High-speed, Underwater 3D Imaging with an In-Pixel Histogramming SPAD

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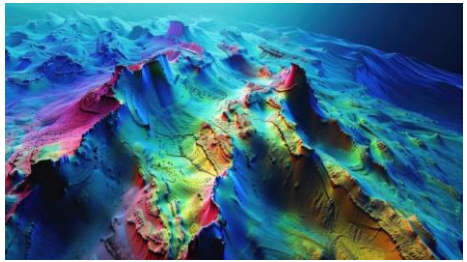
Applications of Underwater 3D Imaging

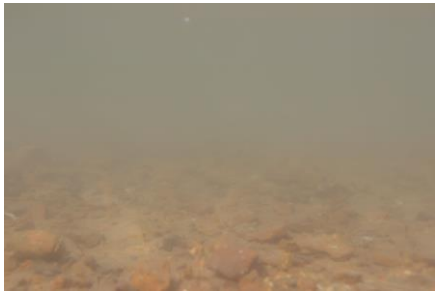
Inspection of installations



Seafloor mapping

Autonomous underwater vehicle (AUV)

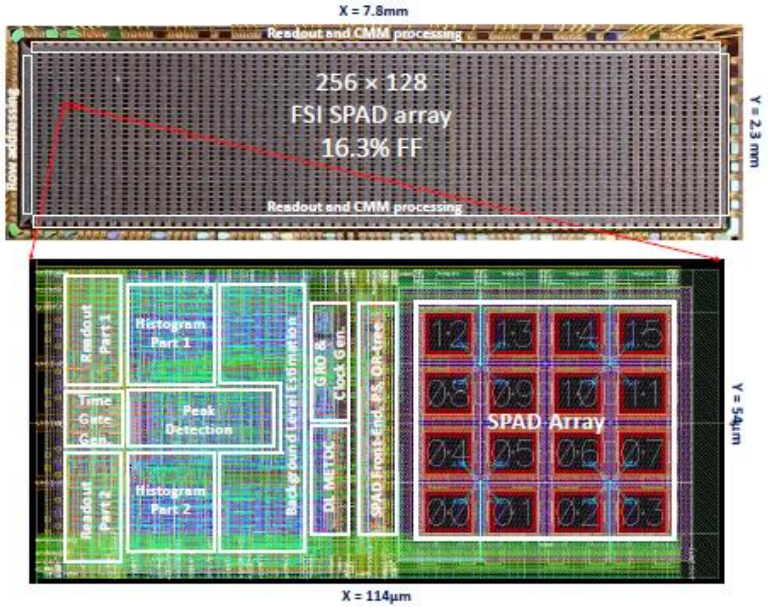
Harbour inspection



Vision in turbid water

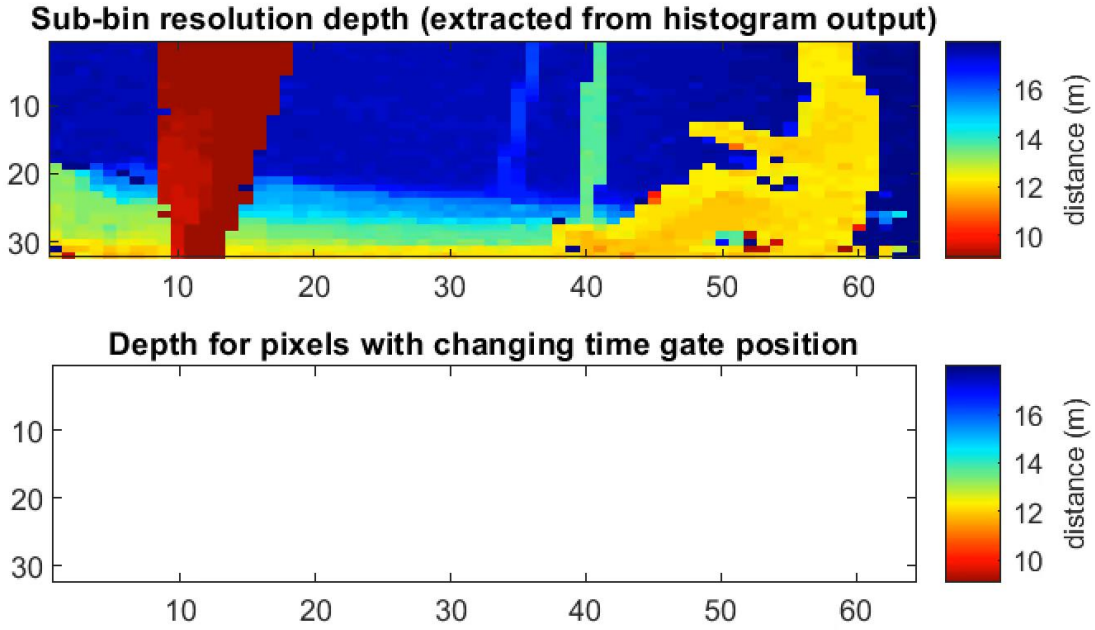
HSLIDAR sensor

- 32 × 64 macropixels
- 4 × 4 SPAD per macropixel
- In-pixel multi-event histogramming TDC
- 8 bins/histogram (>250ps bin width)
- Individual time gates per pixel
- Manual or automatic time gate control



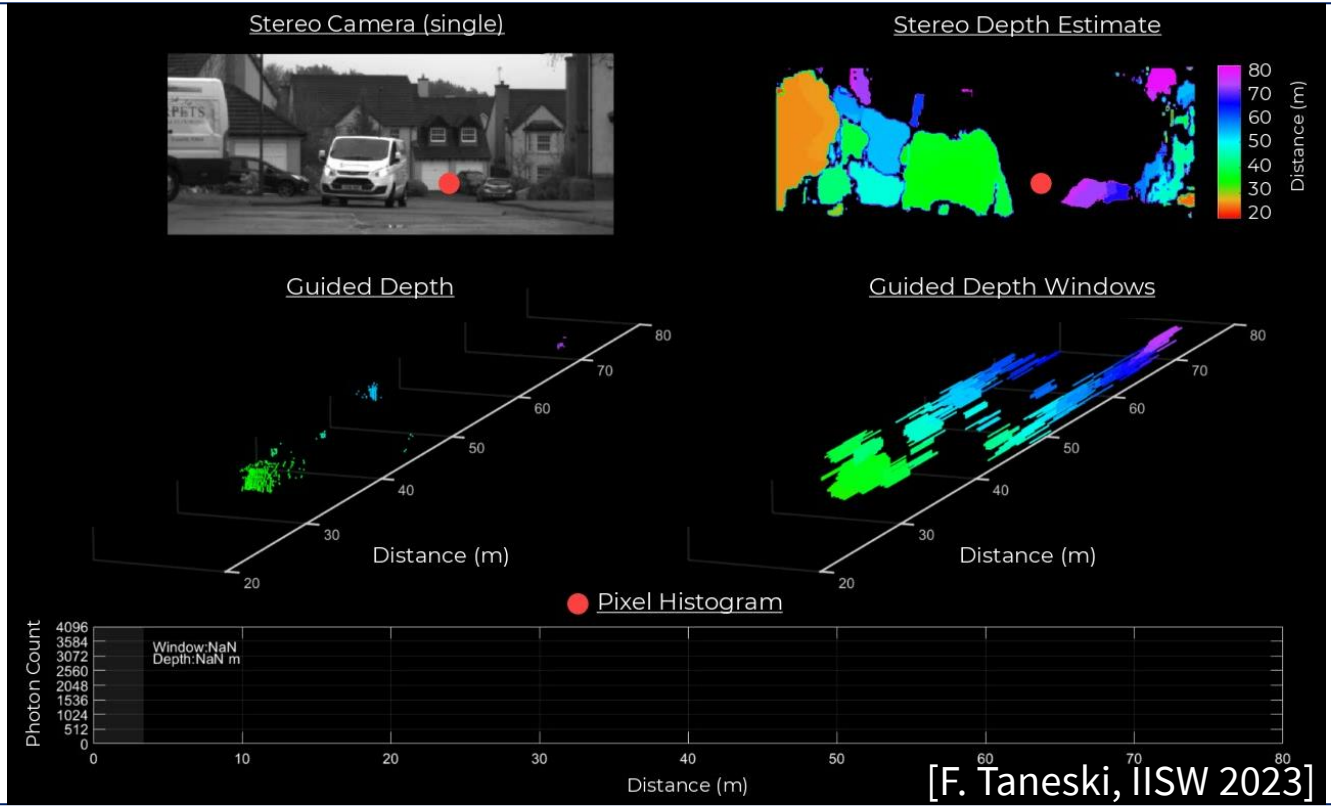
[I. Gyongy, JSTQE 2023]

HSLIDAR sensor – automatic time gate adaptation



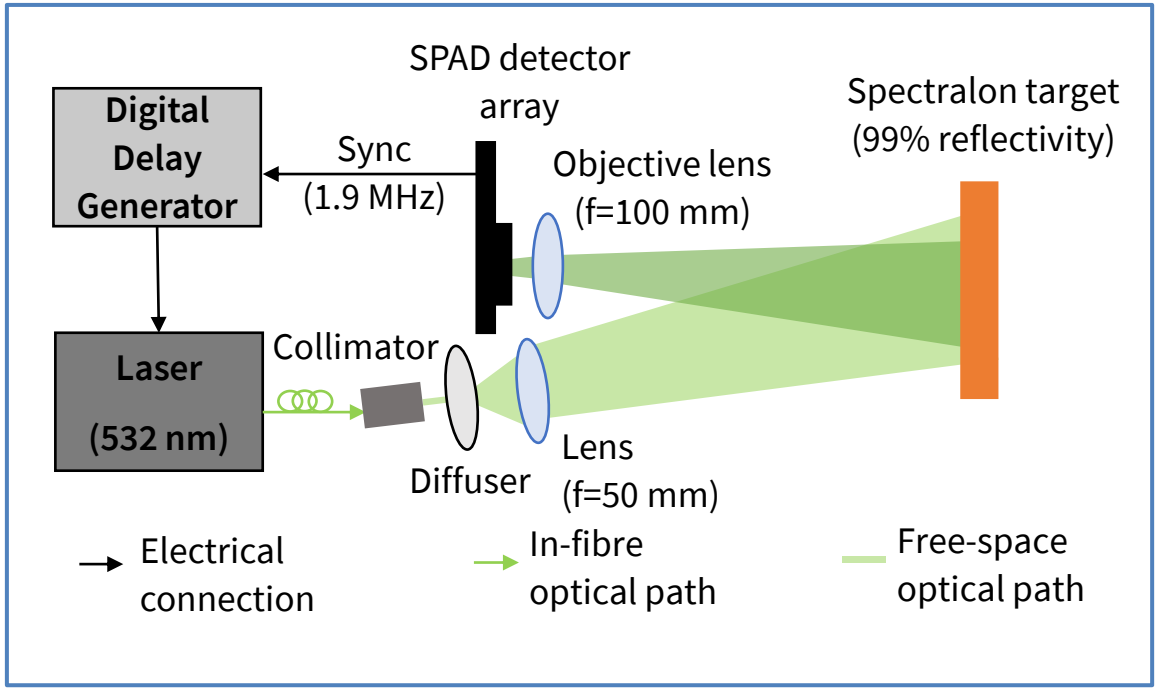
[I. Gyongy, ISSW 2022]

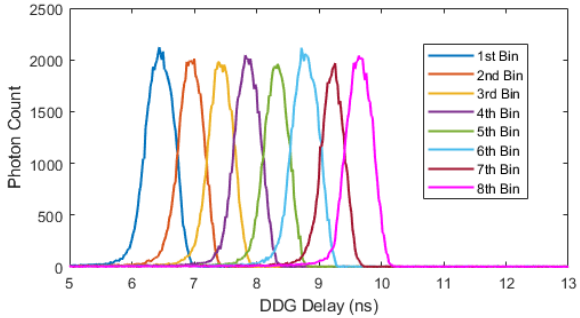
HSLIDAR sensor – externally controlled time gates



[F. Taneski, IISW 2023]

HSLIDAR sensor – calibration

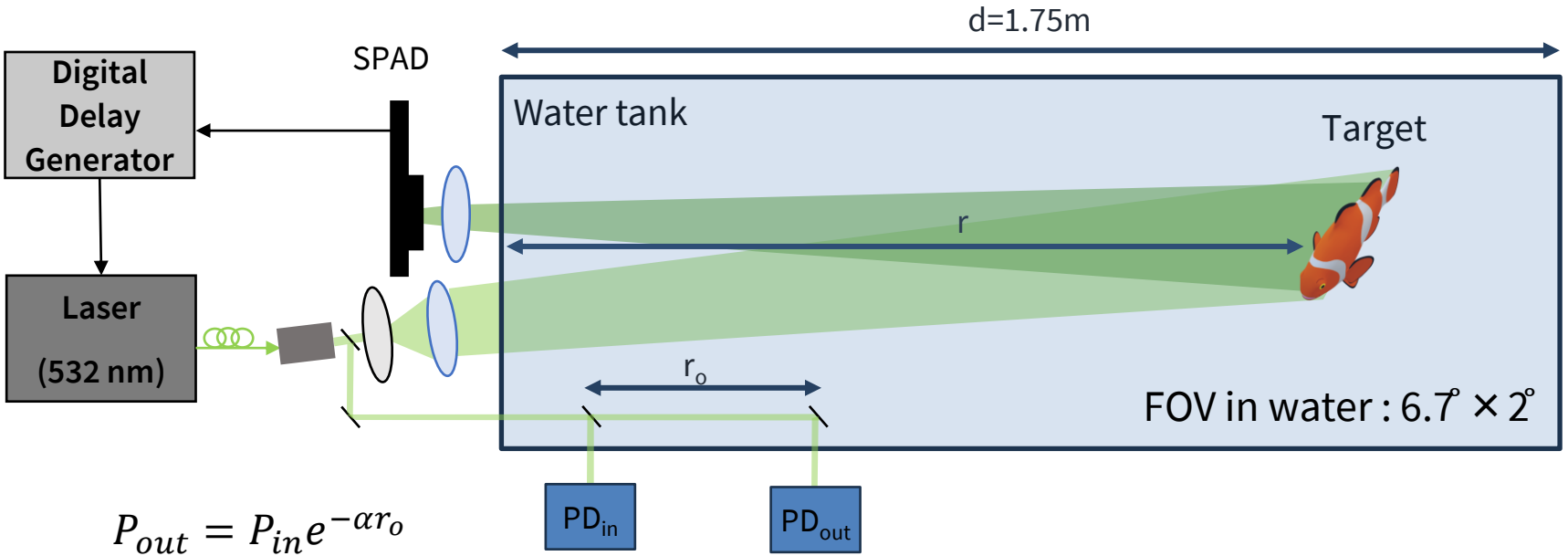




Correction for

- Left-right timing skew
- Histogram non-linearity

HSLIDAR sensor – measurements



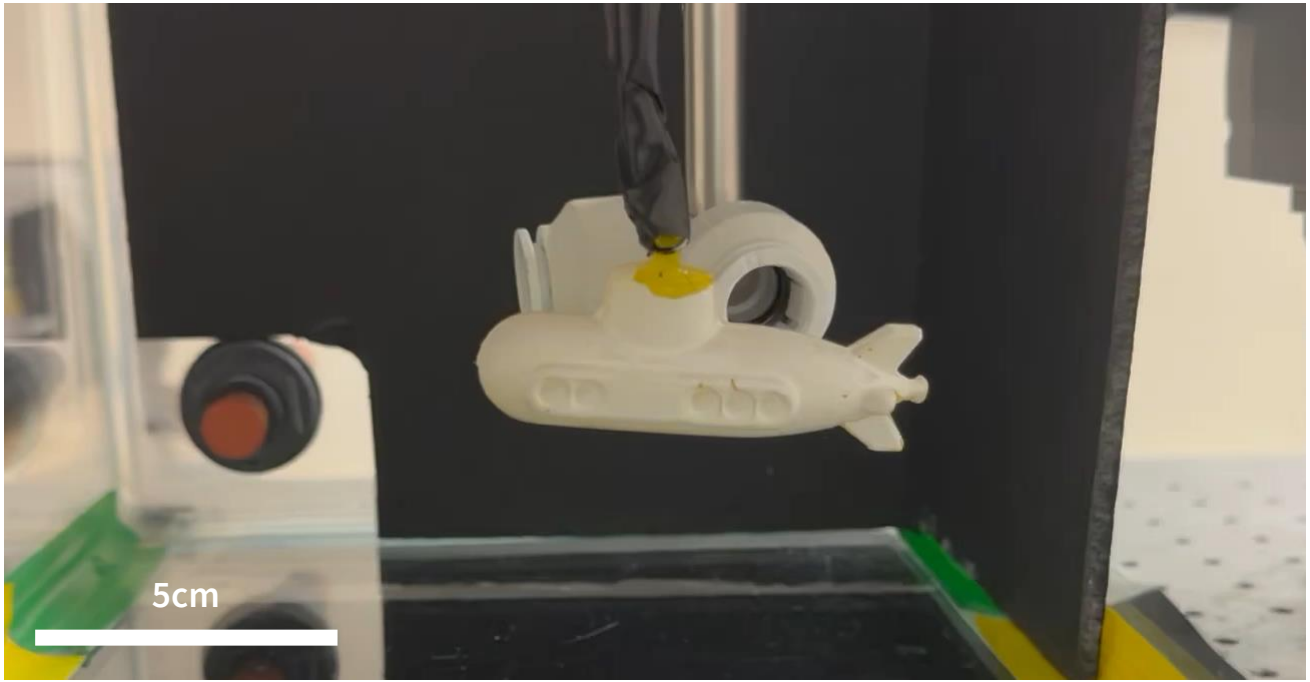
$$P_{out} = P_{in}e^{-\alpha r_o}$$

$$AL = \alpha r$$

α : attenuation coefficient

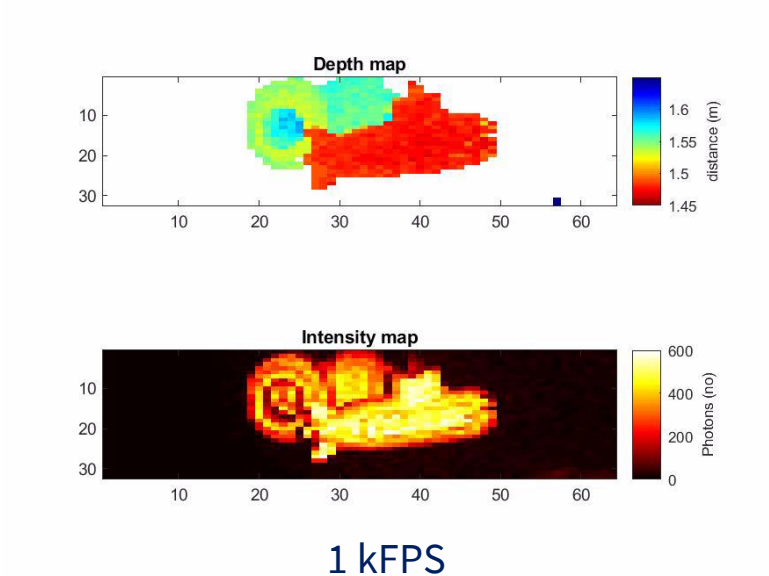
r : distance to target

Underwater scene

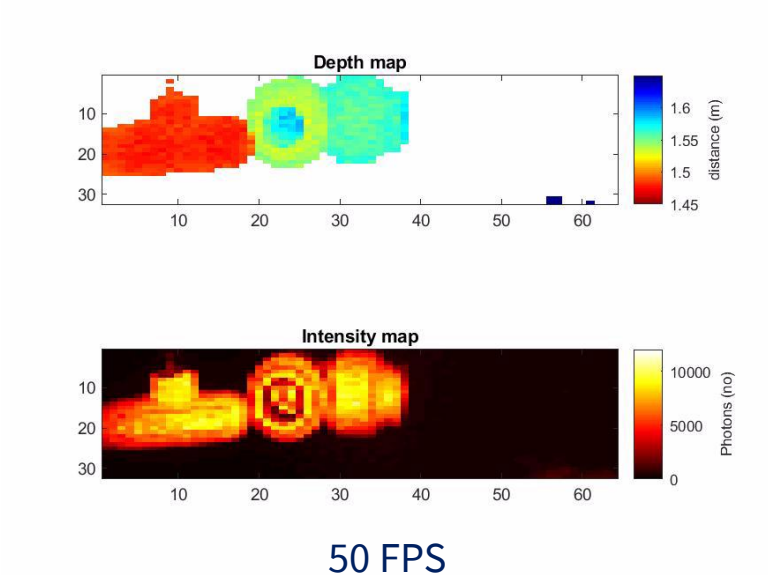


Results – centre of mass processing

Clear water (AL = 0.03)



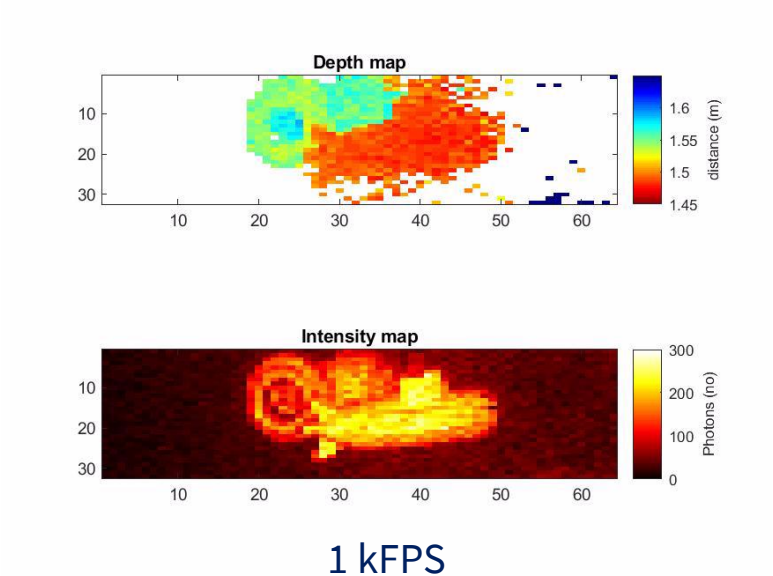
1 kFPS



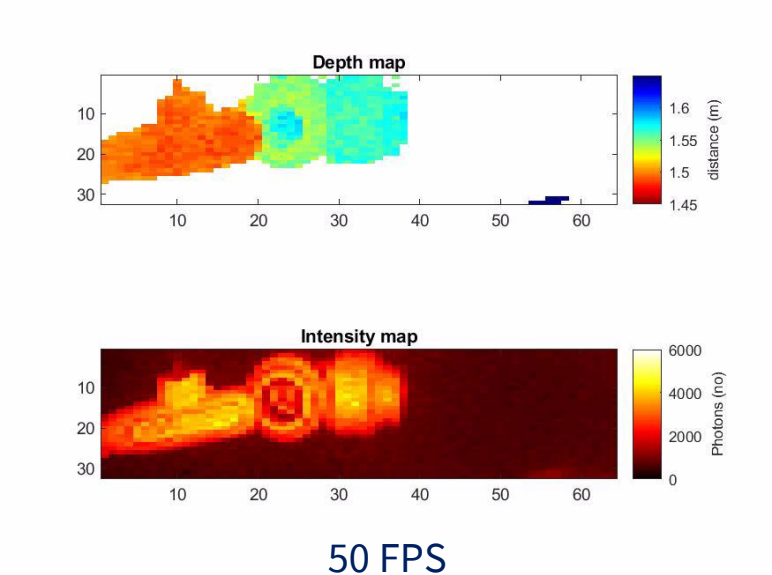
50 FPS

Results – centre of mass processing (cont.)

AL = 1.6 (1/5 attenuation)



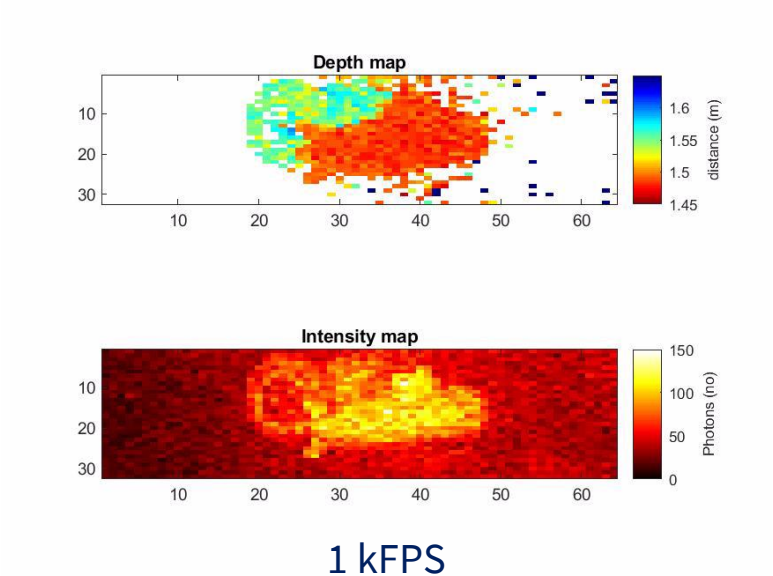
1 kFPS



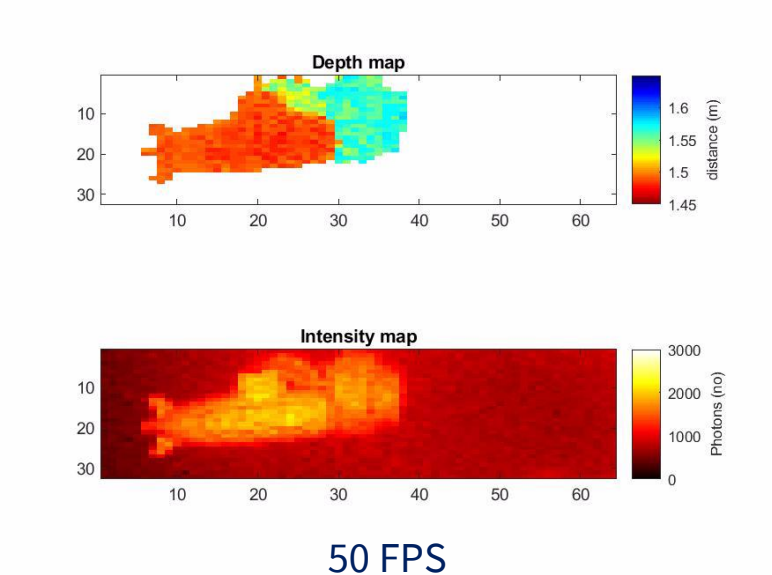
50 FPS

Results – centre of mass processing (cont.)

AL = 2.9 (1/18 attenuation)



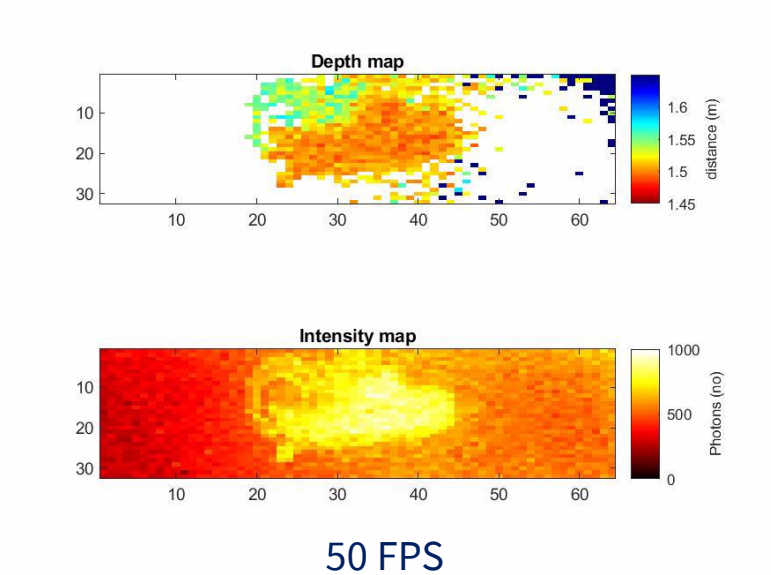
1 kFPS



50 FPS

Results – centre of mass processing (cont.)

AL = 4.1 (1/60 attenuation)

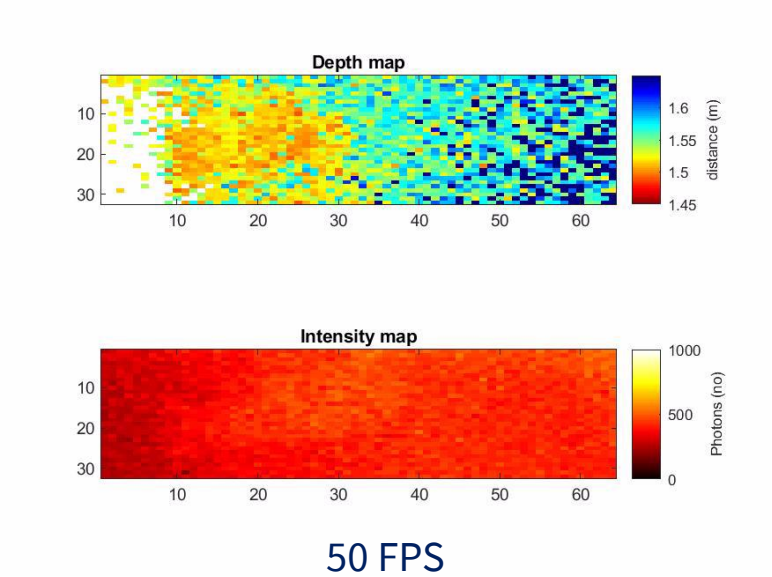


50 FPS

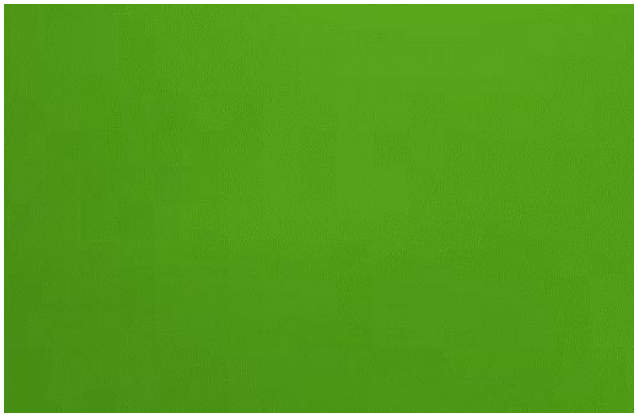
RGB

Results – centre of mass processing (cont.)

AL = 5.9 (1/360 attenuation)



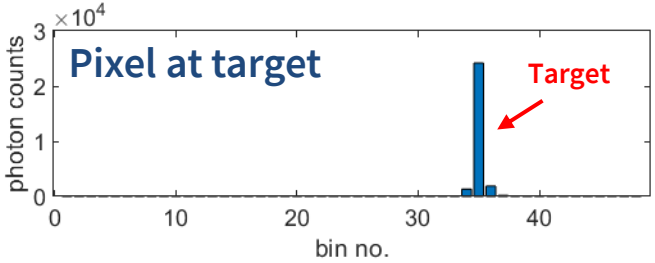
50 FPS

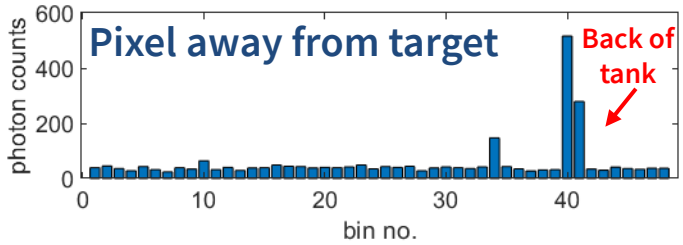


RGB

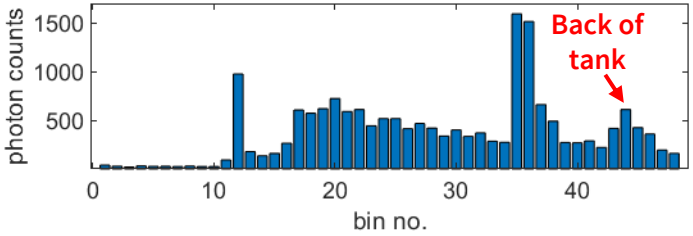
Results – changes in histogram profile

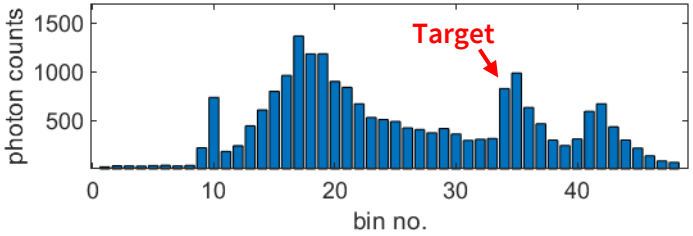
clear water



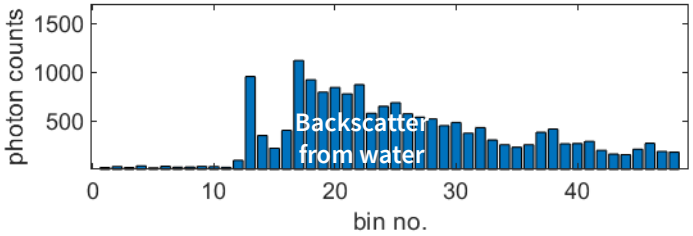


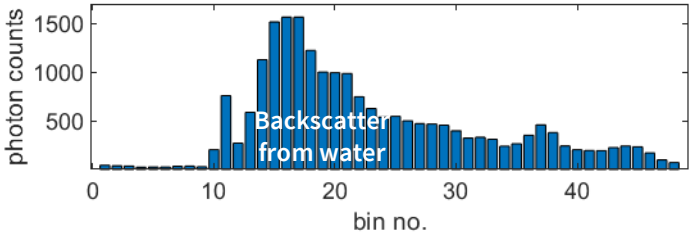
AL = 5.5





AL = 10





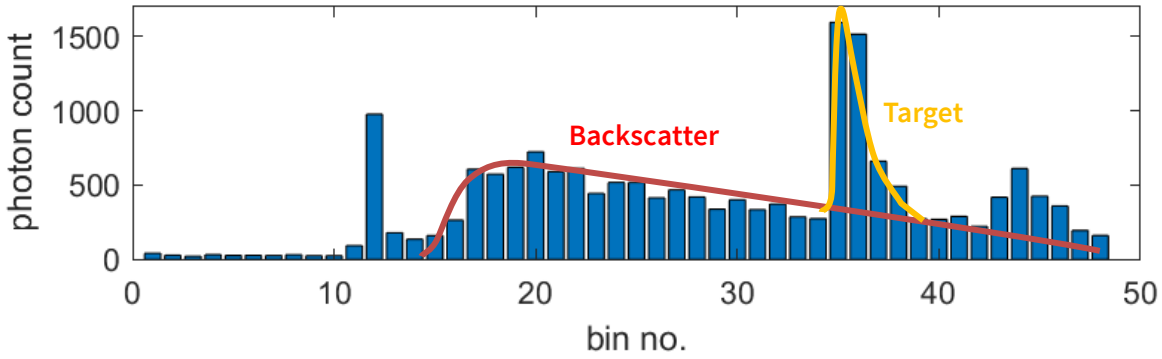
Curve fitting

Exponentially modified Gaussian function

$$f(x;\mu,\sigma,\lambda) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)} \operatorname{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$

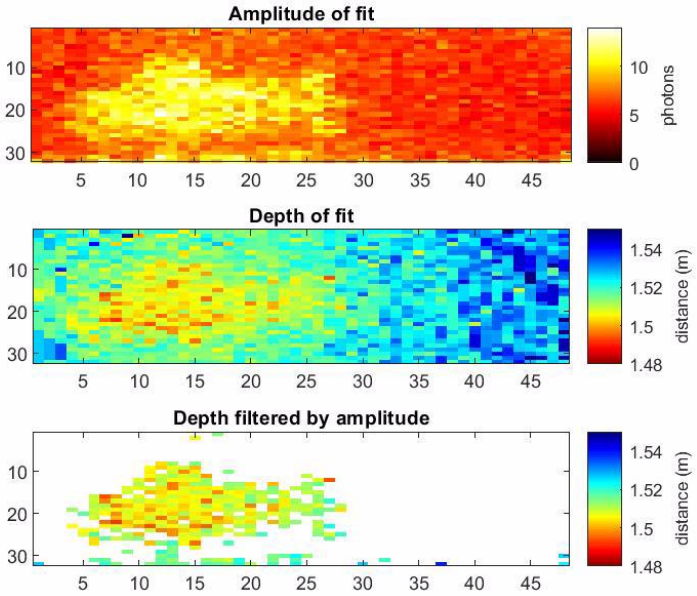
Proposed for LIDAR through fog in
[Holtzhüter, H., Automotive LIDAR, 2021]

Can we use this to separate ballistic photons from target from backscatter and forward scatter?



Results – curve fitting

AL = 5.5, EMG fit

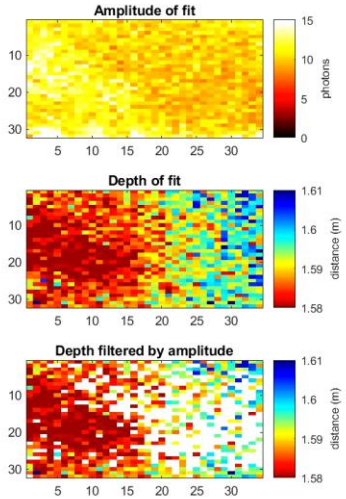


20 FPS

RGB

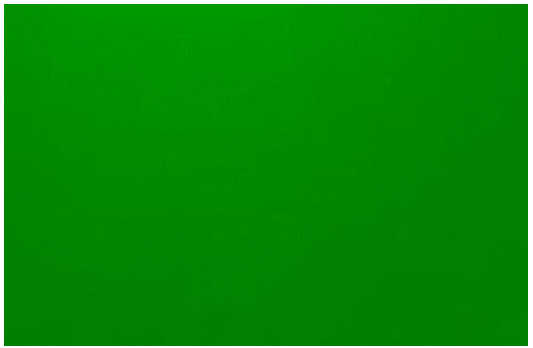
Results – curve fitting (cont.)

AL = 8.6, EMG fit



10 FPS

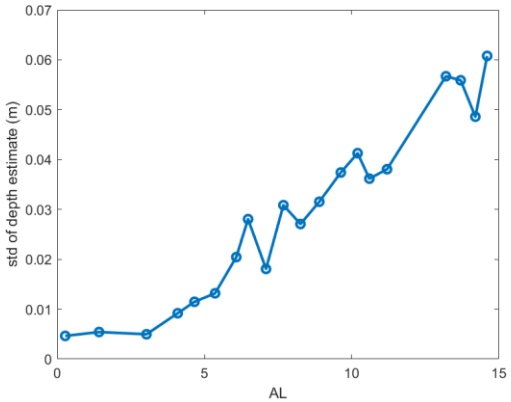
1/5400 (37dB) attenuation in laser power (one-way)

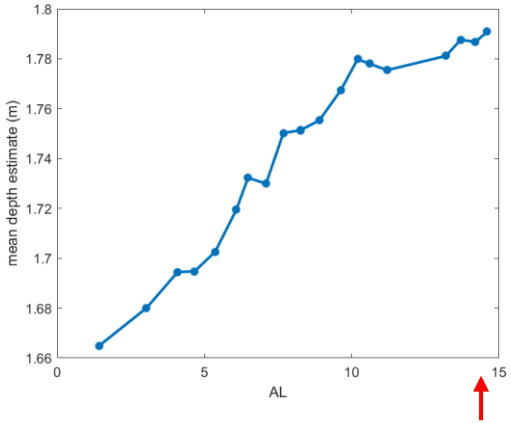


RGB

Results – depth error

Flat target (Spectralon) captured using a single 1 ms exposure (CMM processing)



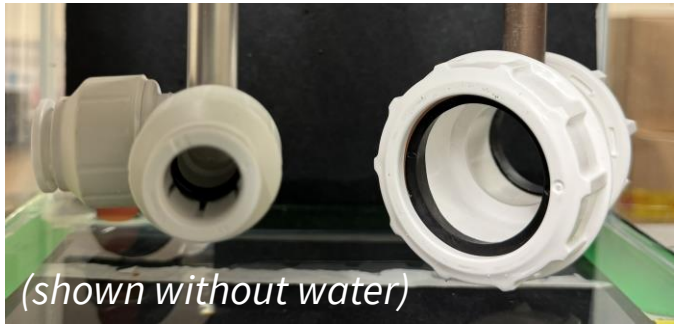


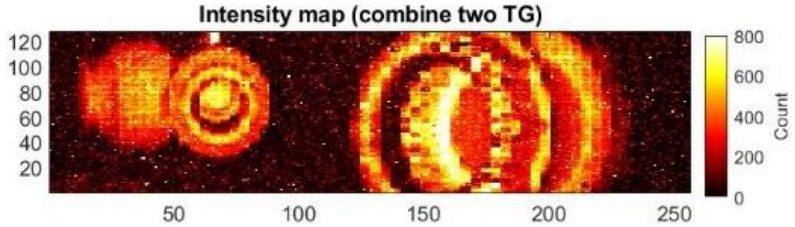
*1/(2.2*10^6) (127dB) attenuation in laser power (one-way)*

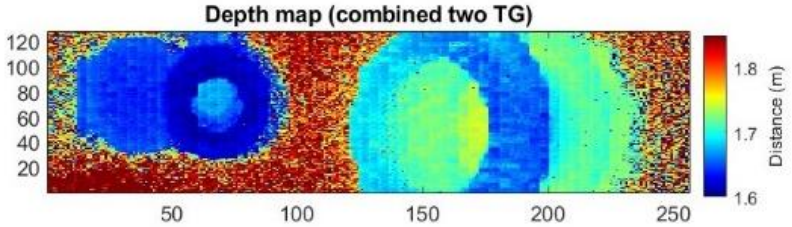
- 30 mW average power (lower for AL < 4)
- Target detected even at AL = 14.6

Results – high resolution mode

Clear water







Conclusions

- High-speed underwater imaging with a dToF SPAD
- Reconstruction in highly scattering conditions (AL>5) is challenging
- Curve fitting is a promising alternative to centre-of-mass (CMM) peak extraction
- Target detection was demonstrated at AL>14
- Time gate adaptation and denoising is still to be explored

Acknowledgements

Innovate UK project “Underwater Single Photon Imaging System”

STMicroelectronics for chip fabrication