Direct time-of-flight imaging with in-pixel peak tracking

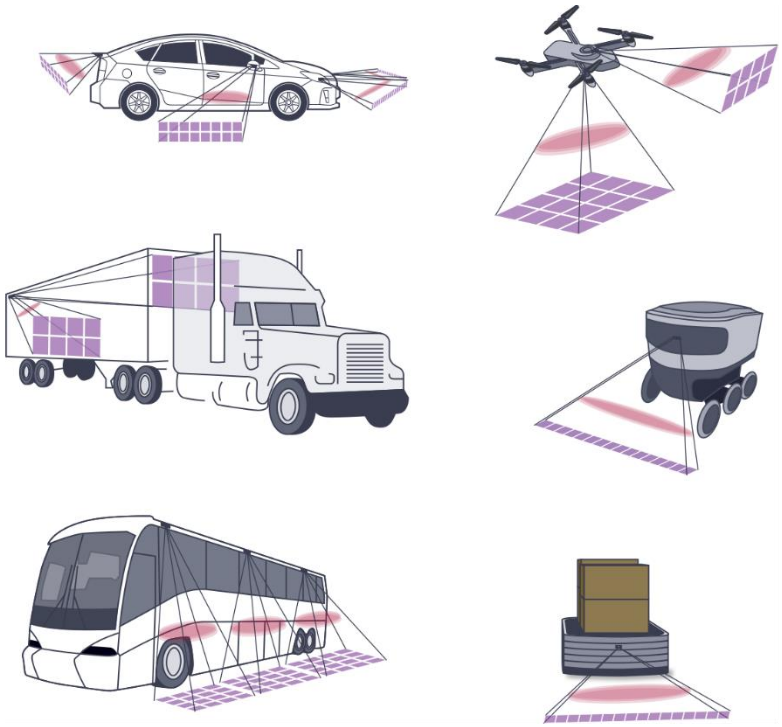
Istvan Gyongy[1], Ahmet T. Erdogan[1], Neale A.W. Dutton[2], Hanning Mai[1], Germán Mora-Martín[1], Alistair Gorman[1], Francesco Mattioli Della Rocca[1,3], Robert K. Henderson[1]

[1]The University of Edinburgh, UK

[2]STMicroelectronics, Edinburgh, UK

[3]*now with Sony, Trento, Italy*

dToF imaging



source: analog.com

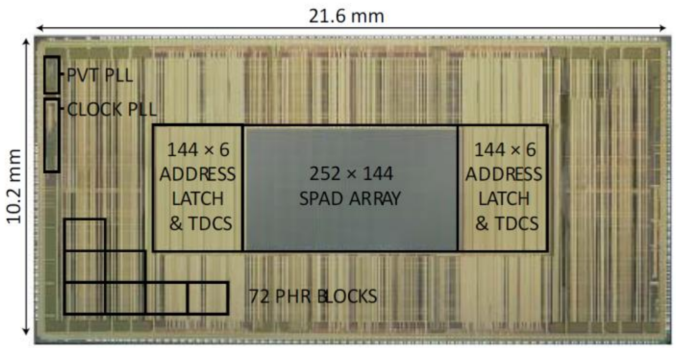
Target:

- Flash LIDAR
- Mid-range (up to ~50m)
- Outdoor conditions
- High-speed/low latency vision (ms time scale)

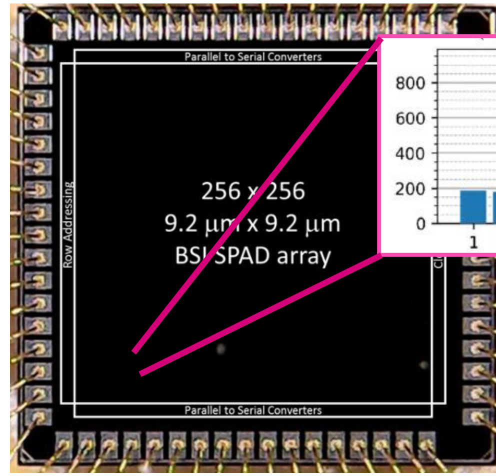
Requirements:

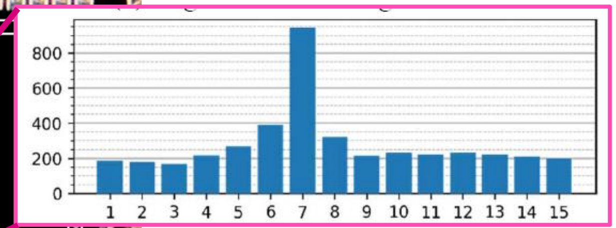
- High photon throughput (10’s of Mph/s per SPAD)
- On-chip data compression (to avoid readout bottleneck/large memory requirements)

On-chip processing

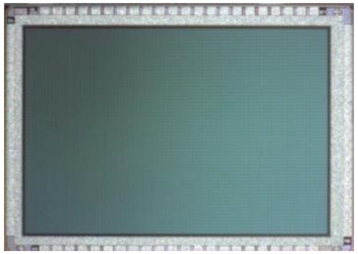


Lindner, VLSI 2018

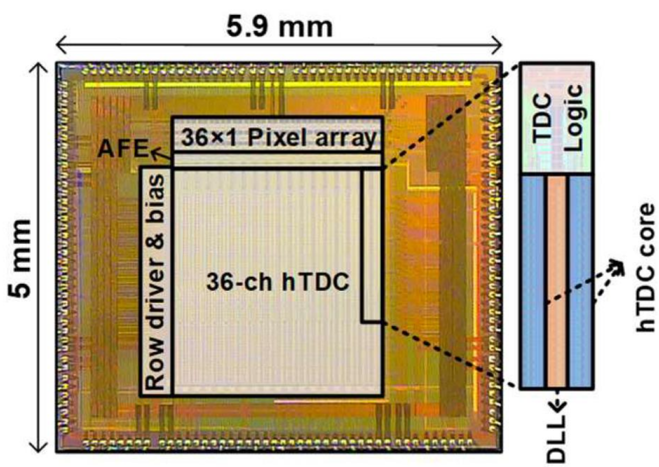




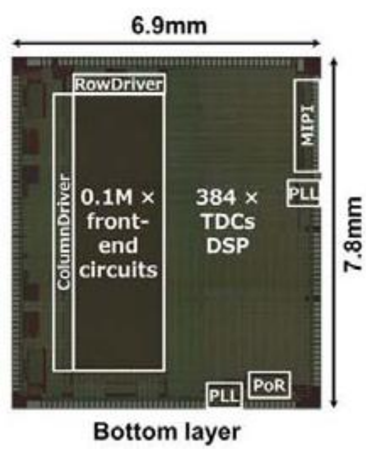
Henderson, ISSCC 2019



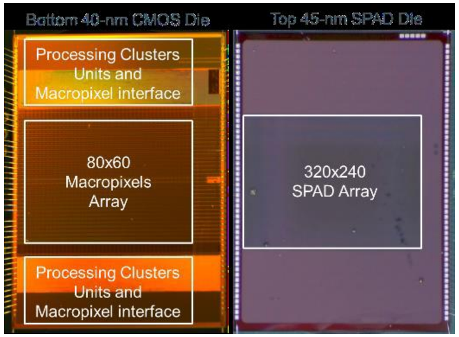
Zhang, OJSSCS 2021



Seo, VLSI 2020



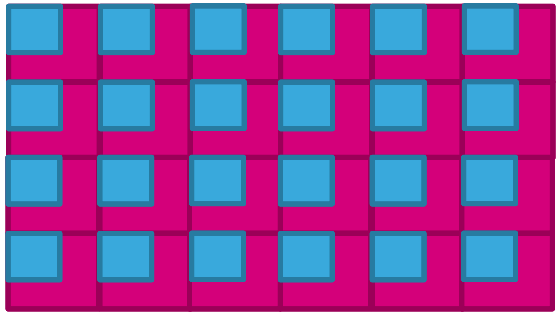
Kumagai, ISSCC 2021



Stoppa, IISW 2021

On-chip processing (II.)

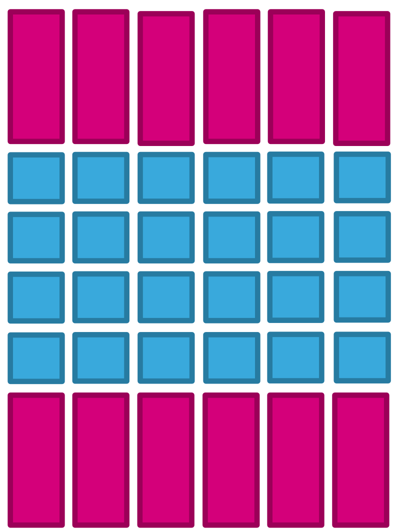
In-pixel



e.g. Henderson (2019)

- ✓ Photons processed "in situ", no bottleneck in transferring out of array
- ✗ Limited space for histogram memory → limited hist. range
- ✗ Large pixel size (unless 3D stacking is used)

Outside array



e.g. Lindner (2018)

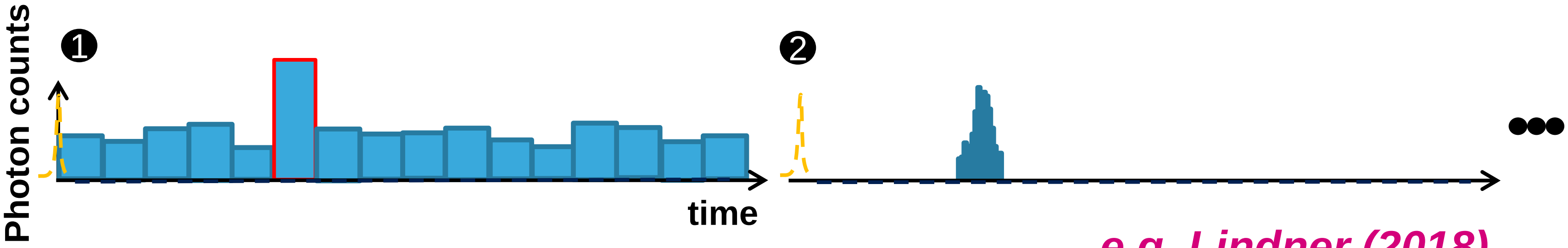
- ✓ Compact, dense pixels
- ✗ Bottleneck (or scalability issues) in transferring data out of the array
- ✗ Memory/frame transfer requirements can be significant

SPAD

Processing

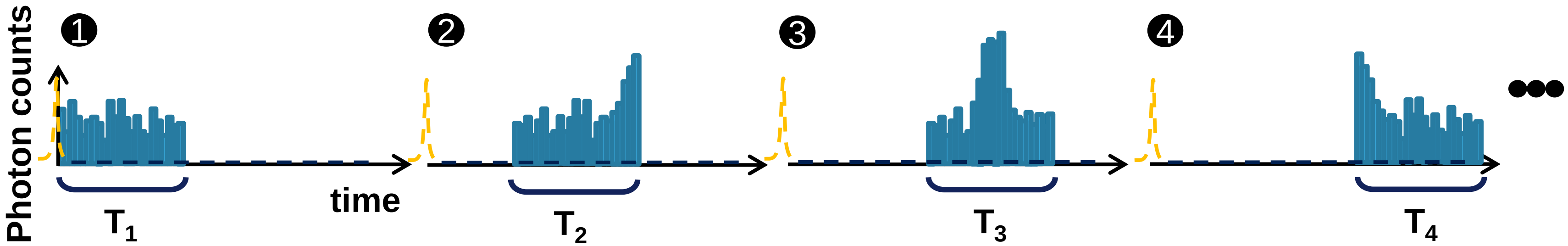
Partial histogramming

Zooming



e.g. Lindner (2018)

Time sweep

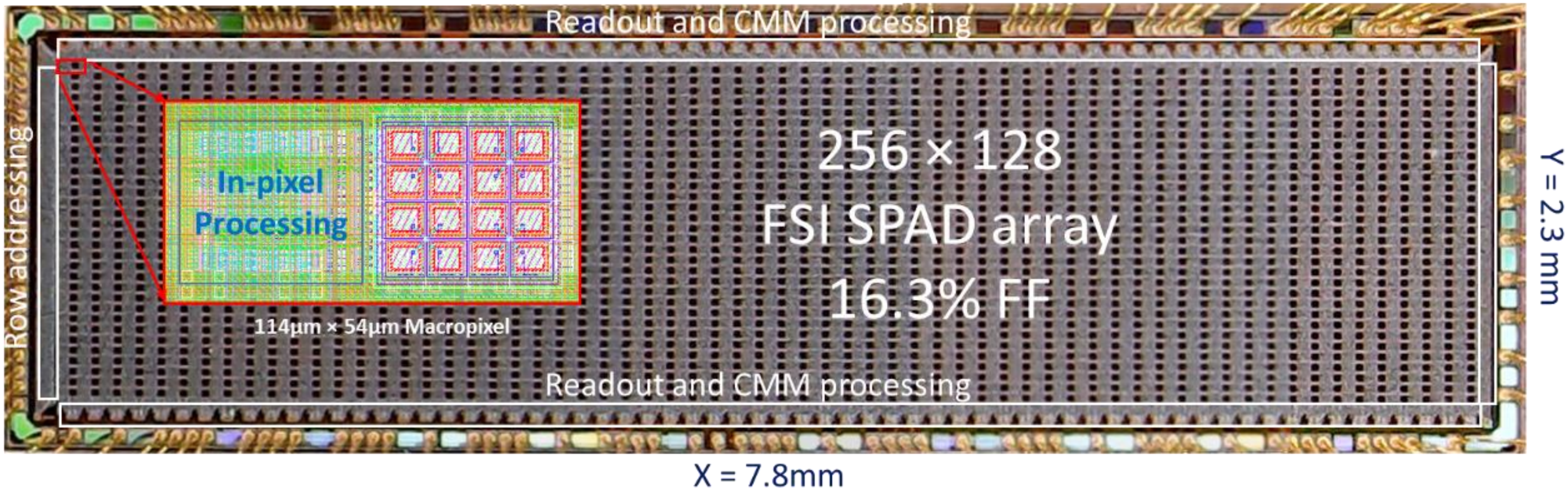


e.g. Stoppa (2021)

dToF SPAD imager

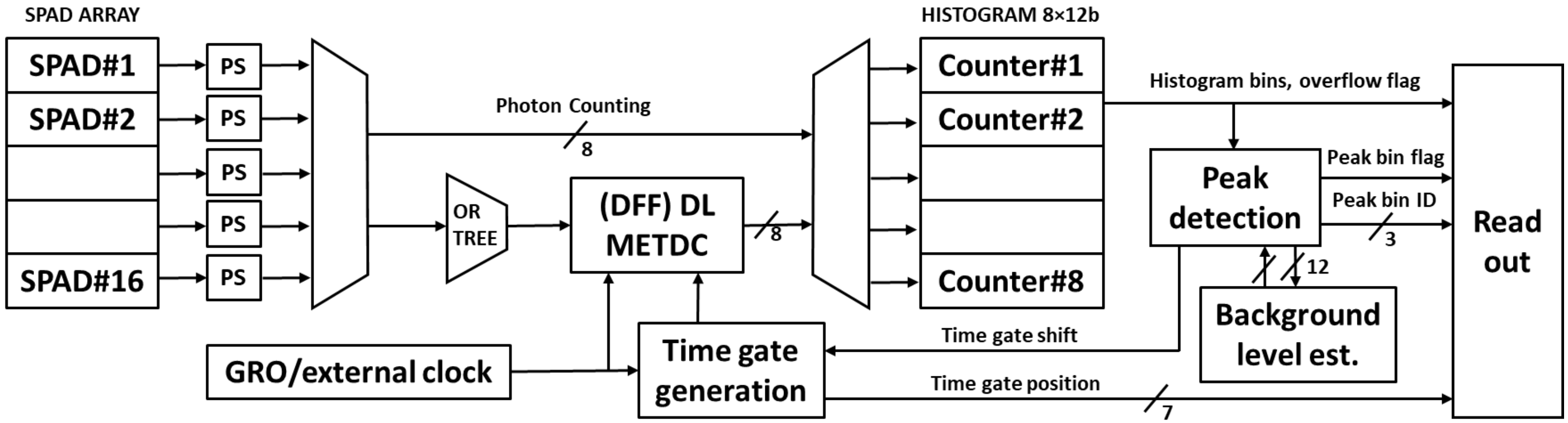
64×32 macro pixels (with 4×4 SPADs + processing unit in each)

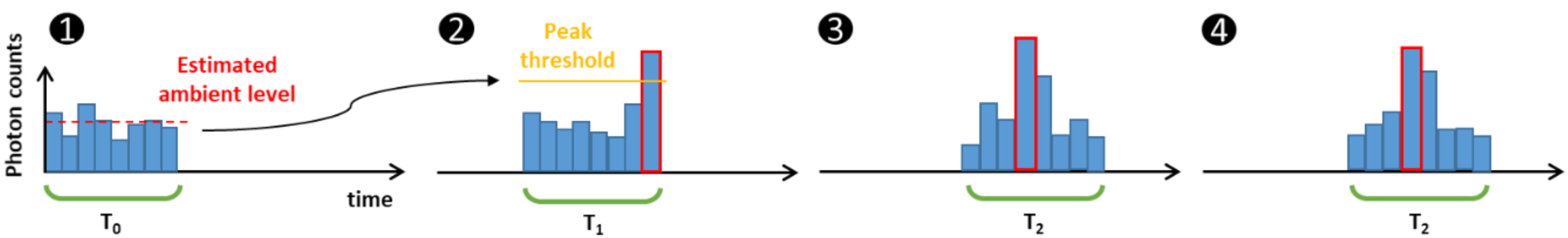
Each macropixel generates an 8-bin (12-bit/bin) histogram that is automatically shifted in time until peak is located



Readout over 64, 100MHz serial output lines

Macropixel operation





Coarse timing (time gate position): GRO or external clock

Fine timing (hist bin width >0.25ns): GRO or delay line or external clock

Output formats

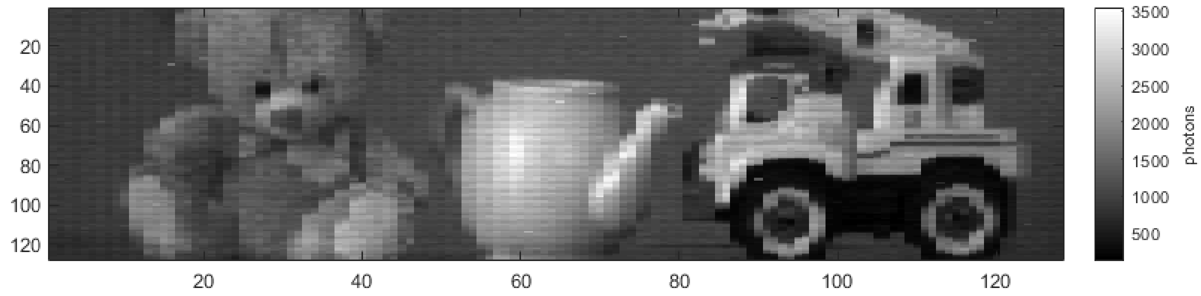
Mode	Output format*	Total no. bits/macro pixel	Max. frame rate (FPS)
Histogram mode (default)	Histogram bins and histogram peak data	108	29k
Bin-resolution depth	Histogram peak data (peak bin flag, peak bin ID and overflow flag)	12	260k
Sub-bin resolution depth	Centre-of-mass of background-corrected histogram bins	15	208k

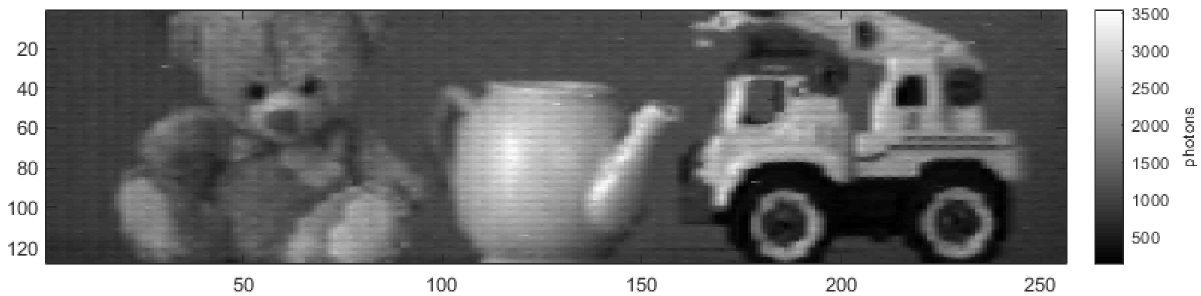
* In addition to 7-bit time gate position

Smart readout: only macro pixels with a peak, or a peak which is moving in are readout (rest replaced with 0's)

128×128 SPC mode

200us exposure time (5kFPS)

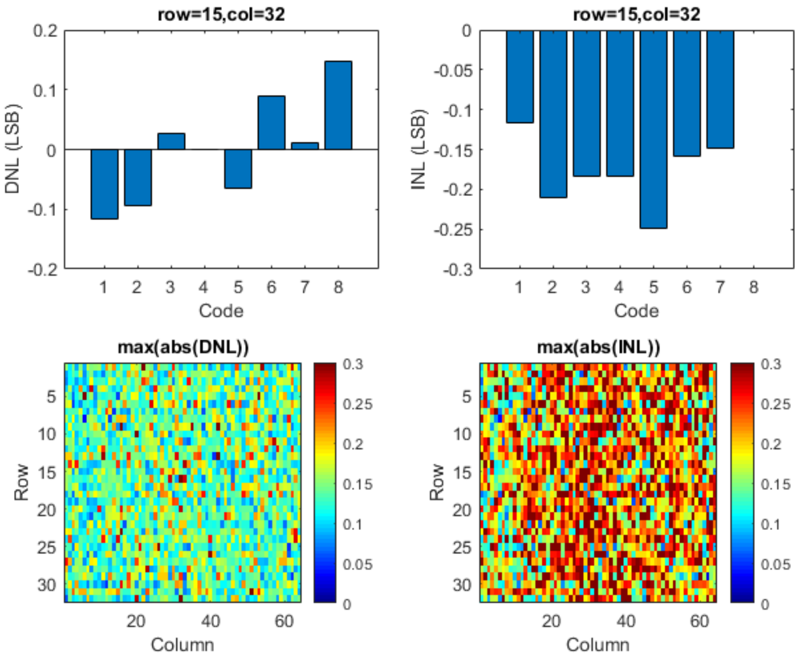




After interpolation

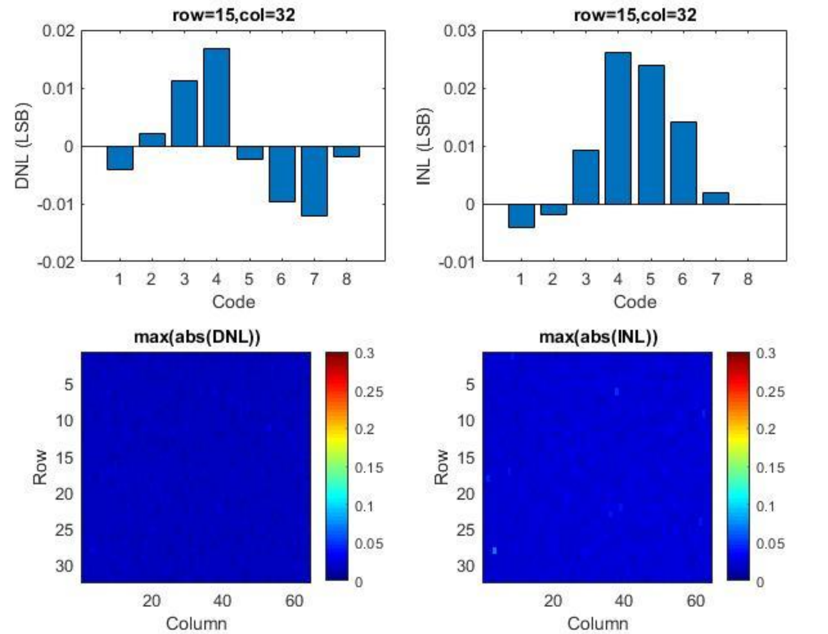
Histogram non-linearity

DL fine timing (1ns bin size)



median of max(abs(DNL)) across array = 14%

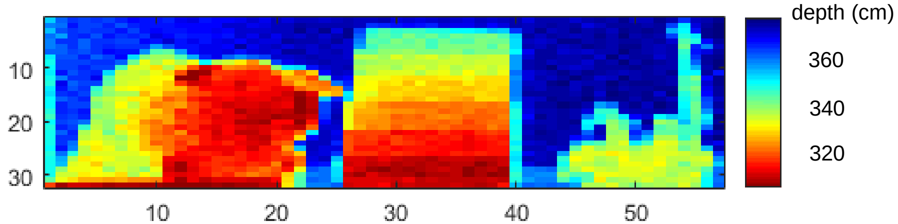
EXT_CLK fine timing (8ns bin size)



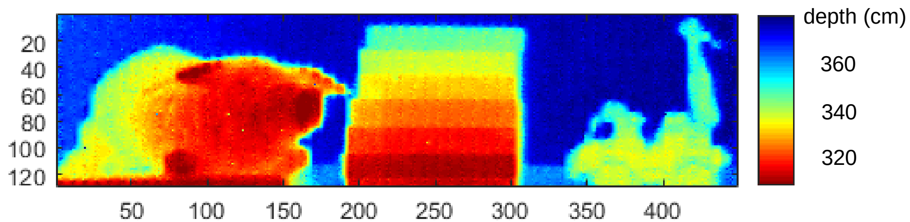
median of max(abs(DNL)) across array = 1.6%

Histogram mode - indoor

850nm laser source, 4.7 MHz rep rate, ~10ns pulse width, 2W peak power



Single 20ms exposure

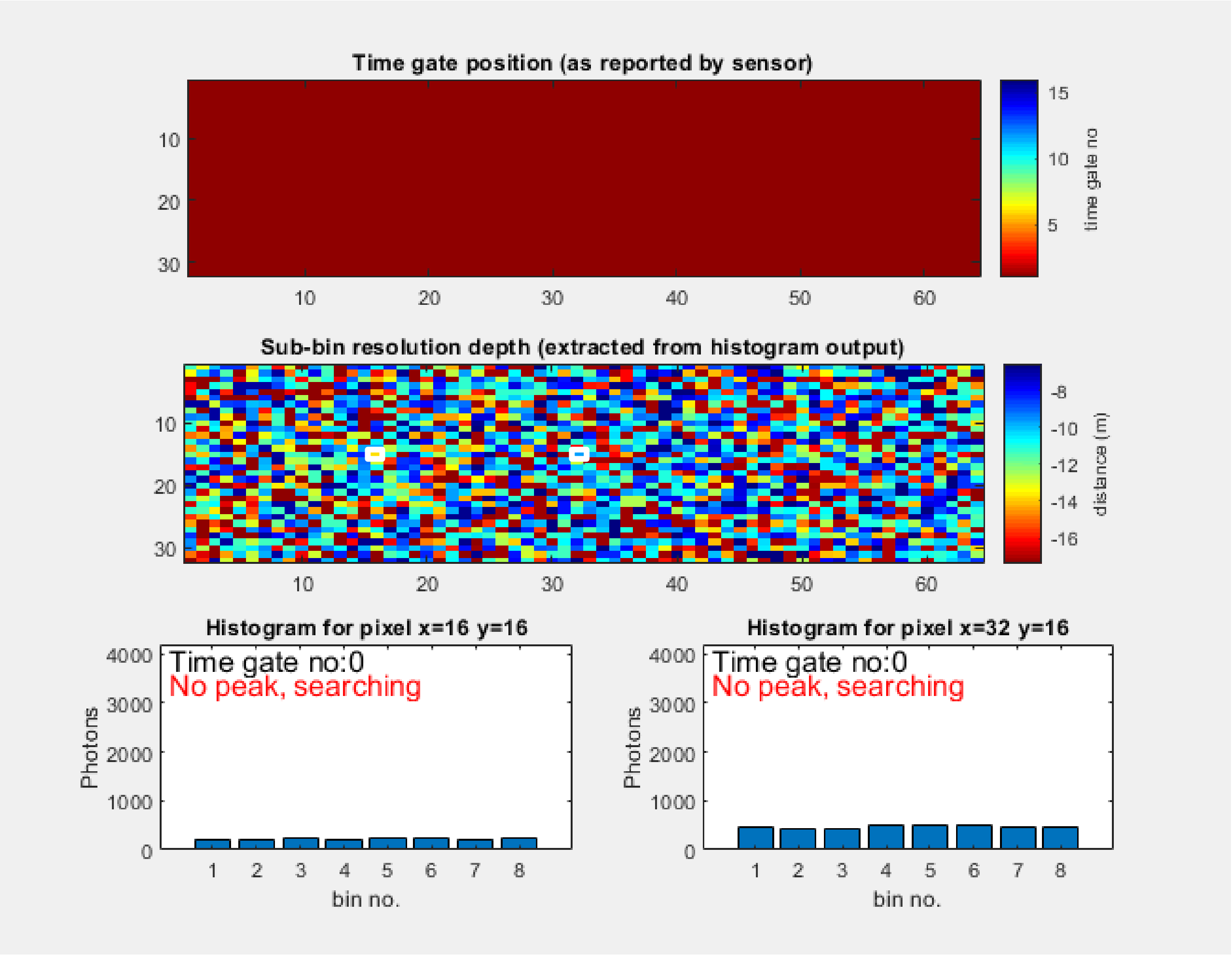


16 exposures (combined off-chip*)

external clock for timing, ~8ns bin size

Histogram mode

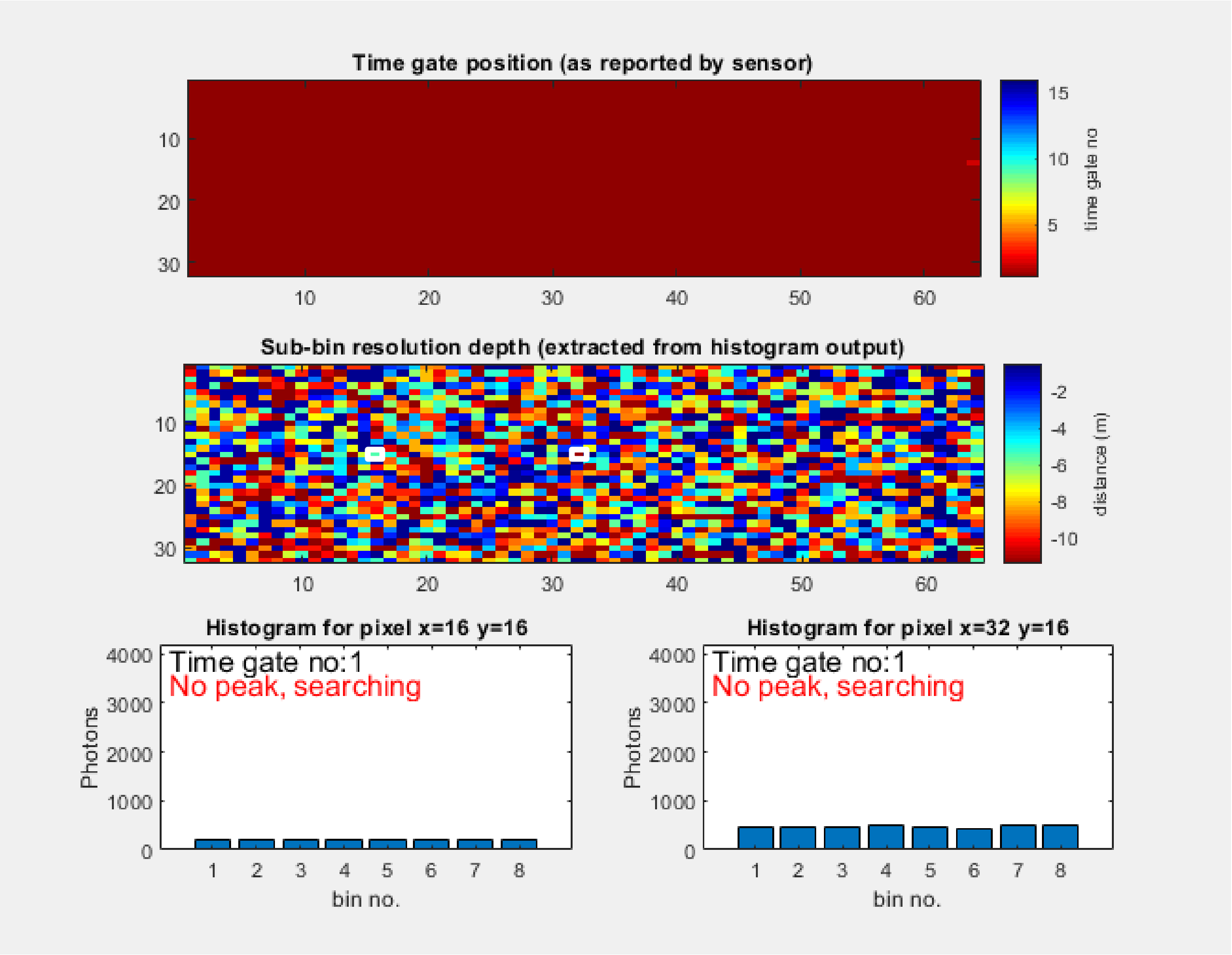
850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



20ms exposure time, external clock for timing, ~8ns bin size

Histogram mode

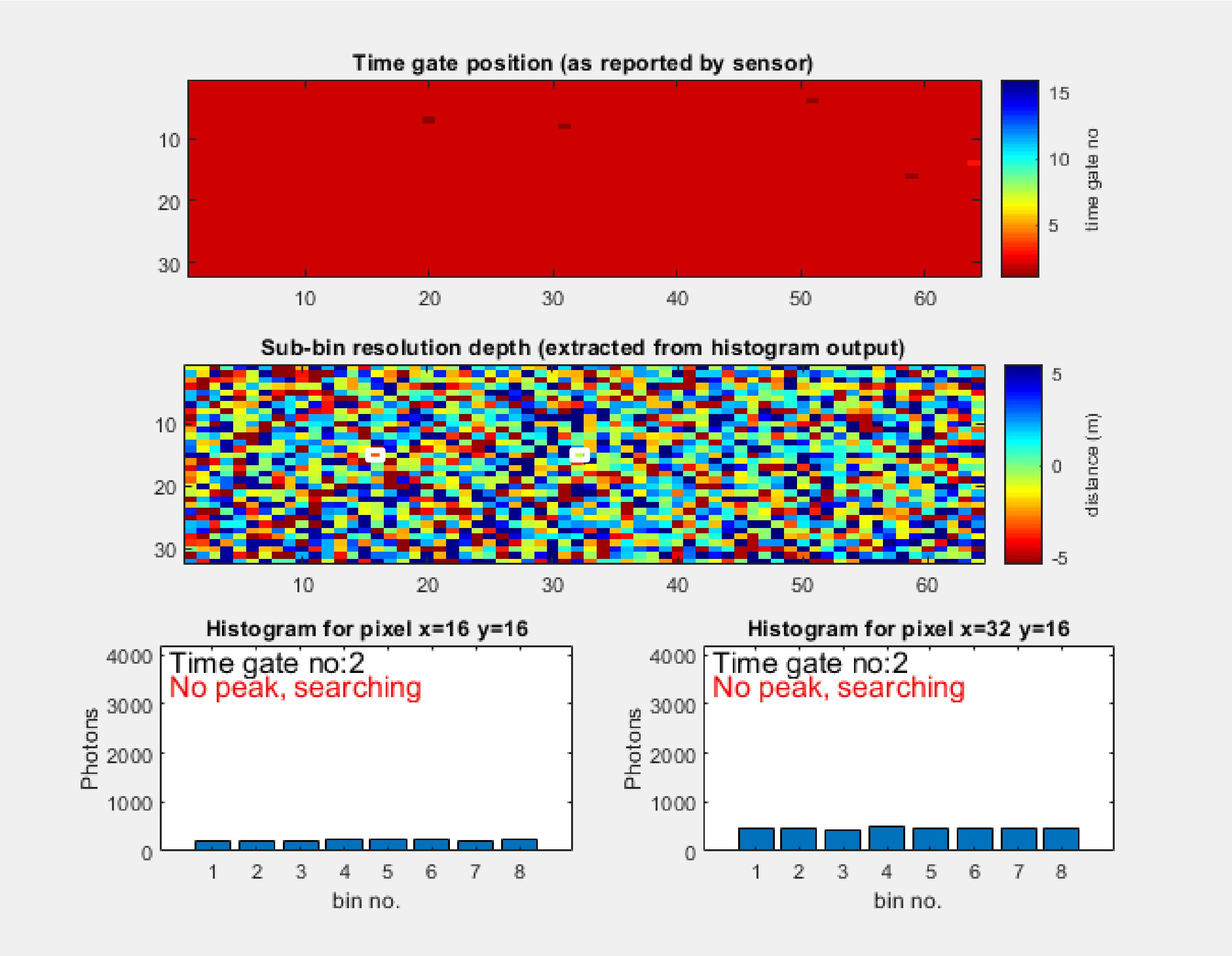
850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



20ms exposure time, external clock for timing, ~8ns bin size

Histogram mode

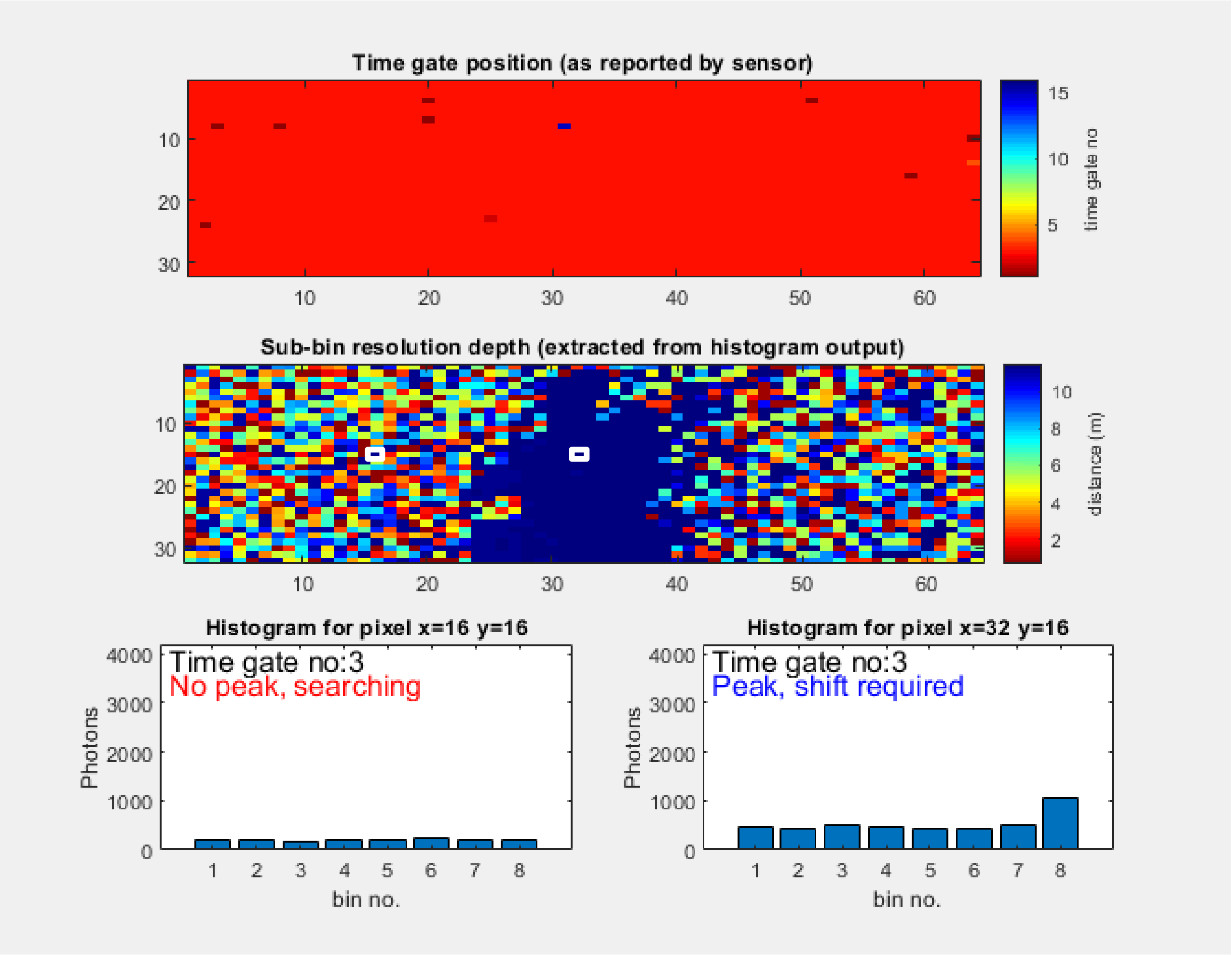
850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



20ms exposure time, external clock for timing, ~8ns bin size

Histogram mode

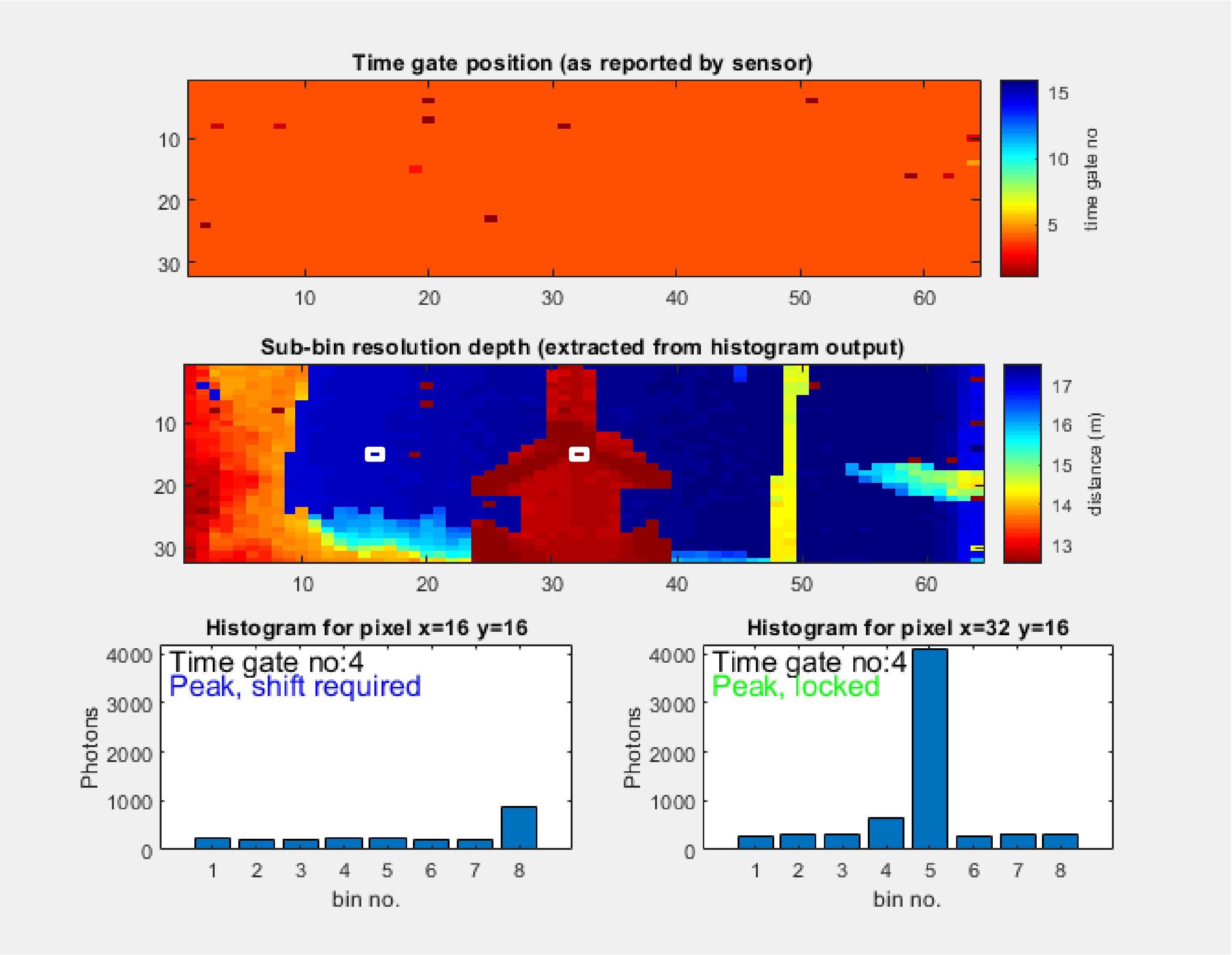
850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



20ms exposure time, external clock for timing, ~8ns bin size

Histogram mode

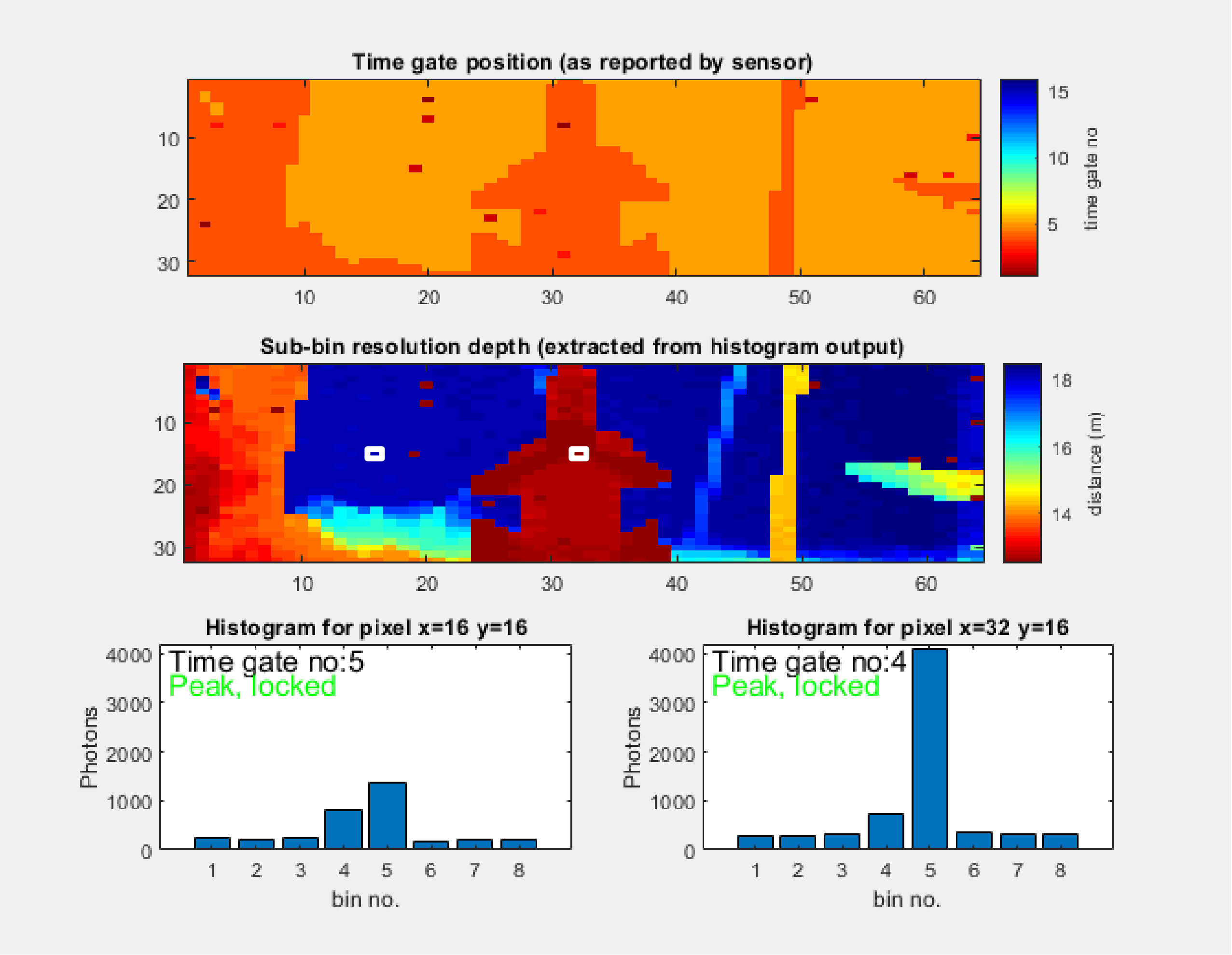
850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



20ms exposure time, external clock for timing, ~8ns bin size

Histogram mode

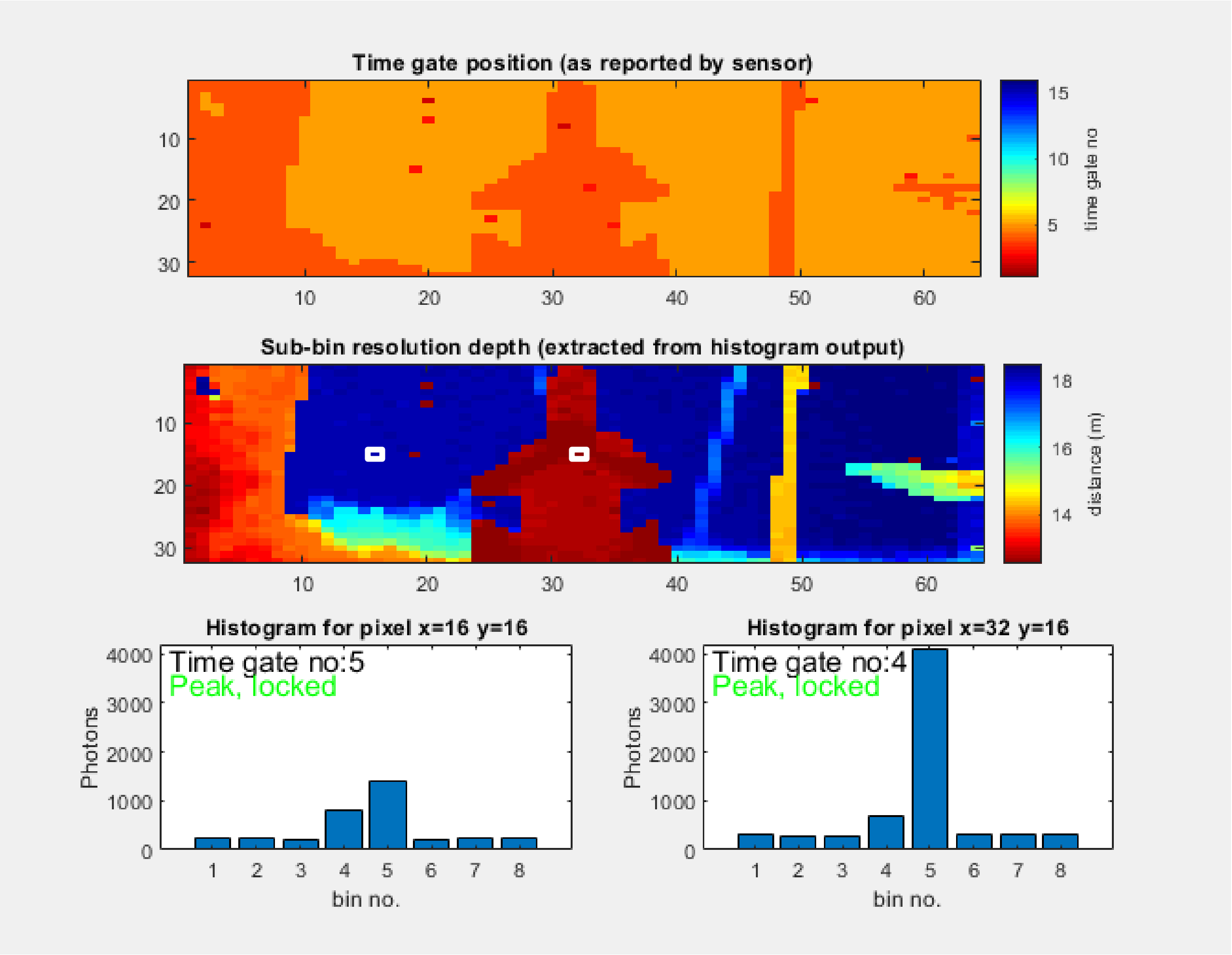
850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



20ms exposure time, external clock for timing, ~8ns bin size

Histogram mode

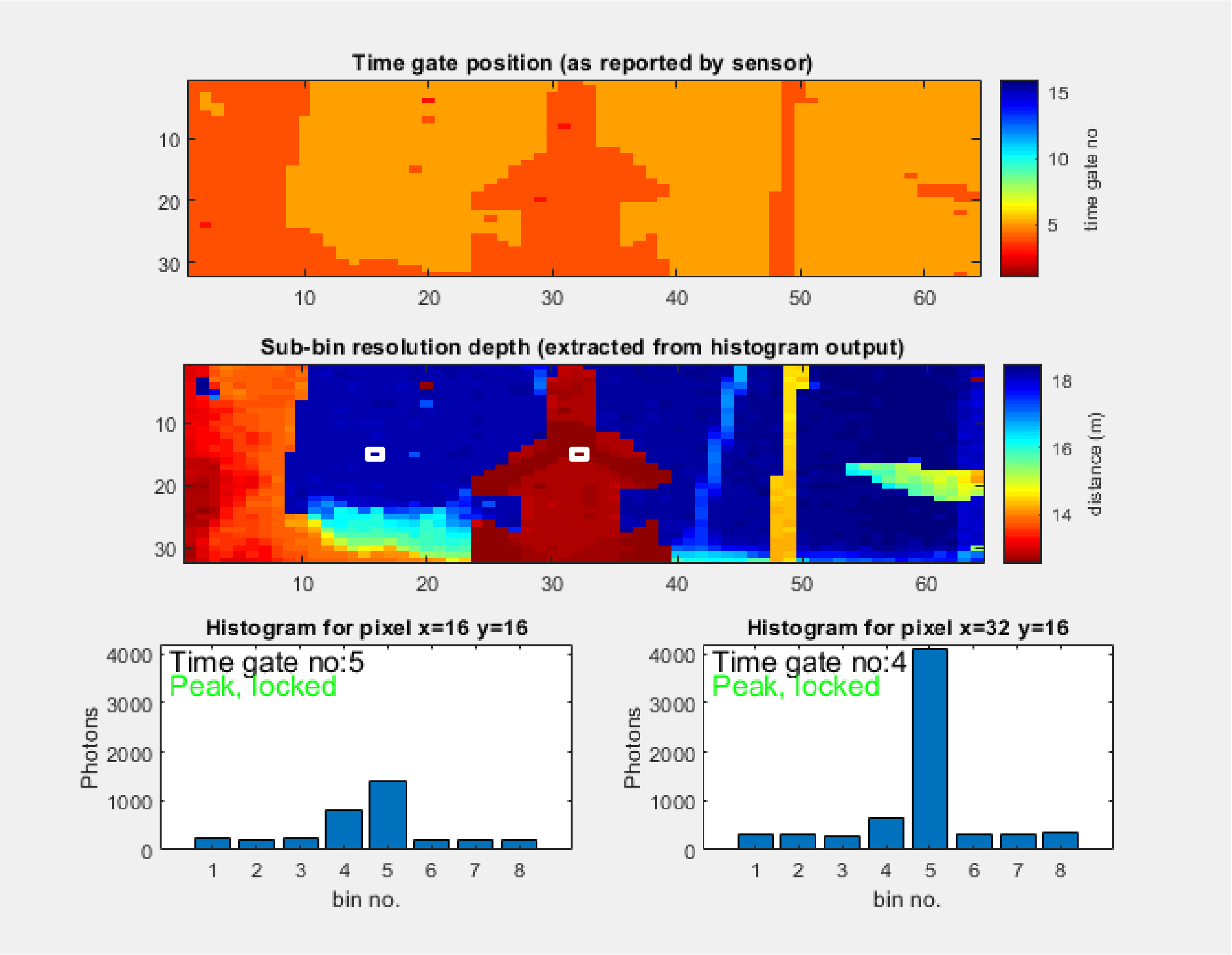
850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



20ms exposure time, external clock for timing, ~8ns bin size

Histogram mode

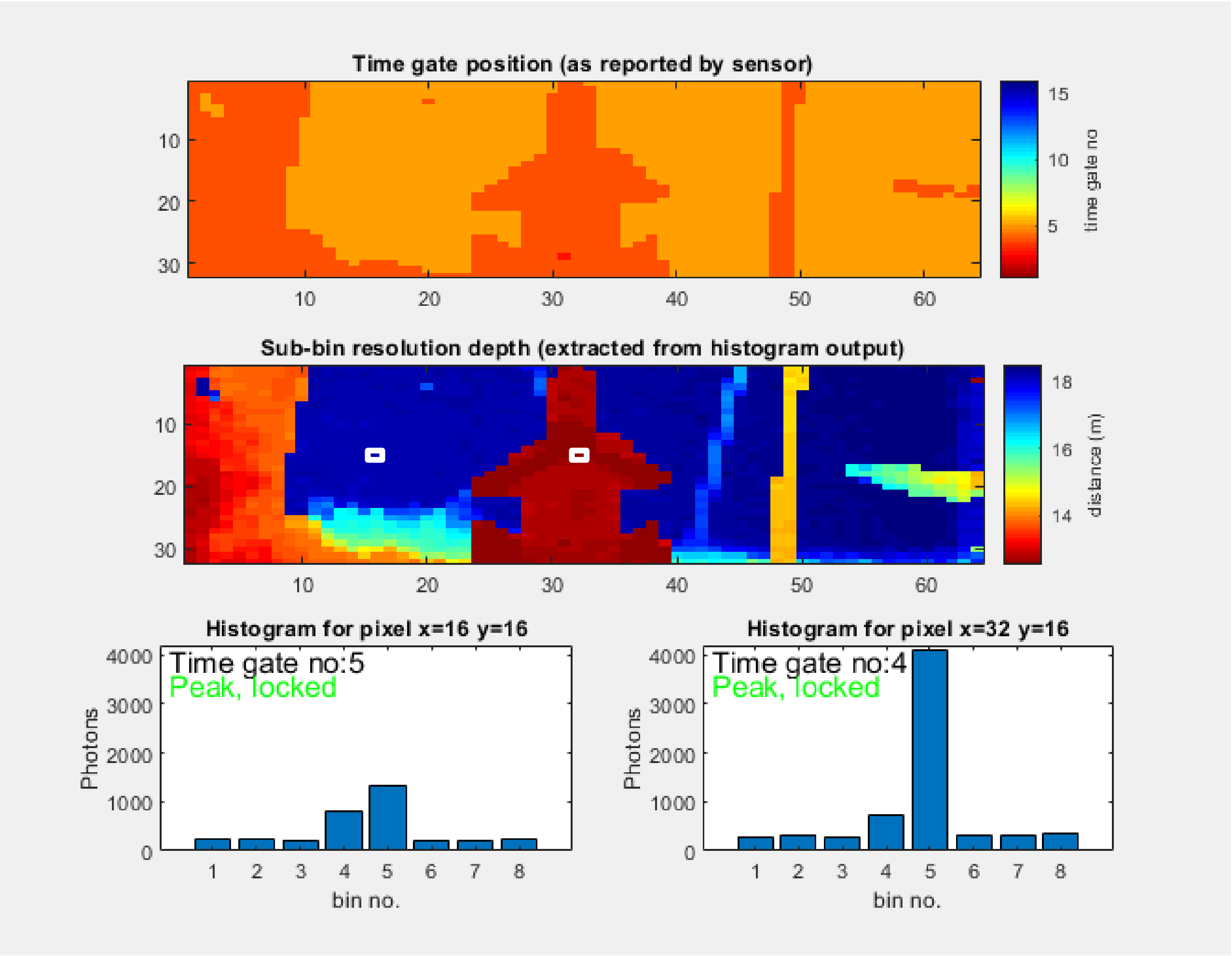
850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



20ms exposure time, external clock for timing, ~8ns bin size

Histogram mode

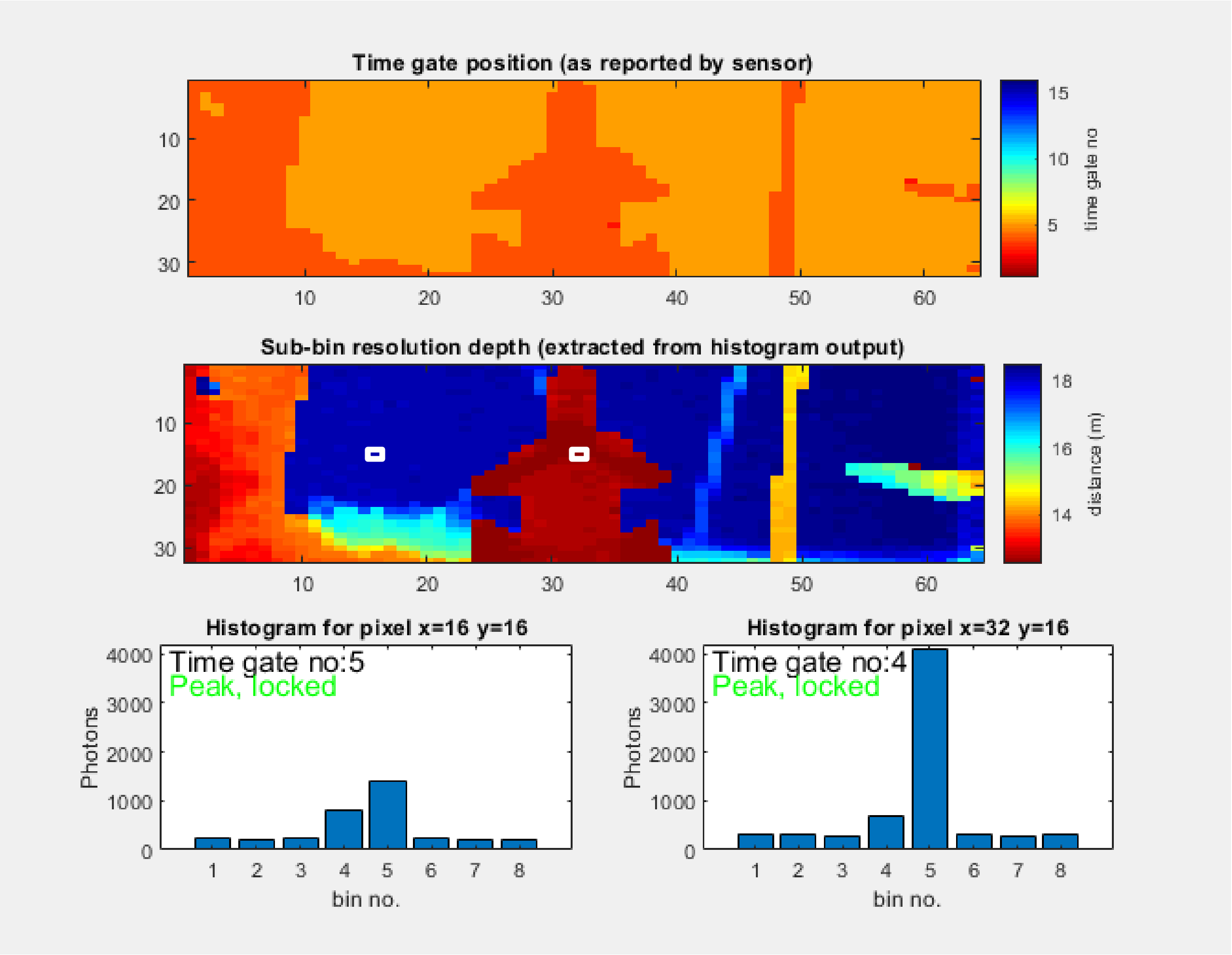
850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



20ms exposure time, external clock for timing, ~8ns bin size

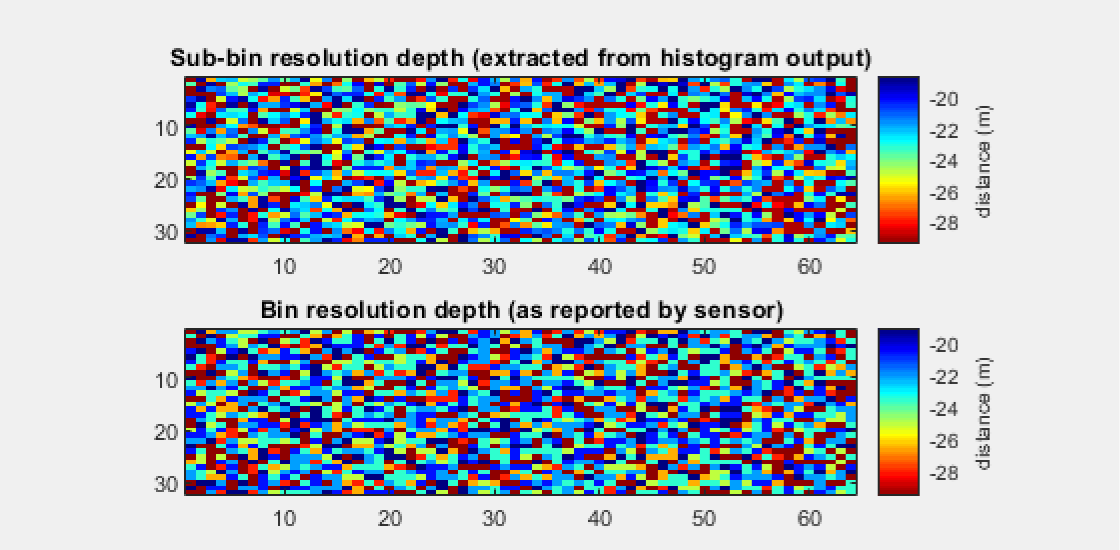
Histogram mode

850nm laser source, 1.2MHz rep rate, ~10ns pulse width, 60W peak power



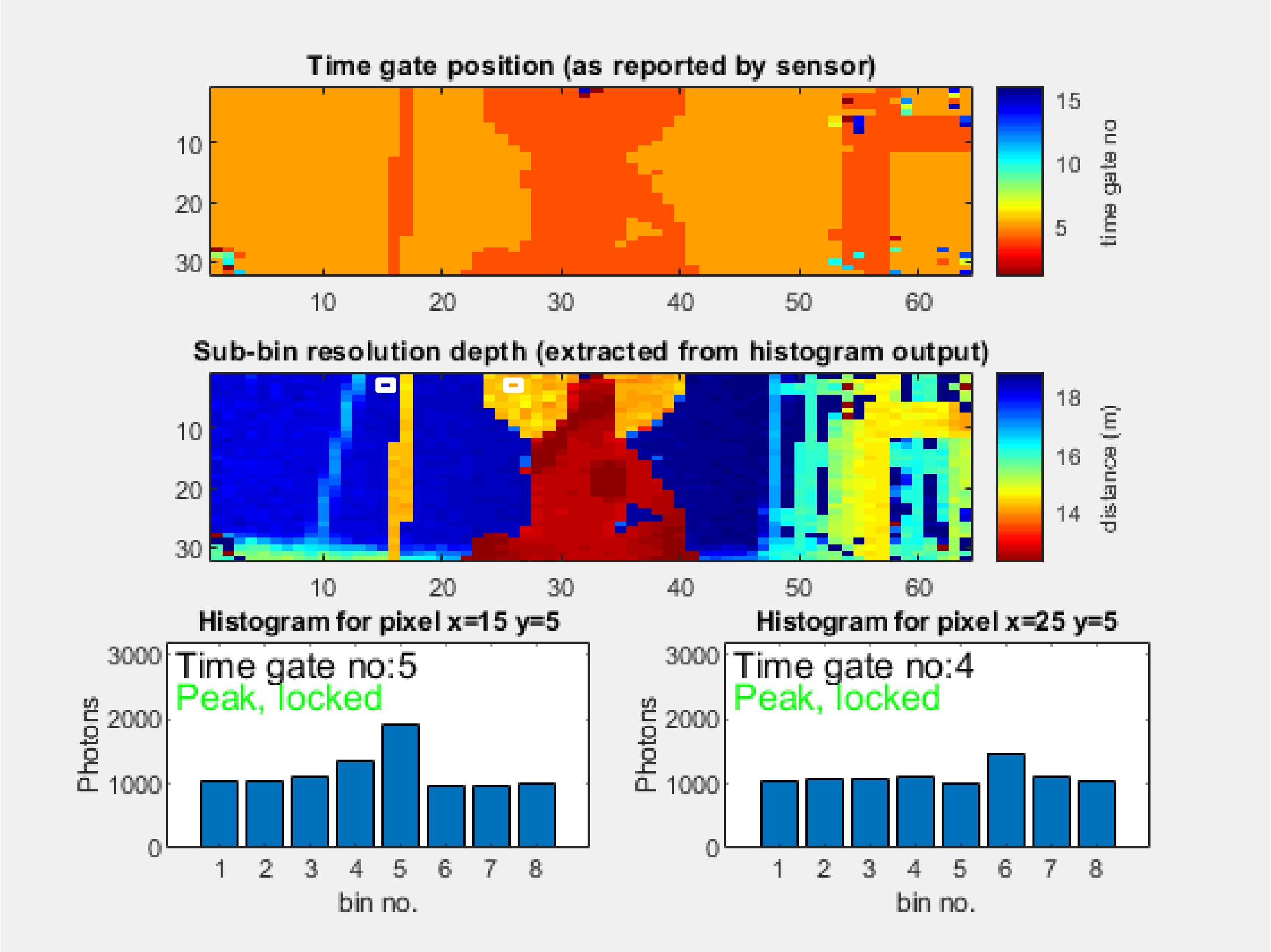
20ms exposure time, external clock for timing, ~8ns bin size

Histogram mode – example 2



Histogram mode – example 3

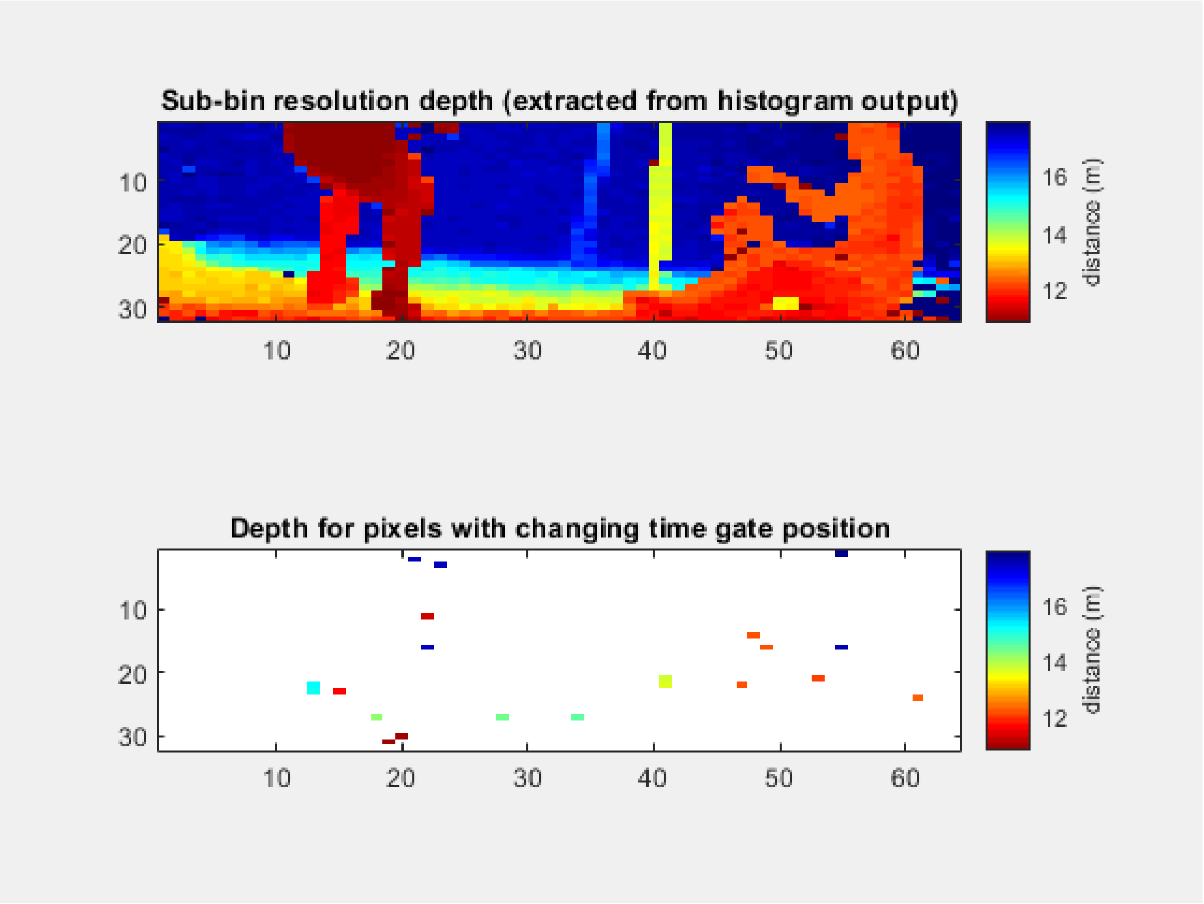
Elevated background level due to bright sun



Playback slowed down by ×5

Histogram mode – example 4

Change in depth sensing (100FPS)



Conclusion

- SPAD dToF imager with in-pixel 8-bin histogram that scans time range and tracks peaks
- METDC architecture for robustness to ambient illumination
- Designed for operation at high-frame rates
- Direct depth reading (sub-bin precision peak extraction) and detection of moving surfaces
- Scaleable – substantial compression, moderate power consumption of I/O and photon processing

Acknowledgements

This research was funded by EPSRC

Engineering and Physical Sciences Research Council

The authors are grateful to STMicroelectronics for chip fabrication