONGY[1]



SBR < 0.1

0.1 < SBR < 0.5

SBR > 0.5

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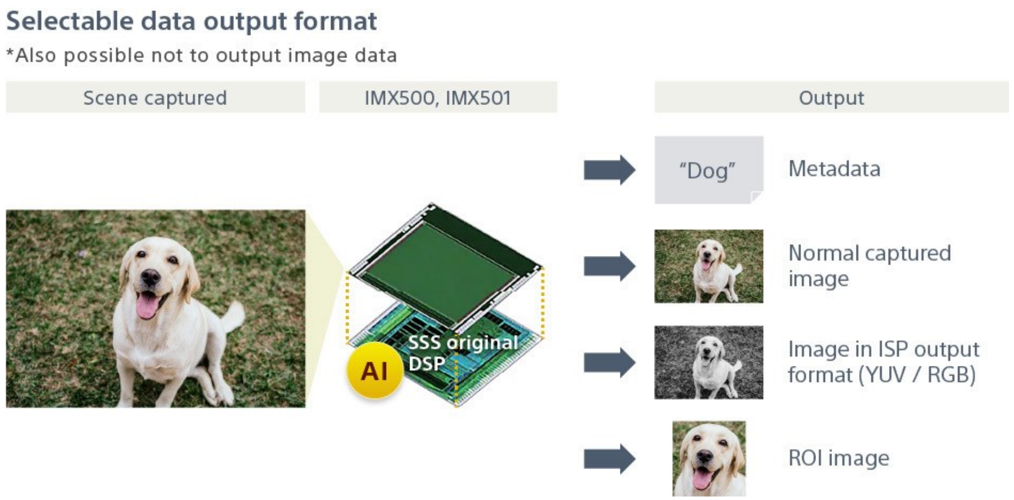
Reconfigurable/Neural Net Processing

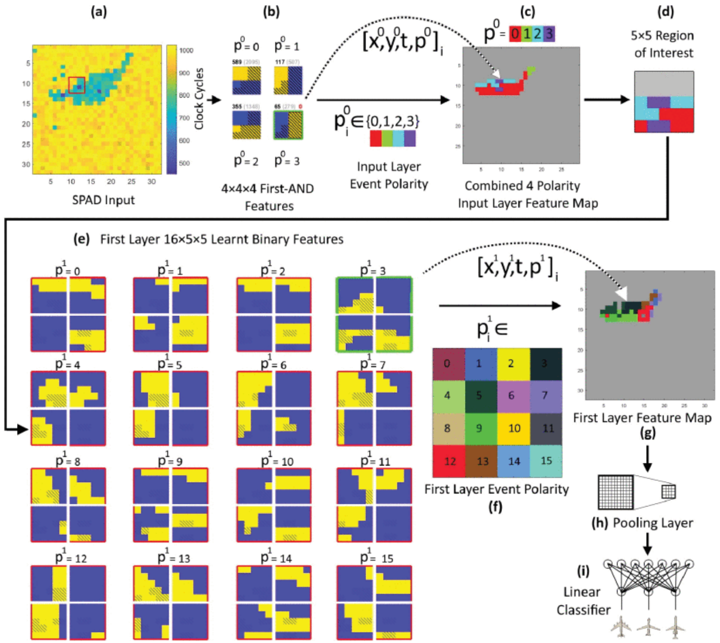
- Processor under the SPAD array [Ardelean, PhD Thesis, EPFL, 2023]
- Higher-level (AI) processing for scene interpretation akin the 2D vision sensors?



Source: https://www.sony-semicon.com/

Reconfigurable/Neural Net Processing (cont.)

- SPAD array with on-chip logic to generate events depending on order that neighbouring SPADs fire
- Overlapping "receptive fields" with 4×4 SPADs
- 81 fold reduction in data rate
- Asynchronous readout to FPGA with spiking neural network for object classification



[S. Afshar, IEEE Sensors 2020]

Conclusions

- Recent advances in stacked 3D SPAD technology have resulted in high PDE SPADs, and enabling focal-plane photon processing in advanced technology nodes
- There is still a lot of opportunity for circuit and system innovation to address angular resolution, power reduction and dynamic range challenges, especially in longer-range LIDAR
- In the coming years, we are likely to see more sophisticated embedded processing, including programmable logic, machine learning, and SNNs.

Acknowledgements

- Robert Henderson, Jonathan Leach, Abderrahim Halimi, Germán Mora-Martín, Alex Turpin, Alice Ruget, Stirling Scholes, Ahmet Erdogan, Neale A.W. Dutton, Alistair Gorman, Hanning Mai, Francesco Mattioli Della Rocca
- Robert Henderson for slides from ESSCIRC 2022 tutorial "3D stacking meets 3D imaging: Vertically Integrated SPAD Sensor Architecture" (material used on slides 7-9 and 12-17 here)
- STMicroelectronics for chip fabrication, PhD sponsorship
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