LIDAR using SPADs in the visible and short-wave infrared

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Gerald S. Buller, Aongus McCarthy, Rachael Tobin, Aurora Maccarone, Abderrahim Halimi, Julián Tachella, Stephen McLaughlin & Yoann Altmann
School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK
*G.S.Buller@hw.ac.uk

[dstl]

Kenneth J. McEwan & Philip J. Soan
Defence Science and Technology Laboratory, Porton Down,
Salisbury, United Kingdom

ISL

Martin Laurenzis & Frank Christnacher
ISL, French-German Research Institute,
Saint-Louis, France

THE UNIVERSITY OF EDINBURGH

Francesco Mattioli Della Rocca & Robert Henderson
School of Engineering, University of Edinburgh, UK

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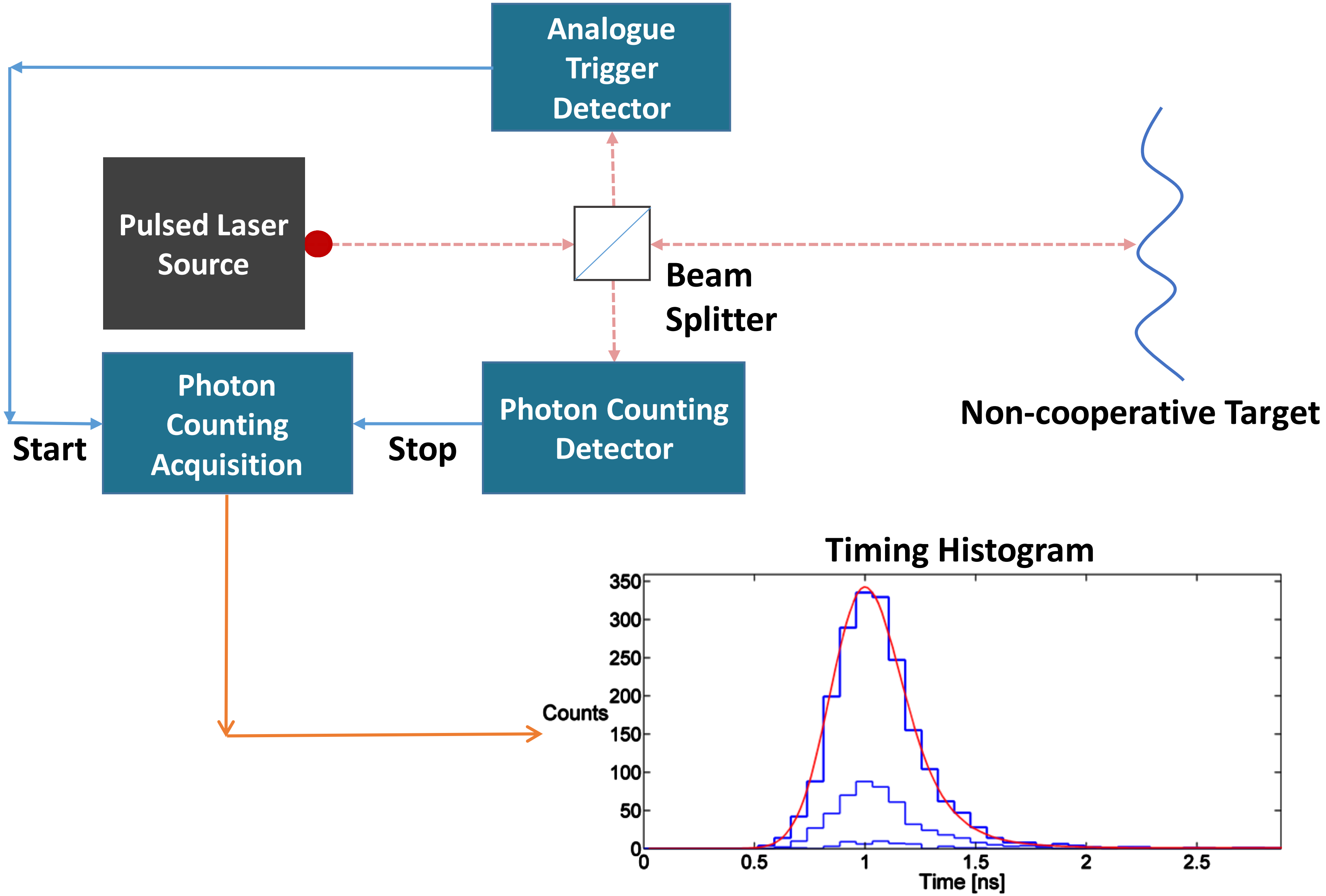
Outline

- Time-correlated single-photon counting (TCSPC)
- Why short-wave infrared (SWIR) wavelengths for free-space imaging?
- Imaging through obscurants using a single-photon avalanche diode (SPAD) scanner and a SPAD detector array camera in fog
- Complex (multiple surfaces per pixel) scenes at 300 metres
- Underwater imaging at visible wavelengths

Time-of-flight measurements using time-correlated single-photon counting (TCSPC)



Advantages of short-wave infrared (SWIR) wavelengths

SWIR wavelengths: approximately 1.4 µm – 3 µm

- Outside retinal hazard region (400 - 1400 nm)

Able to use significantly higher power levels while still being eye safe.

- Lower solar background than visible region

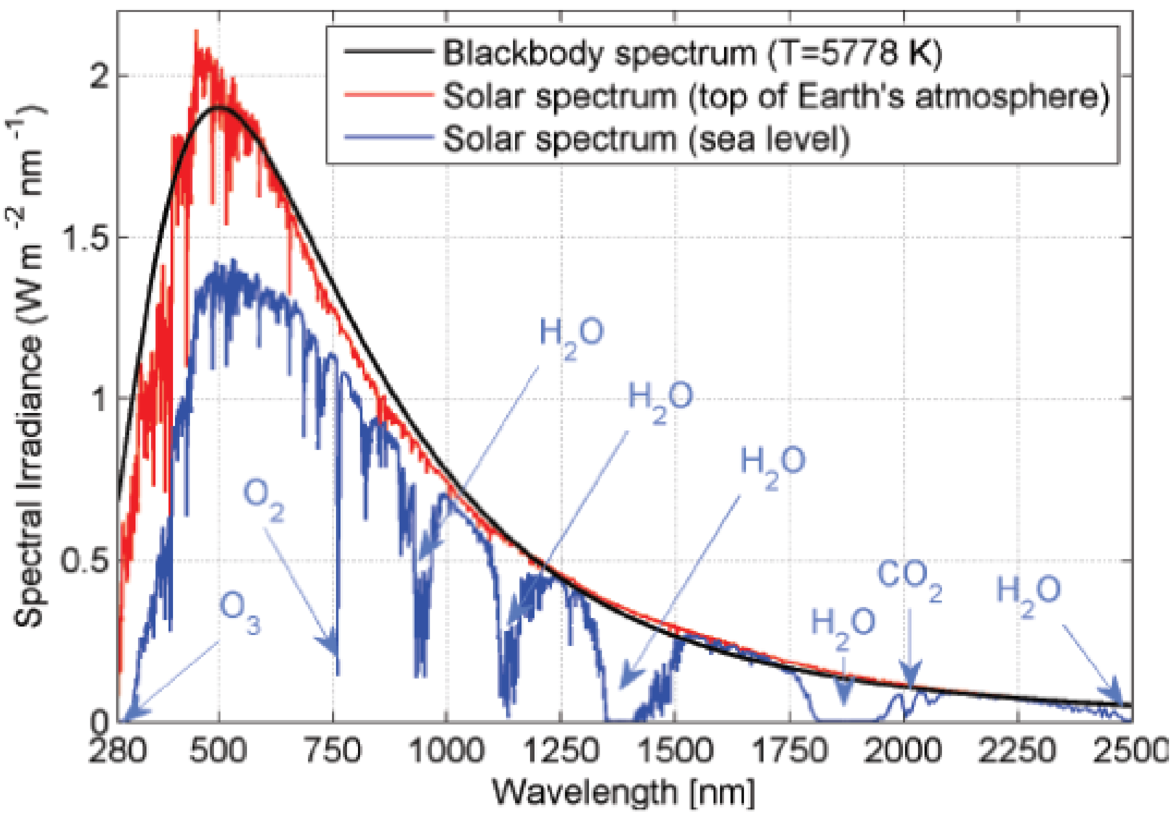
Improved signal-to-noise ratio in single-photon counting

- Increased atmospheric transmission

SWIR wavelengths around 1550 nm
suffer less attenuation than visible band wavelengths.

- Decreased scattering from small particles

Wavelength dependence on scattering from small particles

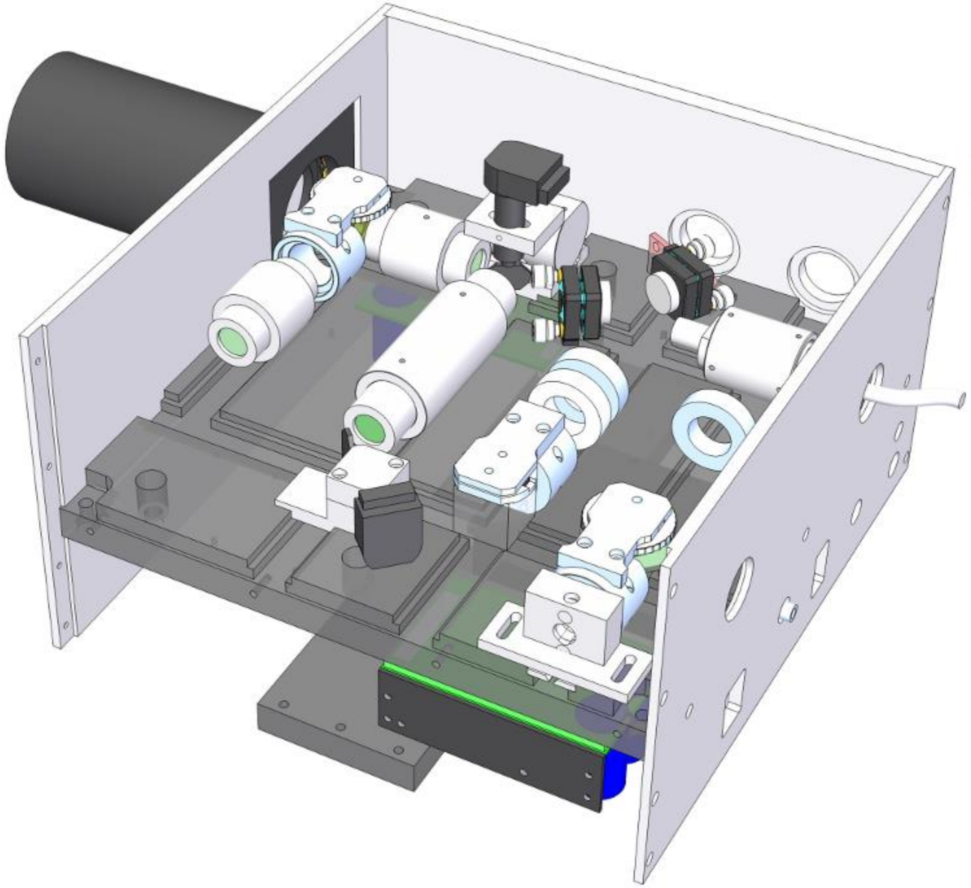


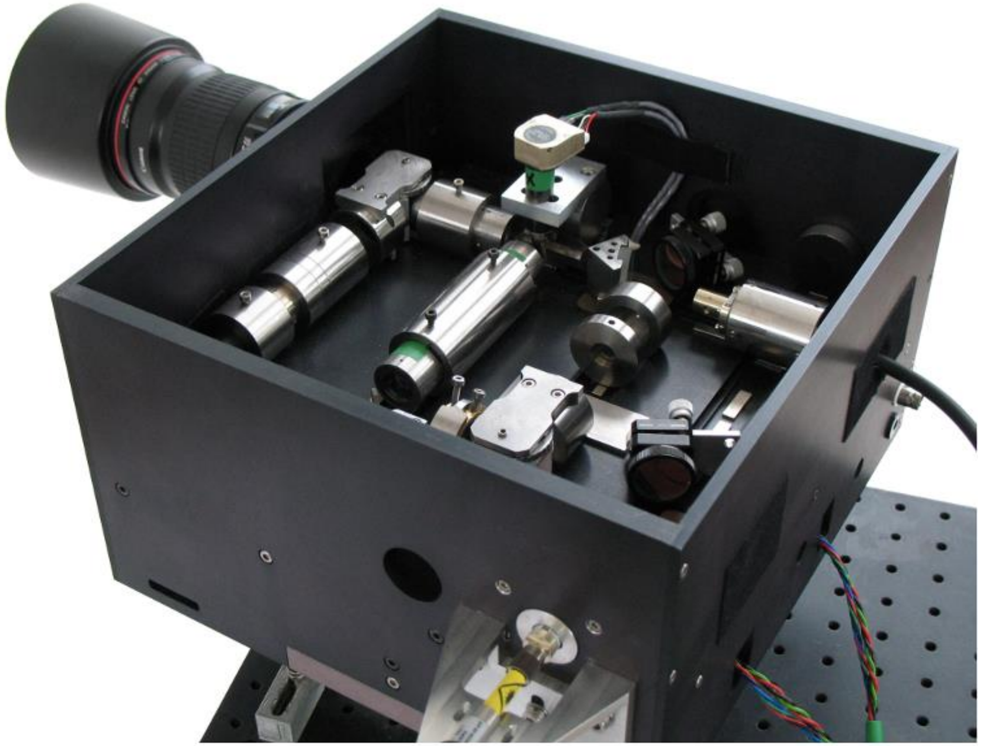
"Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface", Technical report ASTM G173-03, American Society for Testing and Materials, ASTM International, USA (2003).

L. S. Rothman et al., "The HITRAN 2004 molecular spectroscopic database," J. Quant. Spectrosc. Radiat. Transf. 96(2), 139–204 (2005).

Scanning single-photon depth imaging system

- Modular system – testbed for new components.
- Transceiver (275 × 275 × 170 mm)

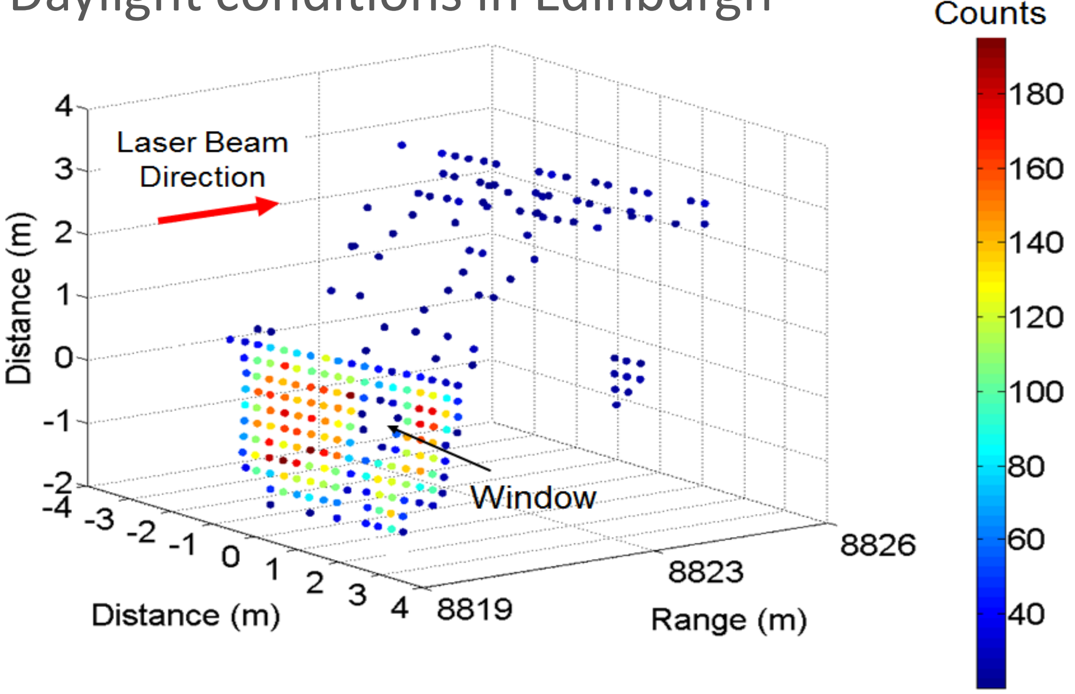


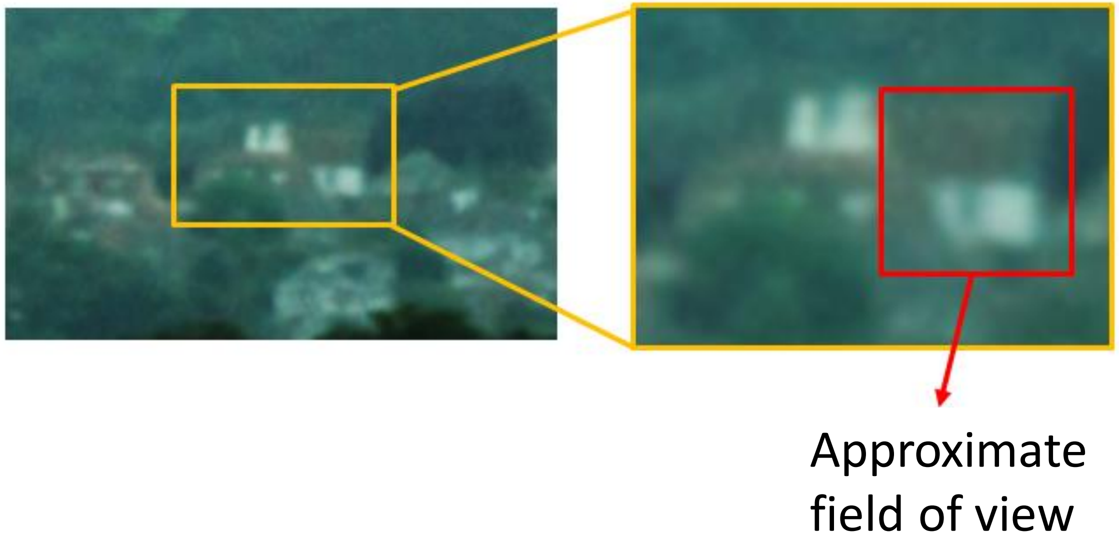


Aongus McCarthy, Robert J. Collins, Nils Krichel, Veronica Fernández and Andy Wallace and Gerald S. Buller *"Long-range time-of-flight scanning sensor based on high-speed time-correlated single-photon counting"* Applied Optics, **48**, pp. 6241–6251 (2009)

Depth imaging at 8.8 km range

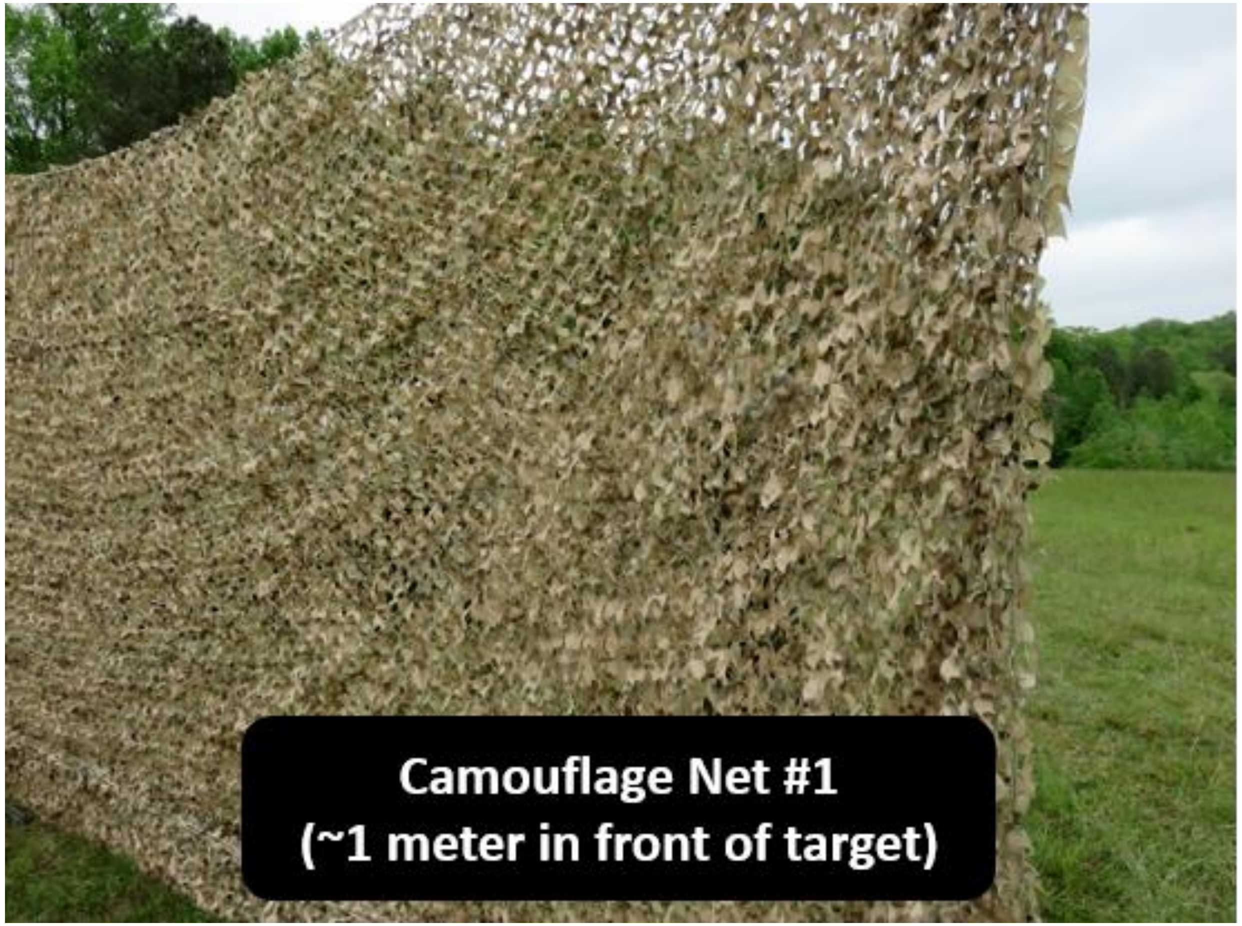
- λ ~ 1550nm
- Average power only **10mW**
- Peltier cooled InGaAs/InP SPAD (260K)
- 850ps jitter
- Daylight conditions in Edinburgh

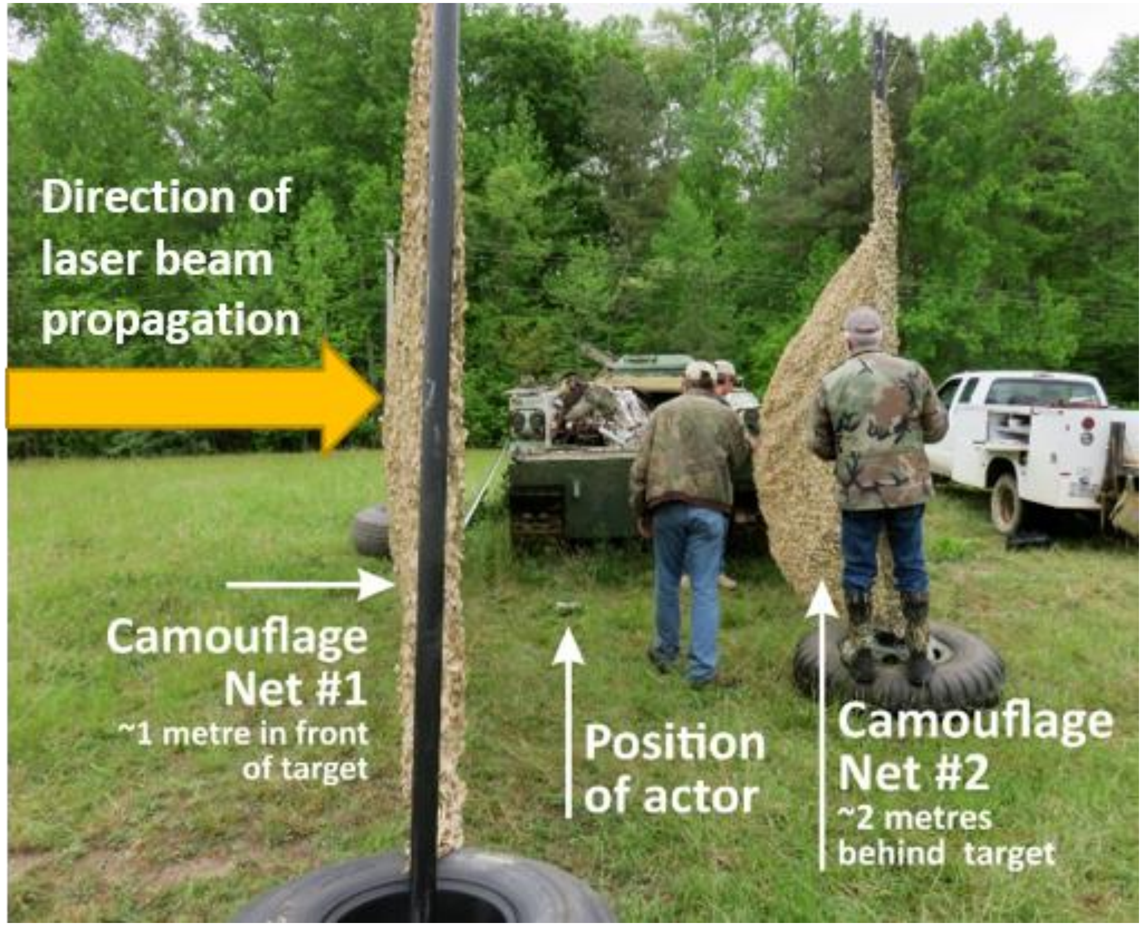




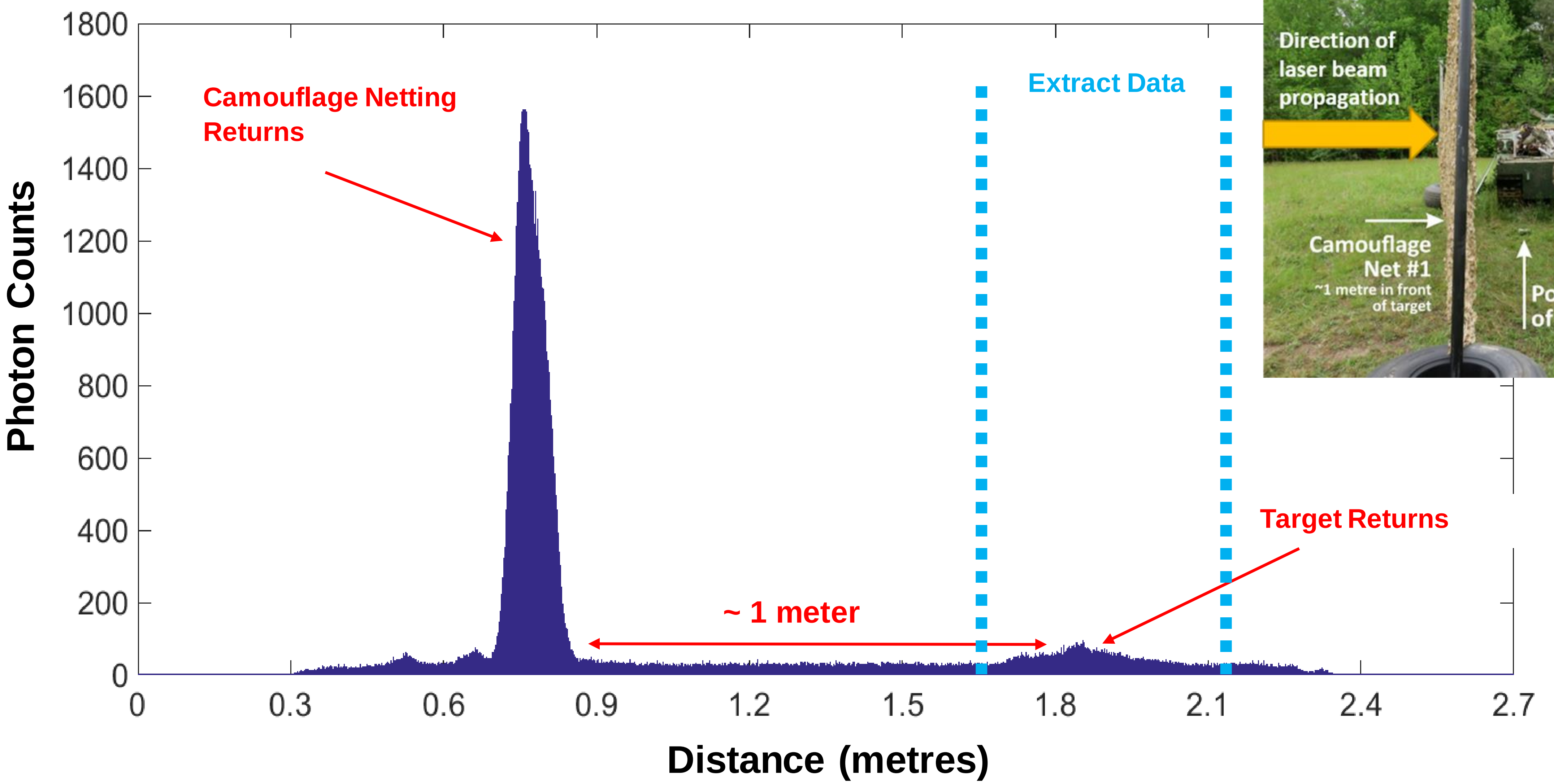
Agata M. Pawlikowska, Abderrahim Halimi, Robert A. Lamb, and Gerald S. Buller, *"Single–photon three-dimensional imaging at up to 10 kilometers range"*, Optics Express, **25**, 11919 (May 2017)

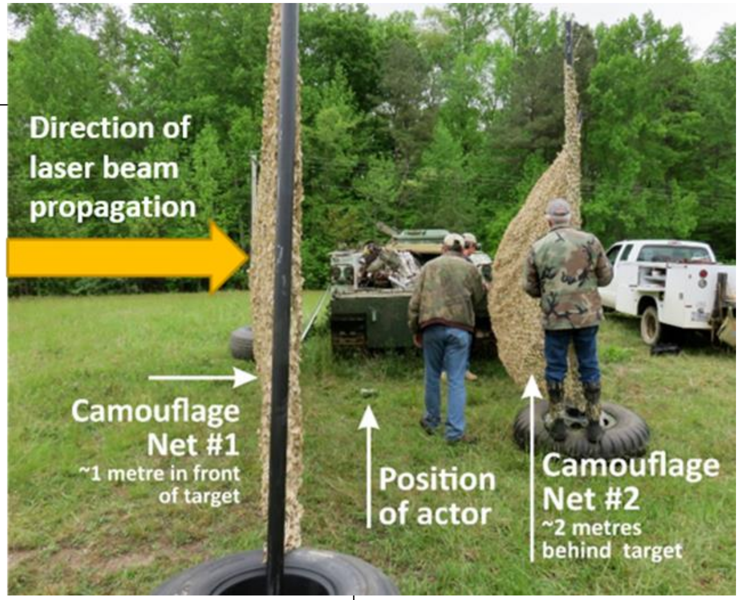
Target identification behind camouflage at 230 metres





Target identification behind camouflage at 230 metres

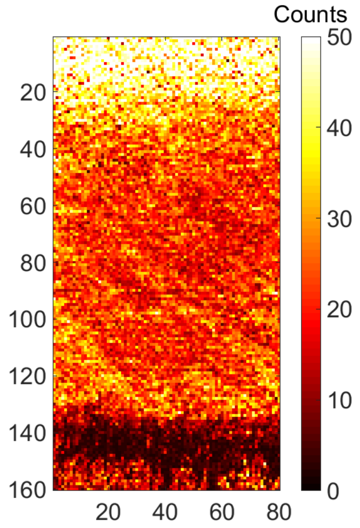




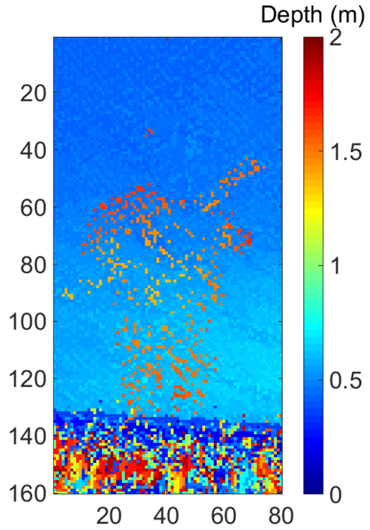
Target identification behind camouflage at 230 metres

Photograph

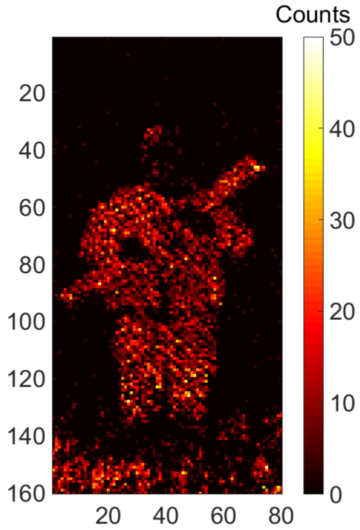
Single-photon Intensity



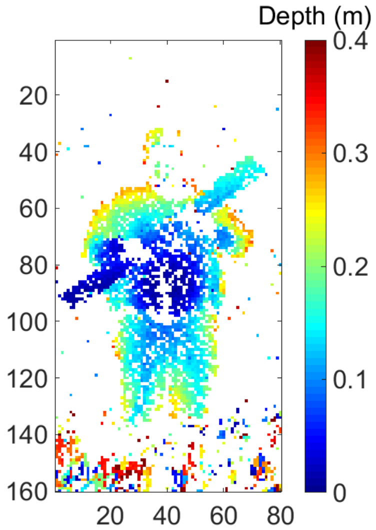
Depth (pixelwise analysis)



Gated Intensity Image

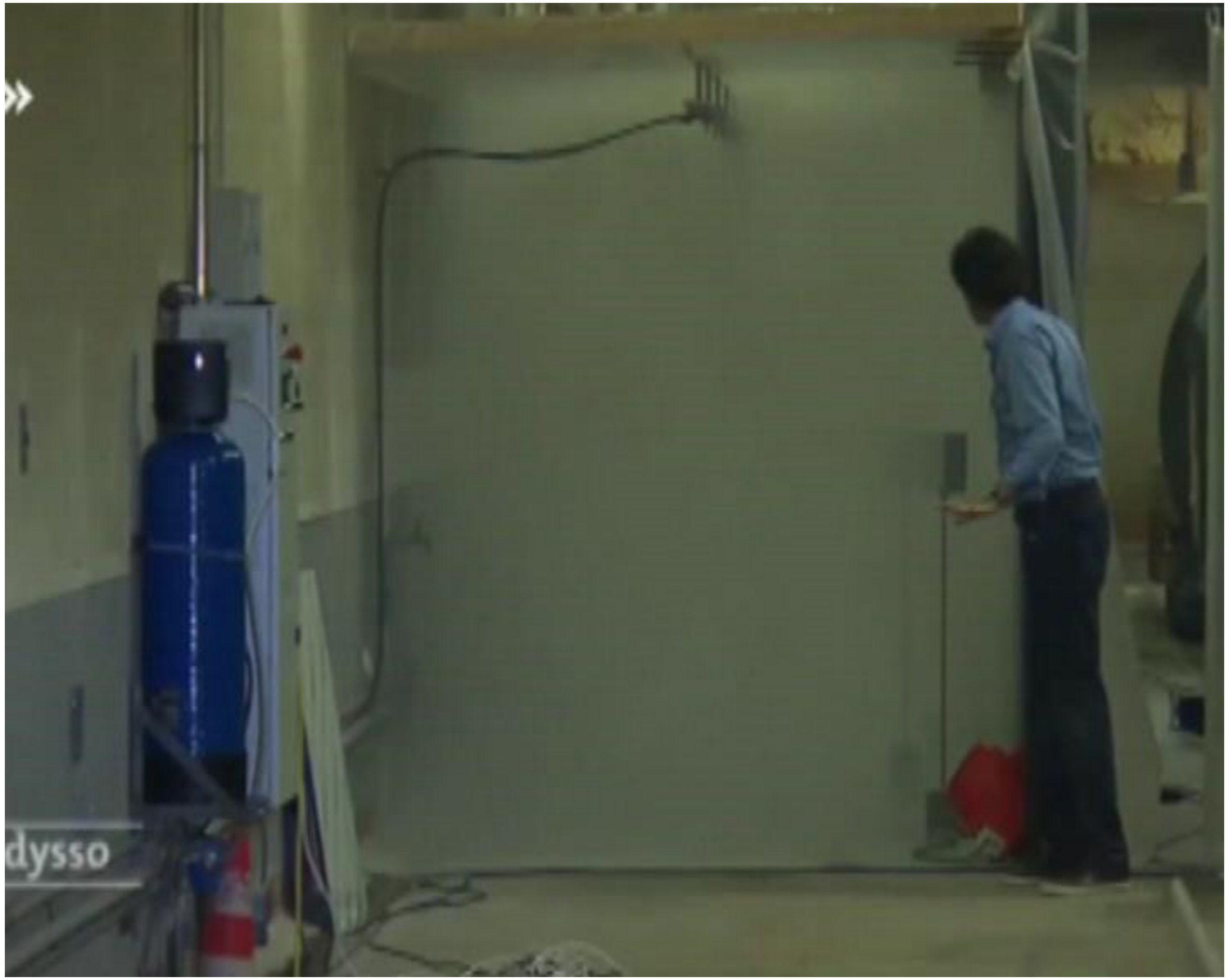


Gated Depth Image



Rachael Tobin, Abderrahim Halimi, Aongus McCarthy, Ximing Ren, Ken J. McEwan, Stephen McLaughlin and Gerald S. Buller
“Long-range depth profiling of camouflaged targets using single-photon detection“
Optical Engineering **57**(3), 031303 (2017)

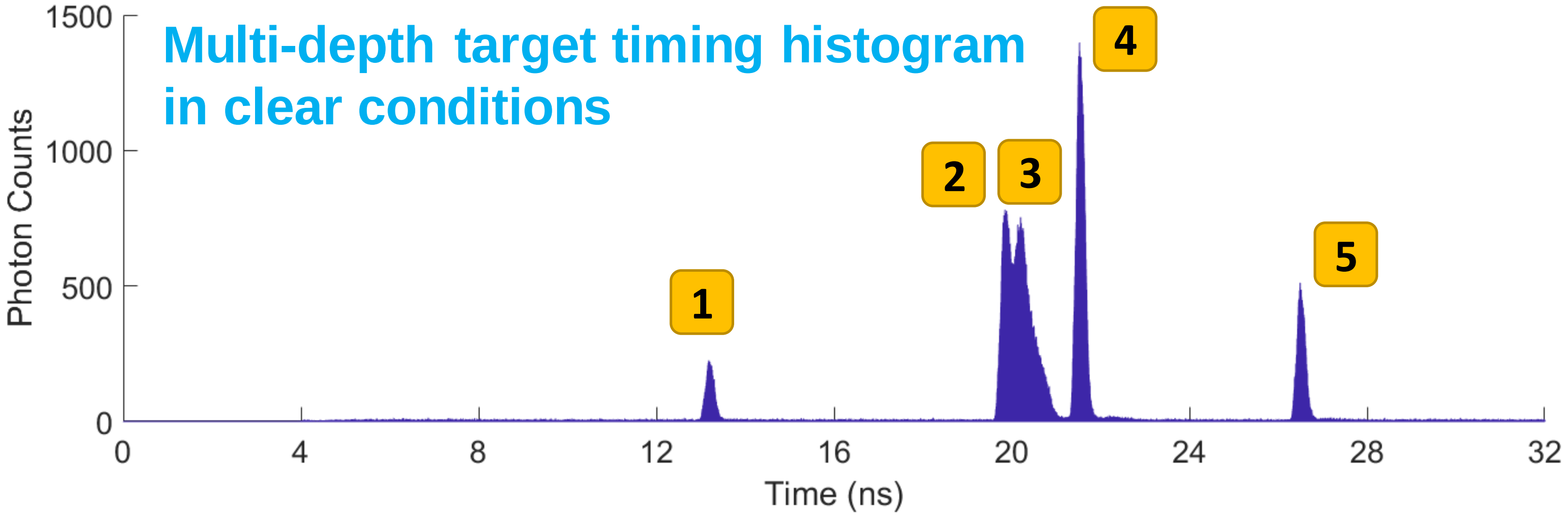
Imaging through obscurants – indoor trials

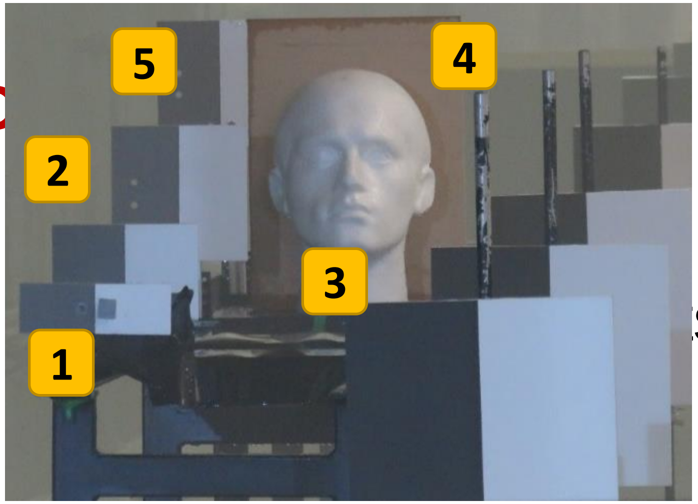


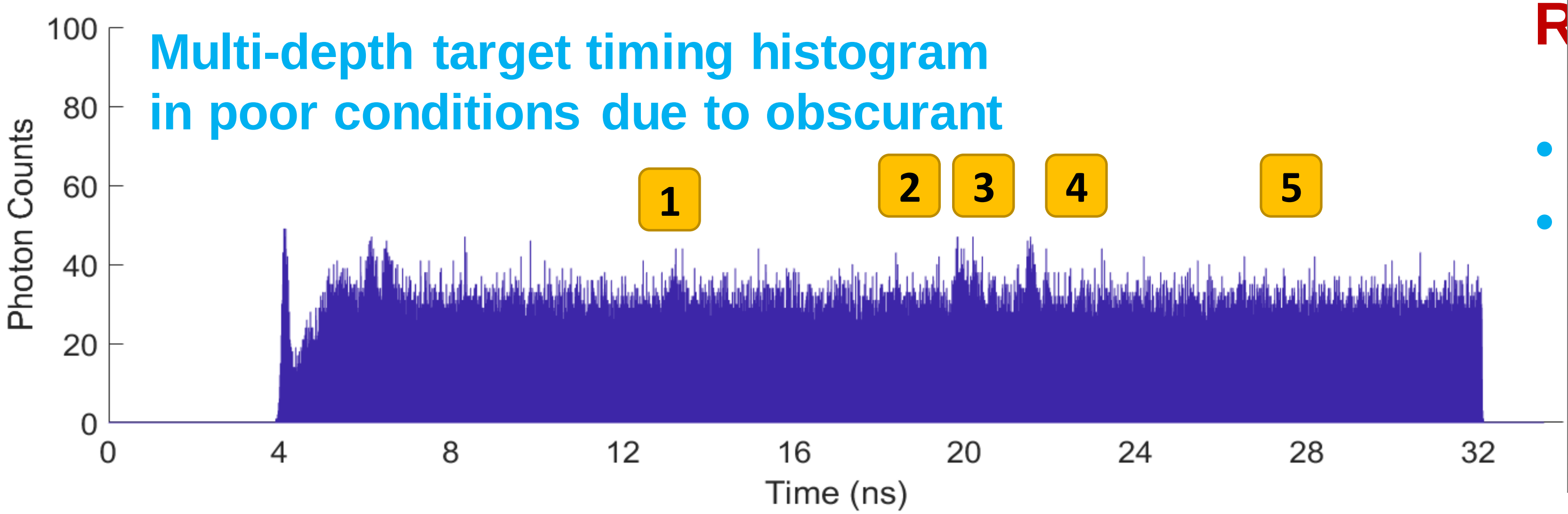
Facility has 26 metre long chamber for smoke or fog conditions.

Conditions vary as smoke/fog disperses with time.

Imaging through obscurants – scanning system



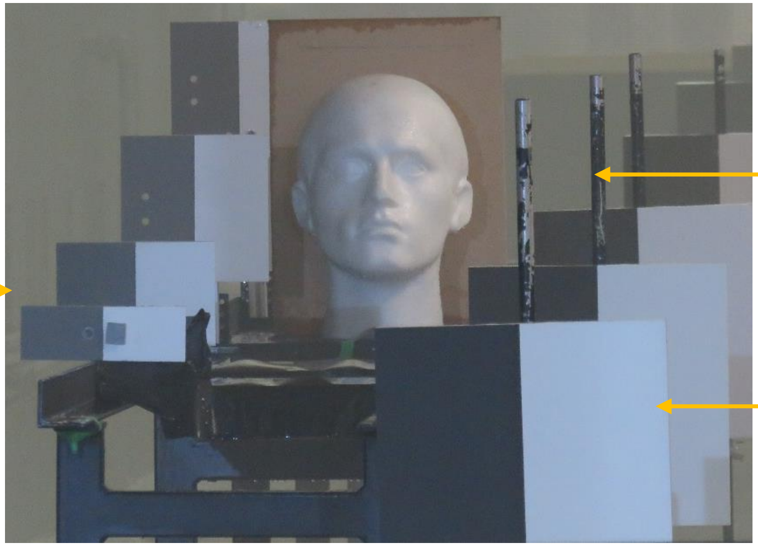




Imaging through obscurants – scanning system

Obscurant dispersion over the course of a measurement set

Time



Polystyrene Head

Calibration targets for 1550 nm attenuation

Calibration targets for visible attenuation

1 attenuation length is the distance over which the light intensity drops to 1/e of its original value

Imaging through obscurants – scanning system

Obscurant: Glycol Vapour

Pixel Format:

115 x 93

Acquisition time:

3 ms per pixel

Total acquisition time:

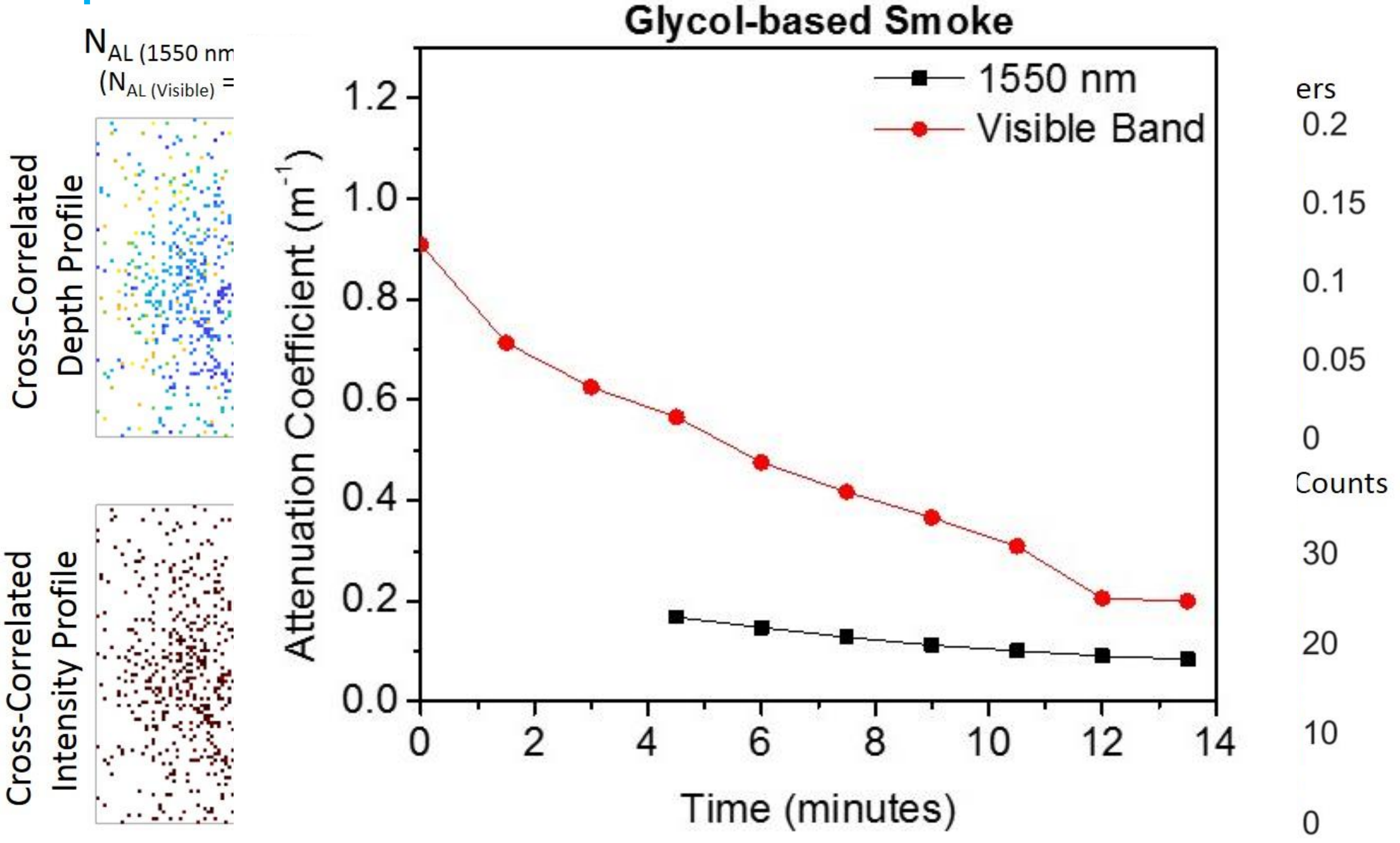
~32 s

Avg Optical Power:

< 1.5 mW

Distance:

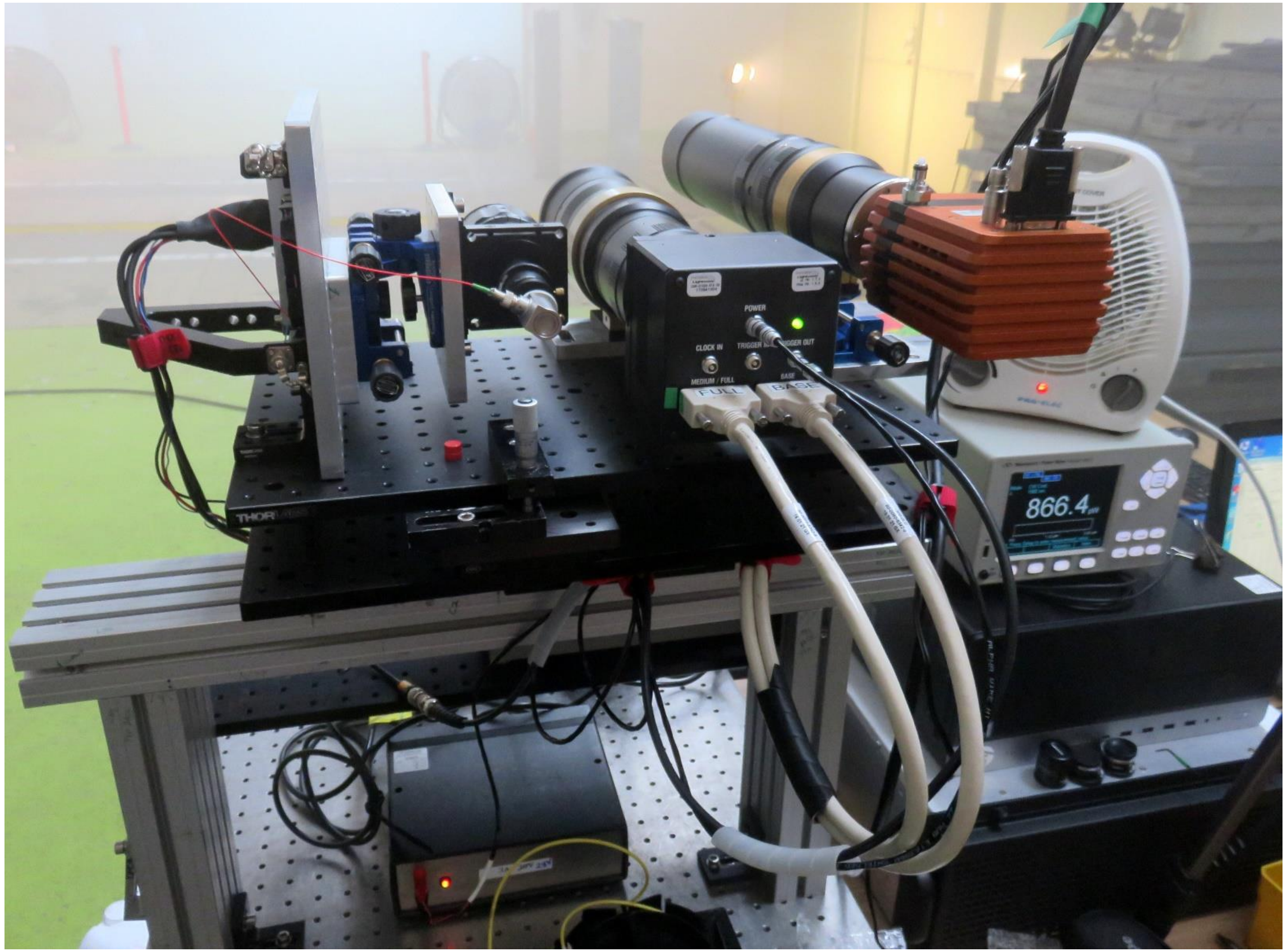
24 meters through smoke



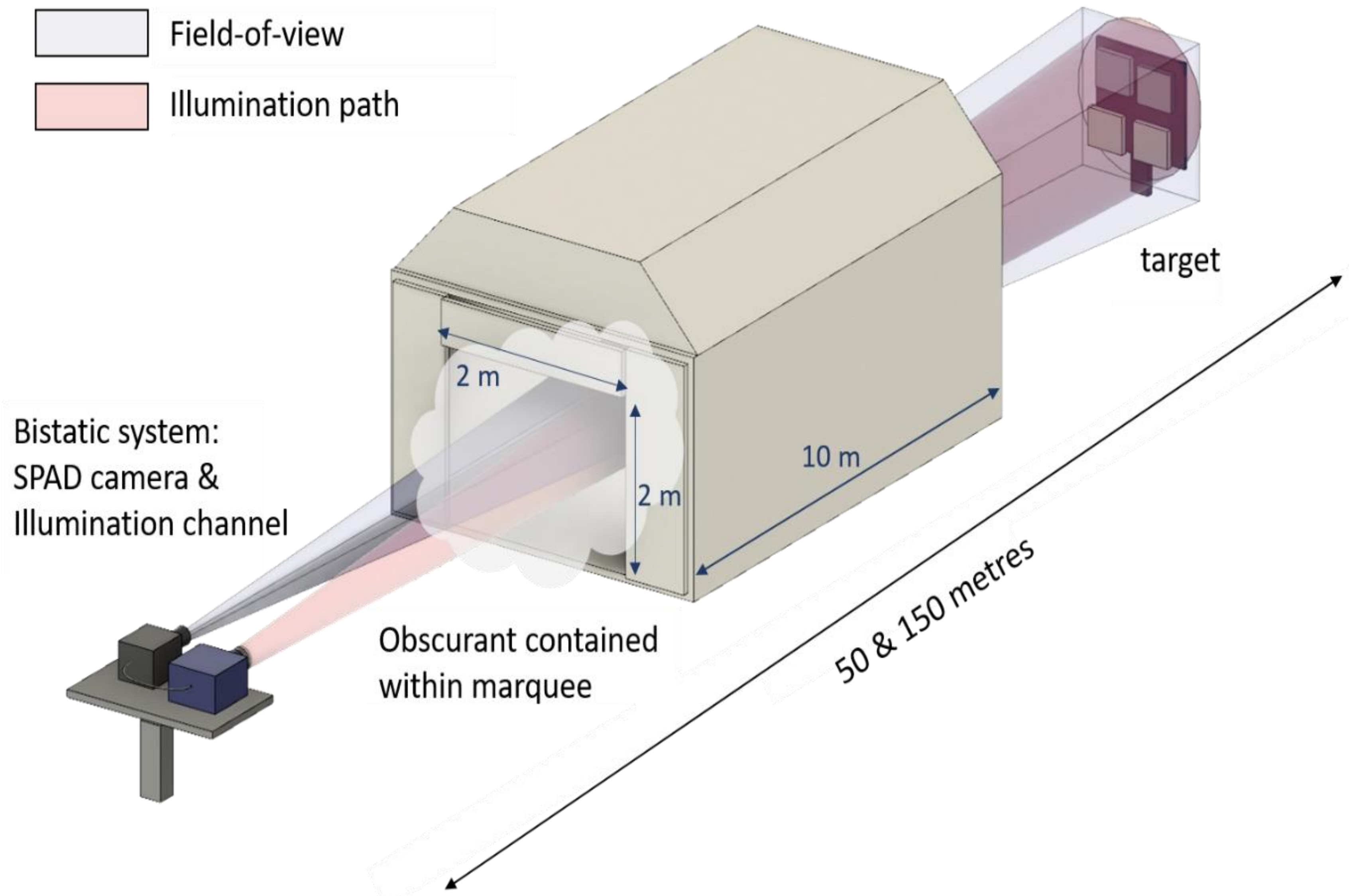
Imaging through obscurants – SPAD array transceiver

SPAD detector array transceiver:

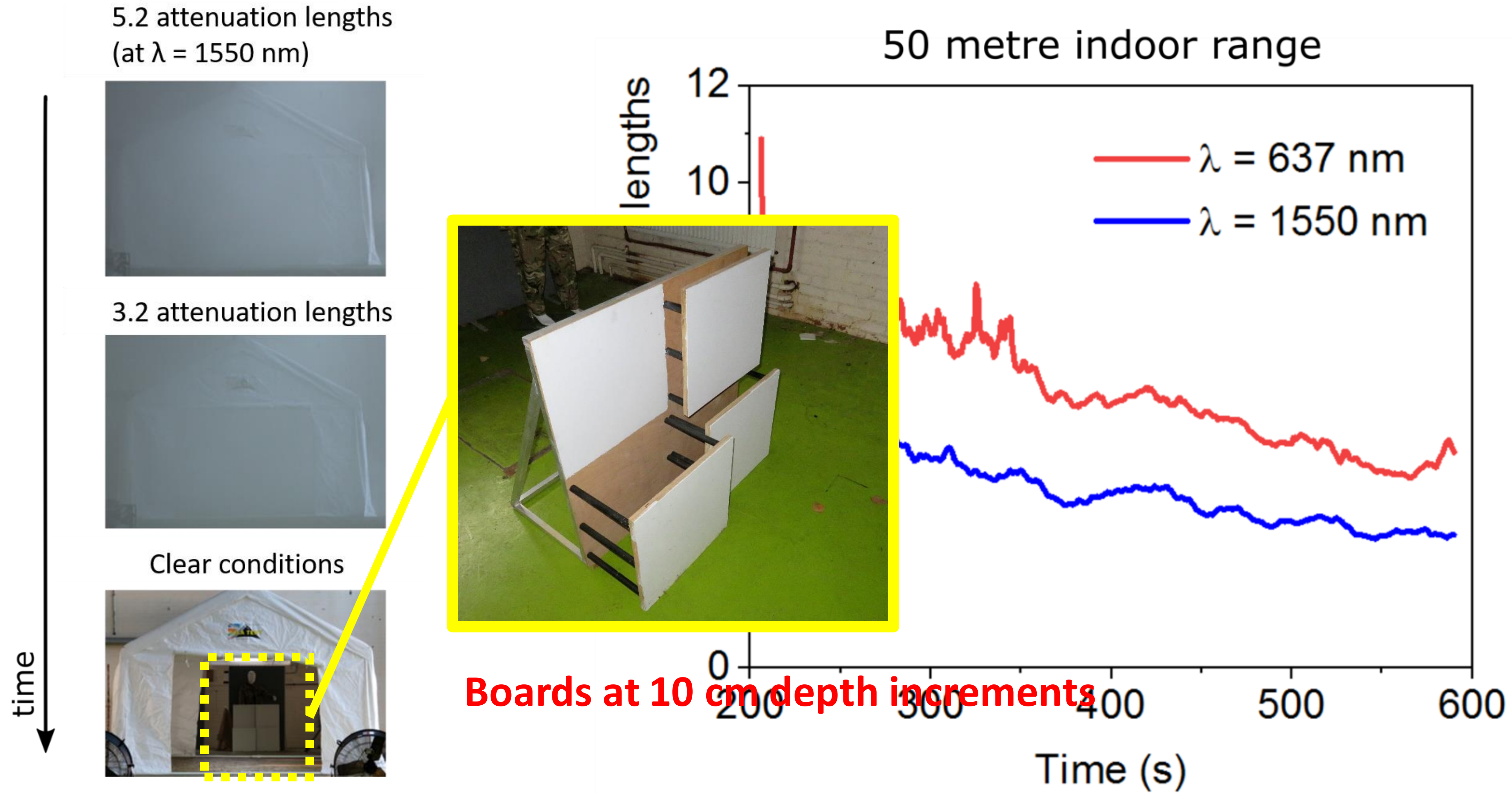
- 32 x 32 InGaAs/InP SPAD array
- λ = 1550 nm
- ~ 20mW – 200mW average power at 150kHz
- Flood-illumination of scene – several metres diameter spot
- Bistatic transceiver



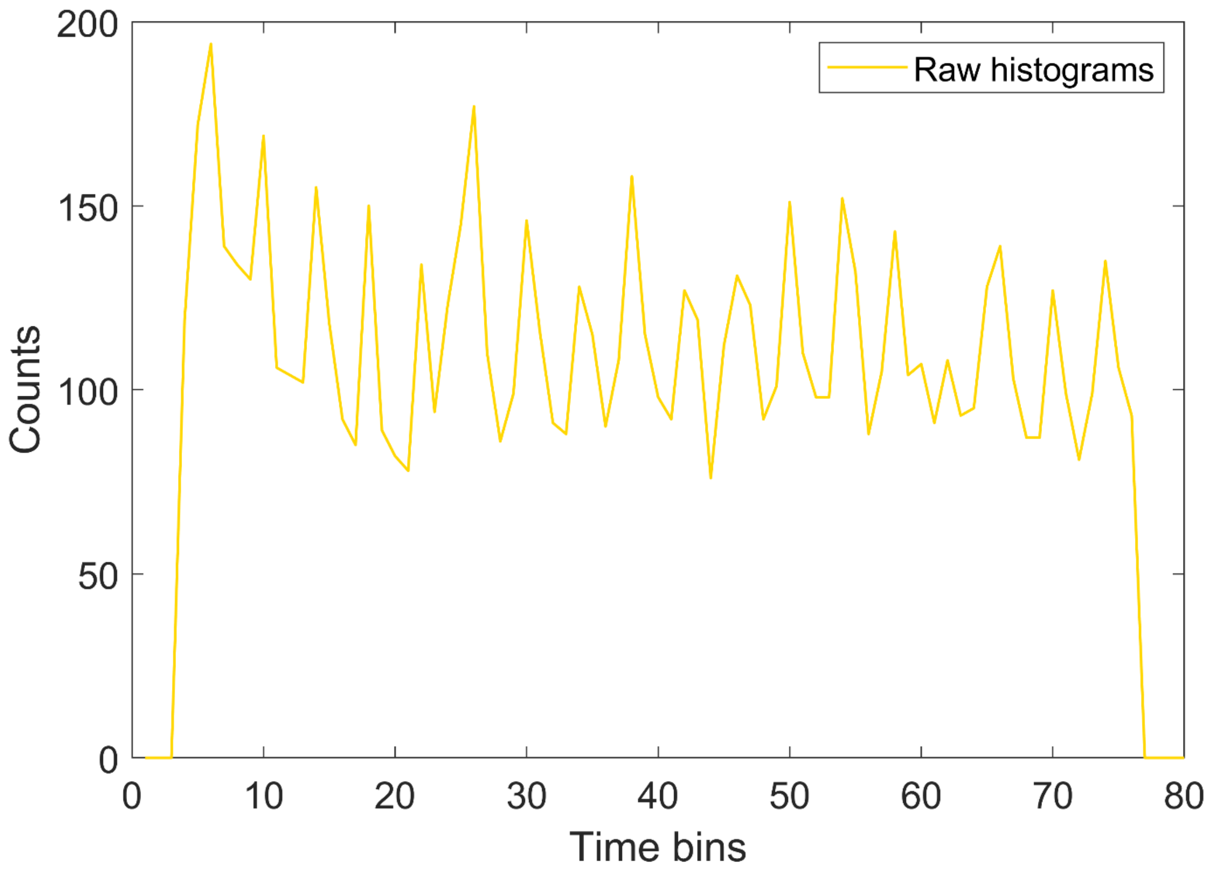
Imaging through obscurants – set-up



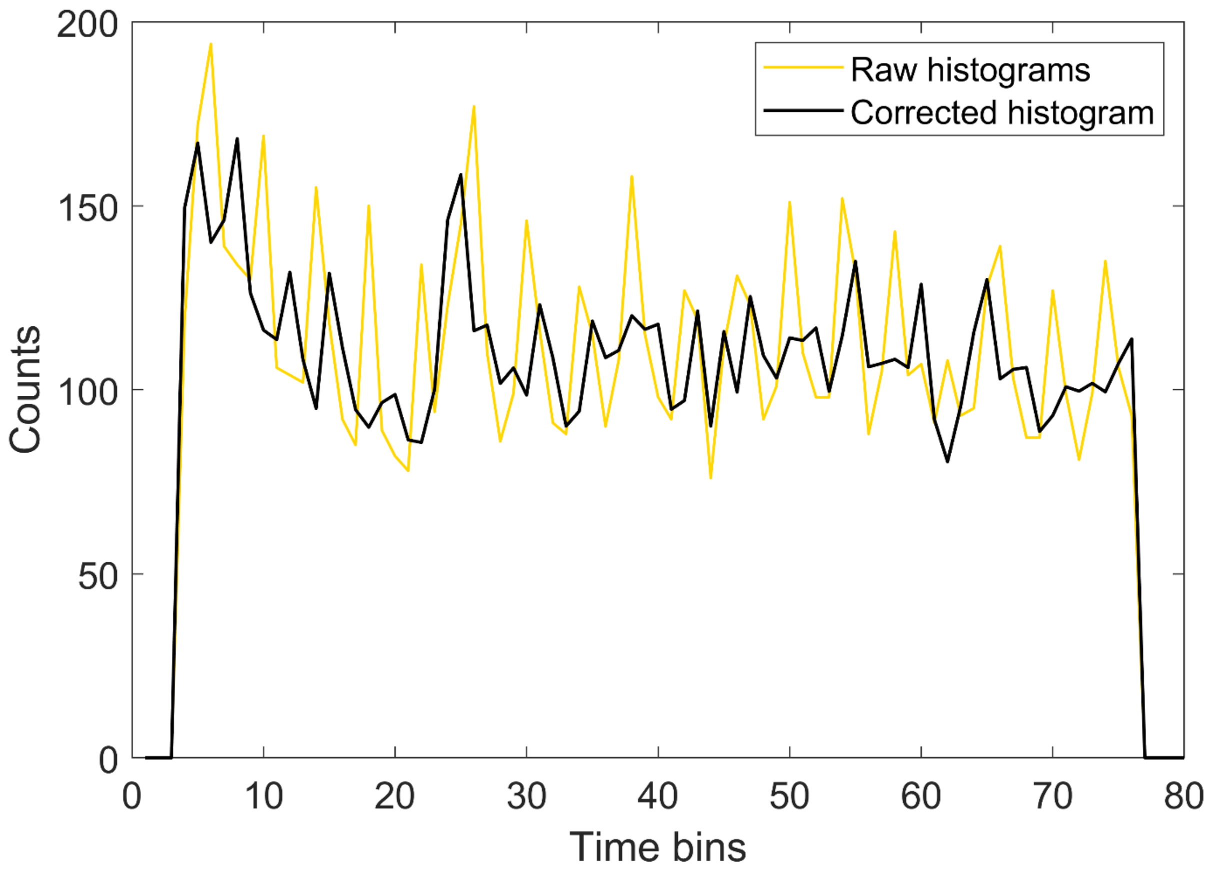
Imaging through obscurants – SPAD array transceiver



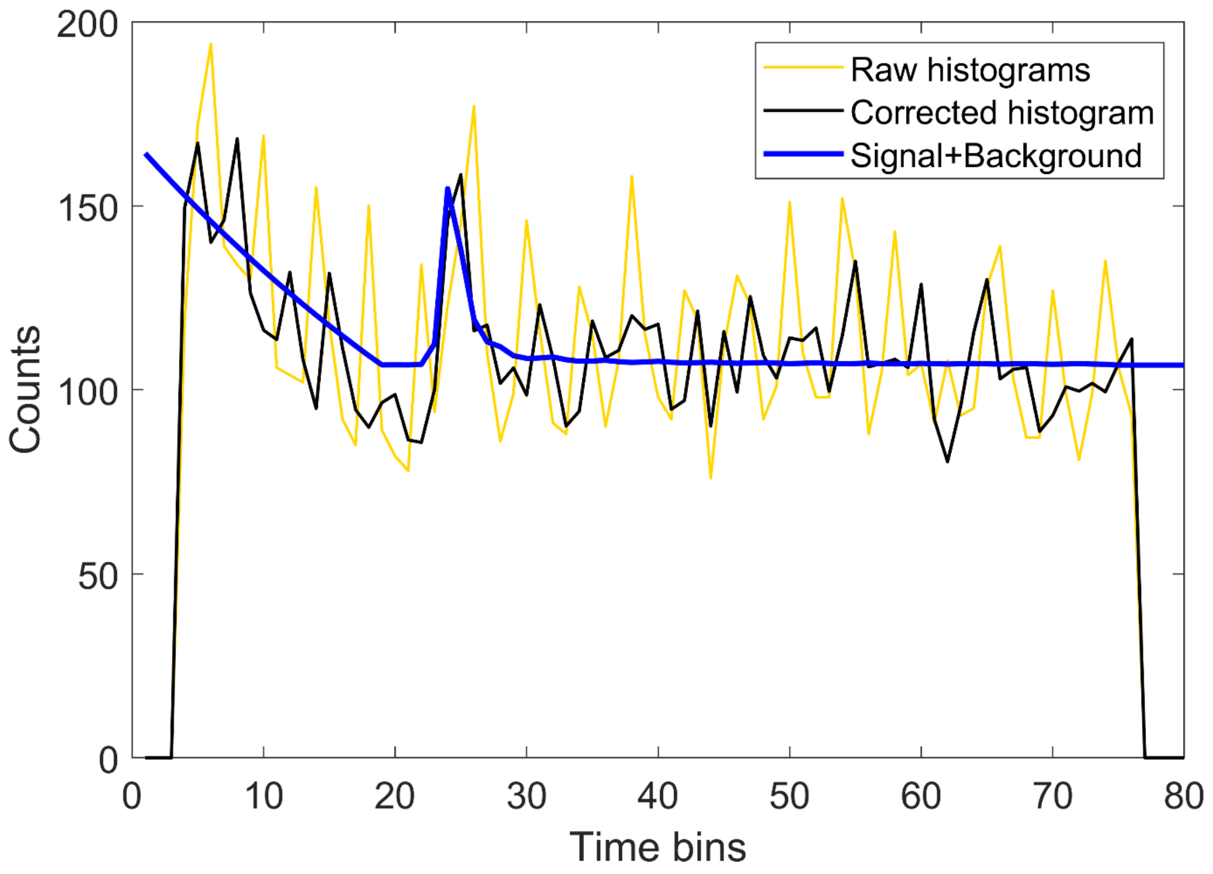
Imaging through obscurants – timing histograms



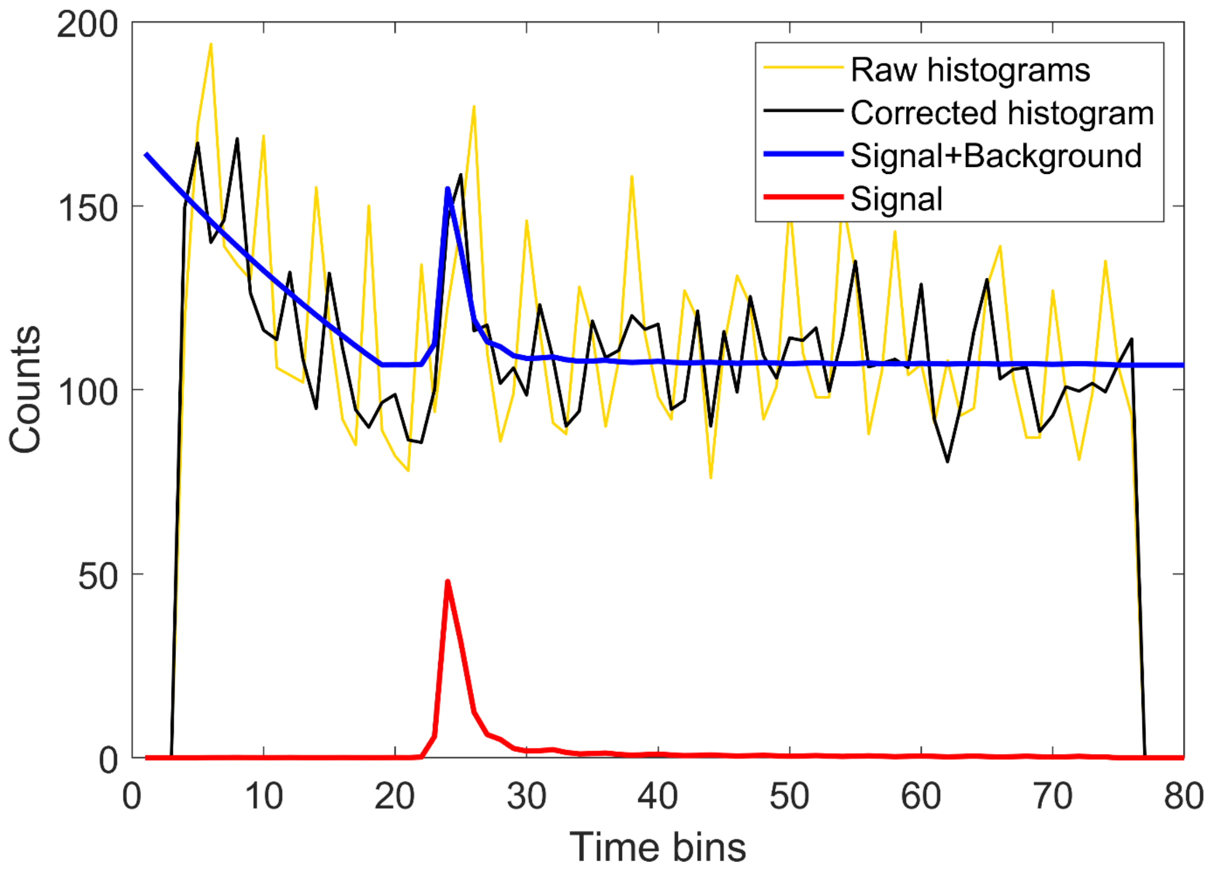
Imaging through obscurants – timing histograms



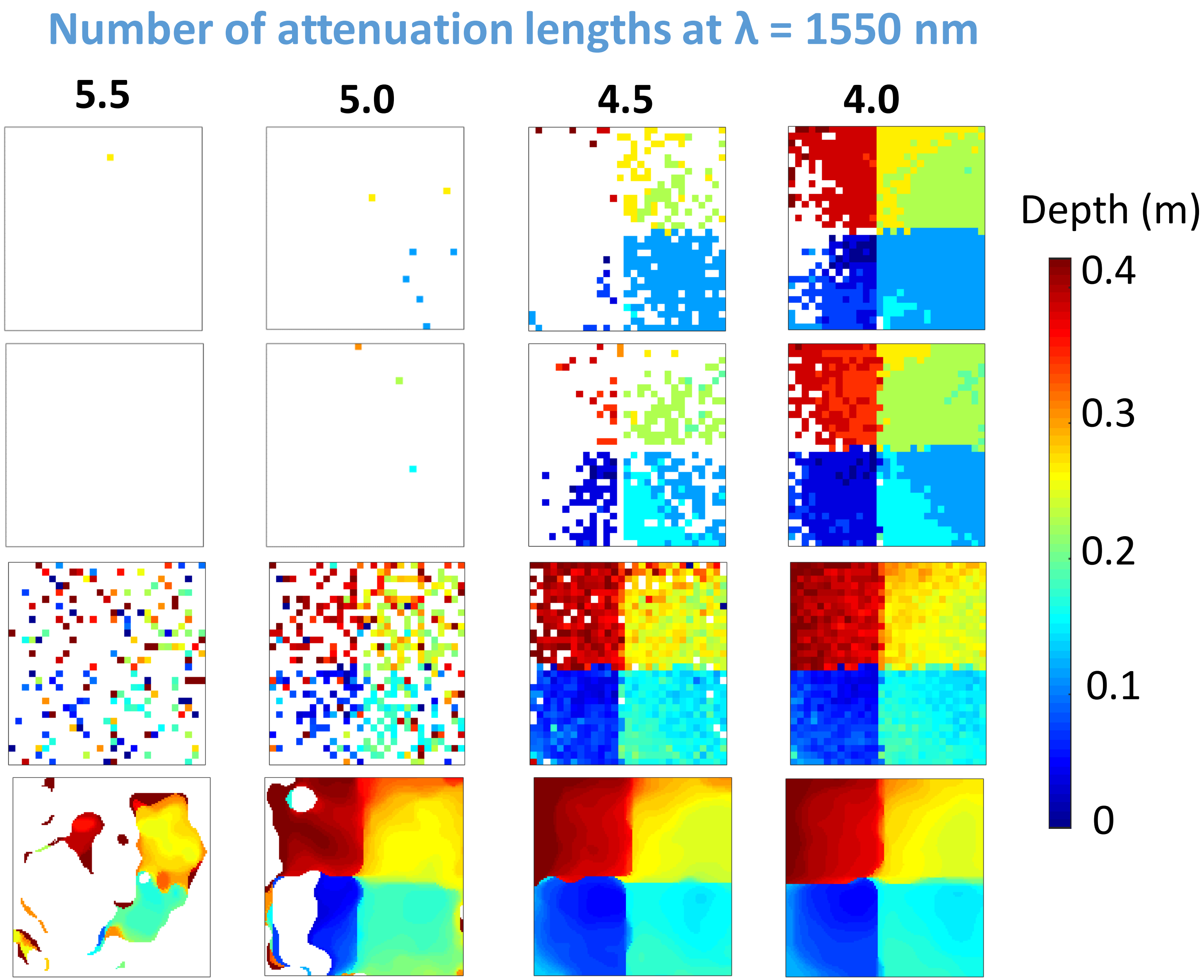
Imaging through obscurants – timing histograms



Imaging through obscurants – timing histograms



Imaging through obscurants - 50 metres range



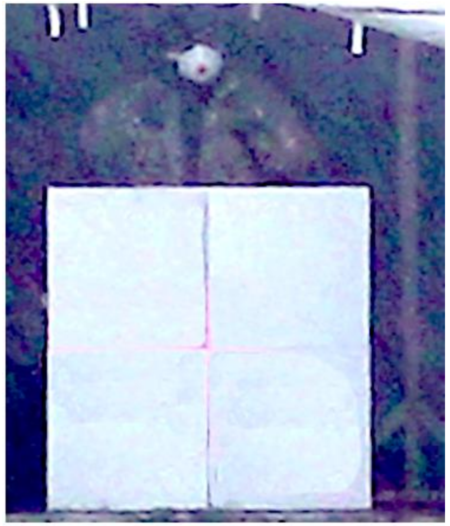
Cross-correlation
without histogram correction
but without
exponential background

Cross-correlation
with histogram correction
but without
exponential background

Cross-correlation
with histogram correction
and exponential background

Proposed algorithm - M2R3D
with histogram correction
and exponential background

Imaging through obscurants - 150 metres range



RGB reference photograph of the target scene

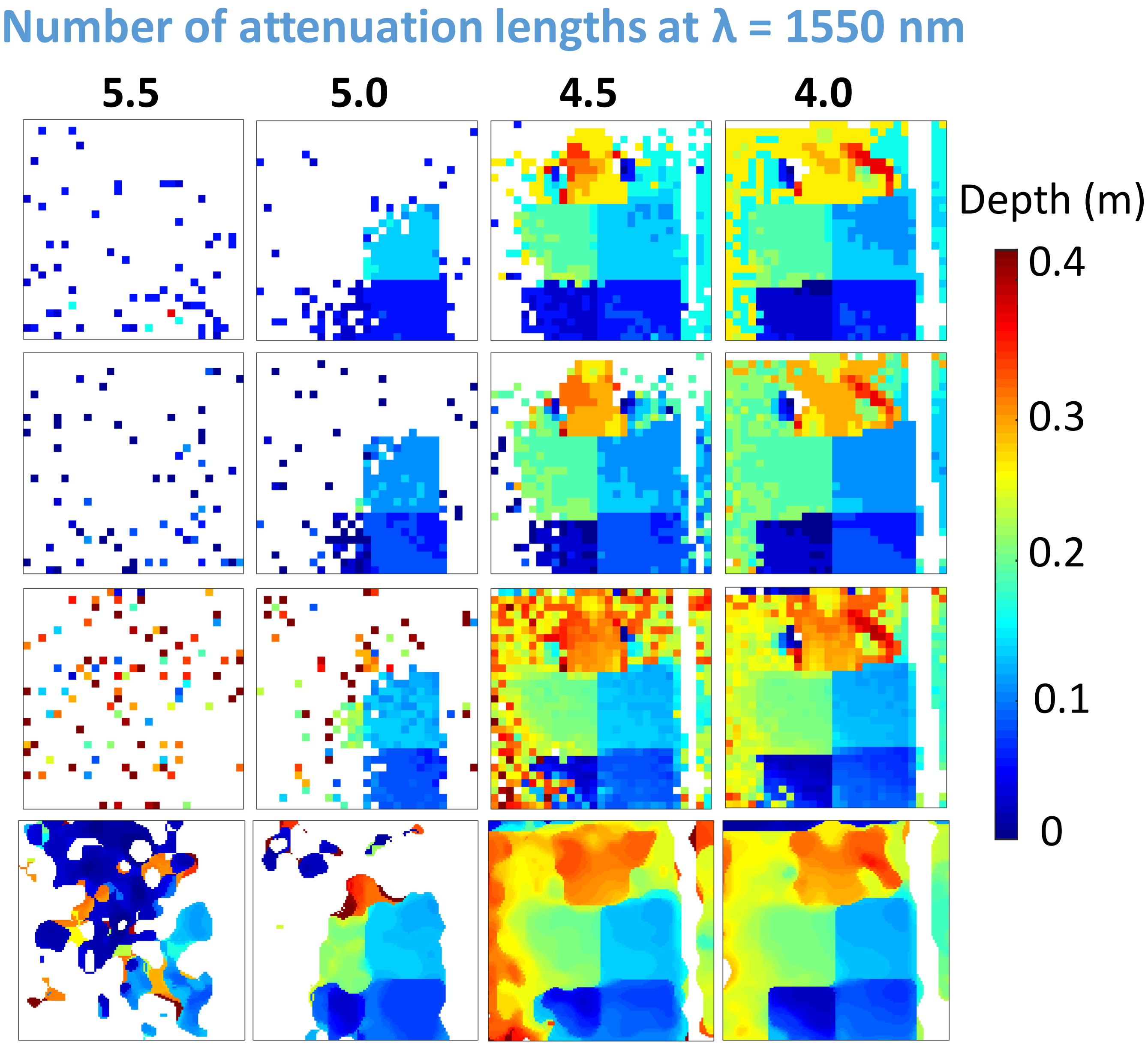
Actor behind wooden depth chart

Cross-correlation without histogram correction but without exponential background

Cross-correlation with histogram correction but without exponential background

Cross-correlation with histogram correction and exponential background

Proposed algorithm - M2R3D with histogram correction and exponential background



Rapid reconstruction of moving images through obscurants

Rapid reconstruction of moving images through obscurants

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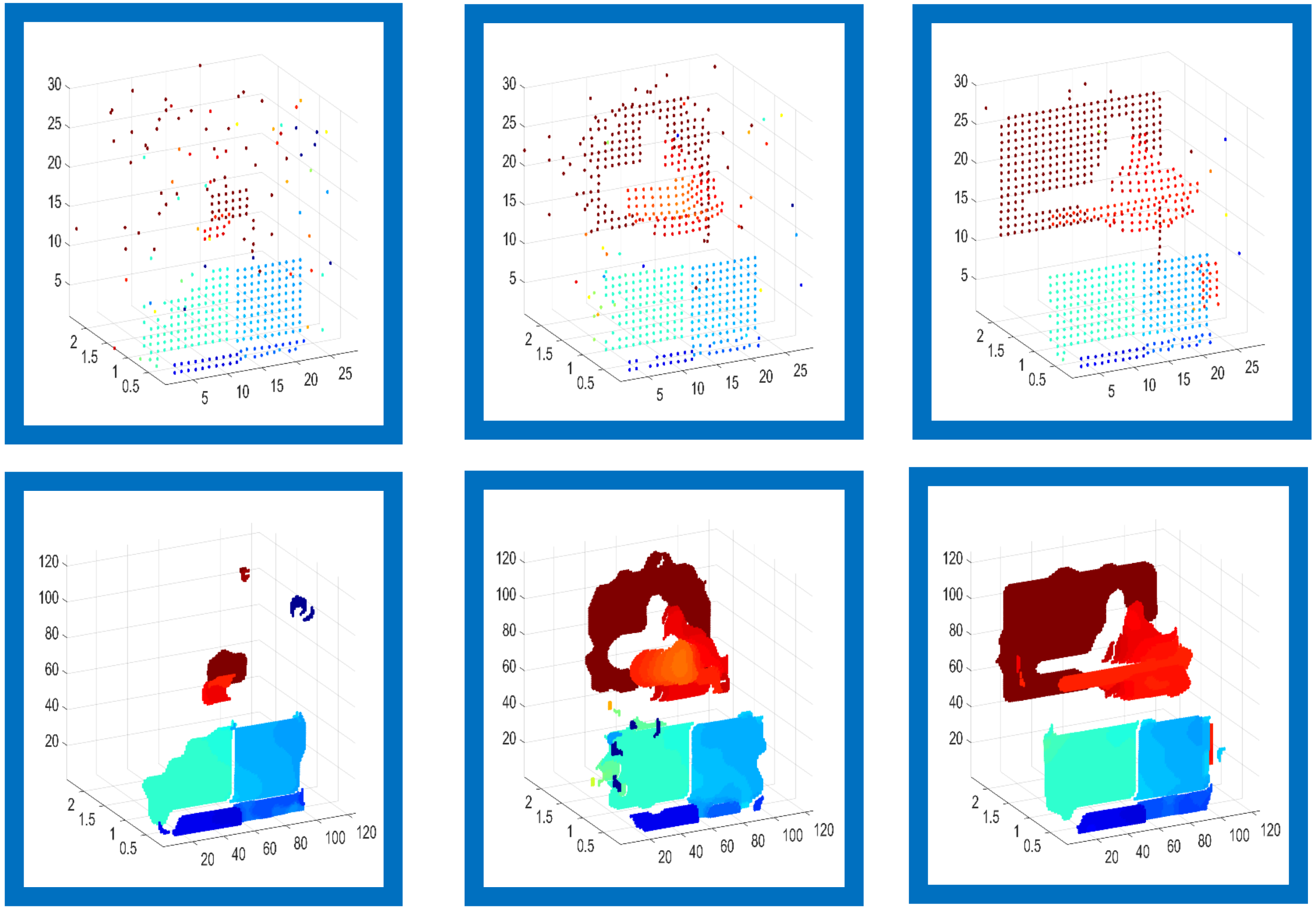
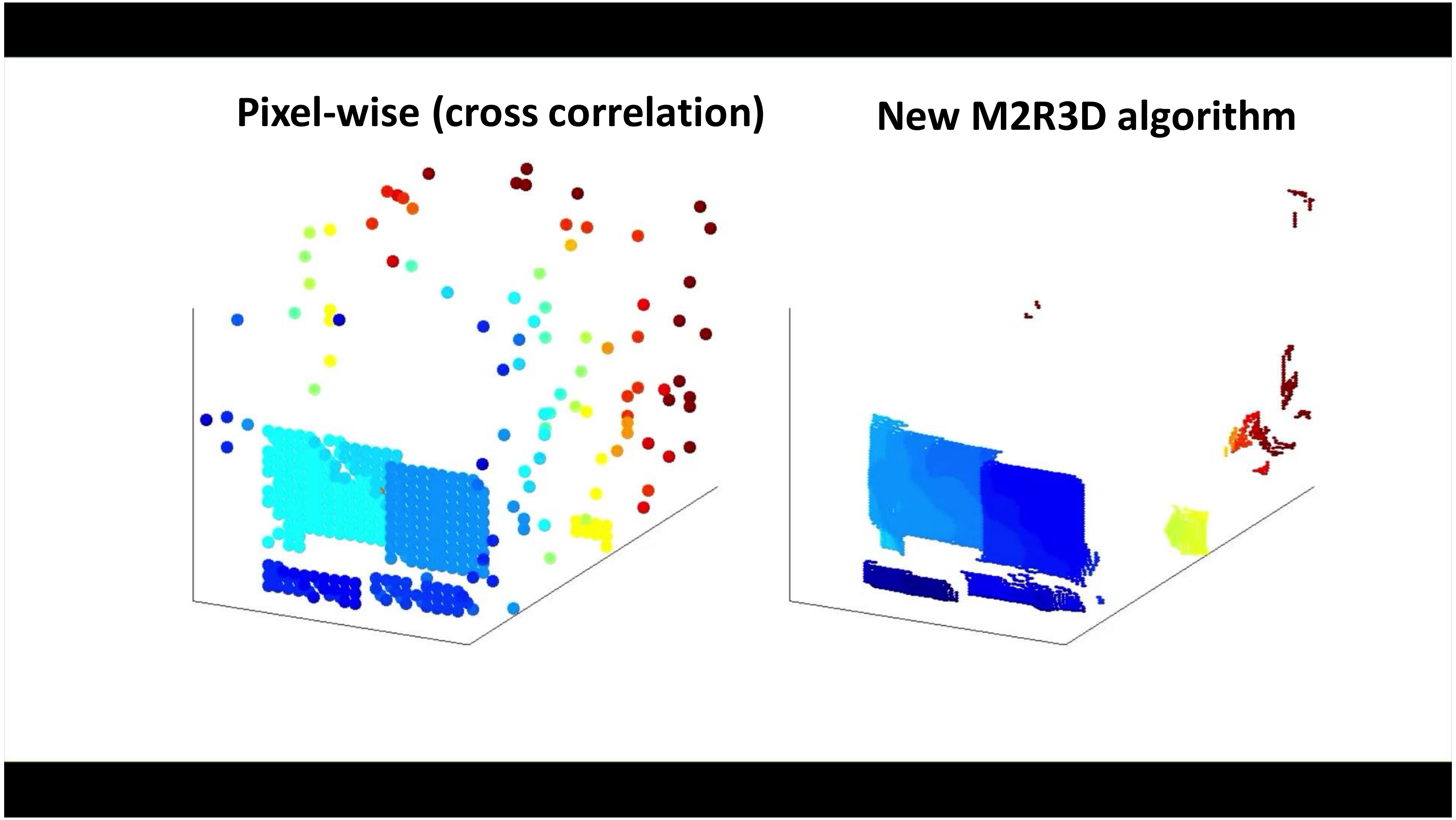
Cross-correlation (Pixelwise)

New M2R3D algorithm



Rapid reconstruction of moving images through obscurants

Cartoon of the scene

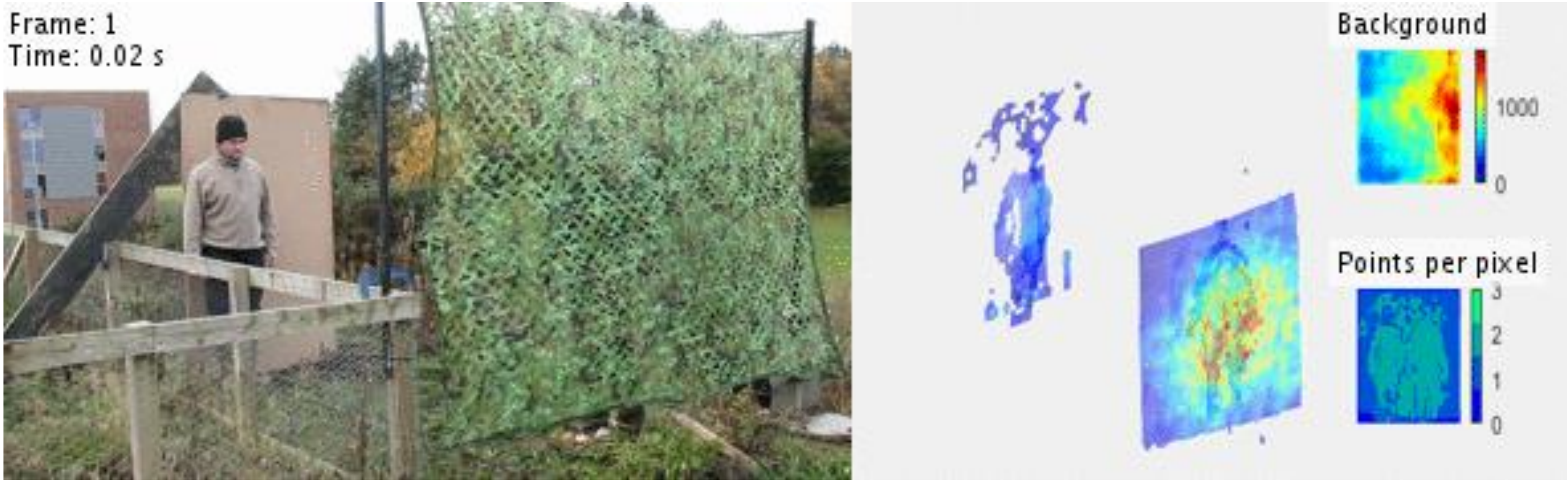


"Real-time single-photon 3D LiDAR imaging of moving targets through atmospheric obscurants"
Rachael Tobin, Abderrahim Halimi, Aongus McCarthy, Philip J. Soan and Gerald S. Buller (under review)

Real Time Reconstruction of Outdoor, Multi-Surface Moving Scenes (at 300 meters range)

- 50 grayscale frames per second
- Real-time processing
- Eye-safe illumination in presence of solar background

Real Time Reconstruction of Outdoor, Multi-Surface Moving Scenes (at 300 meters range)



- Multiple surface
- 50 grayscale frames per second
- Real-time processing
- Eye-safe illumination in presence of solar background

"Real-time 3D reconstruction from single-photon lidar data using plug-and-play point cloud denoisers",
Julián Tachella, Yoann Altmann, Nicolas Mellado, Aongus McCarthy, Rachael Tobin, Gerald S. Buller, Jean-Yves Tourneret, Stephen McLaughlin, Nature Communication 10, 4984 (2019)

Underwater imaging – selection of wavelength

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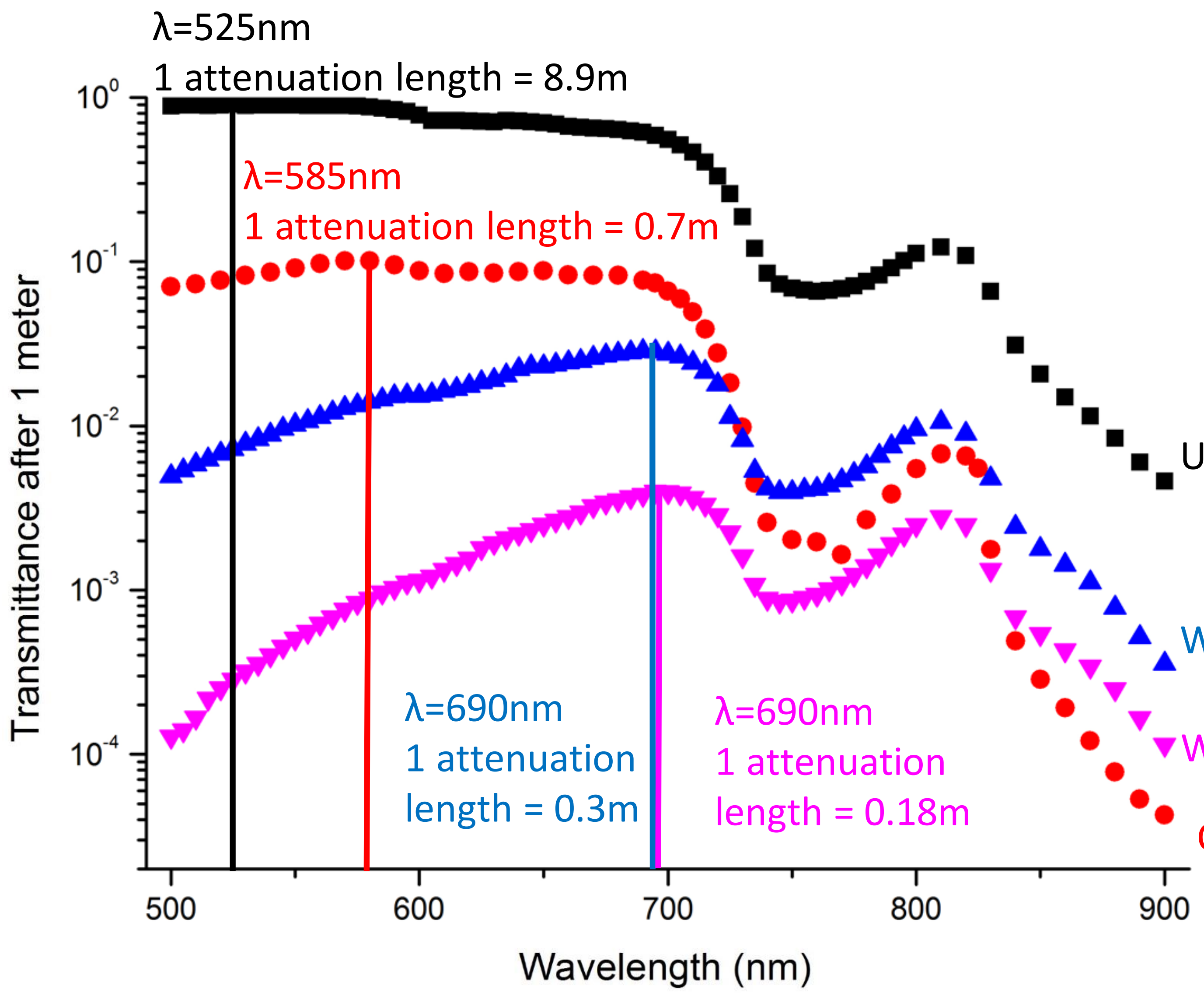
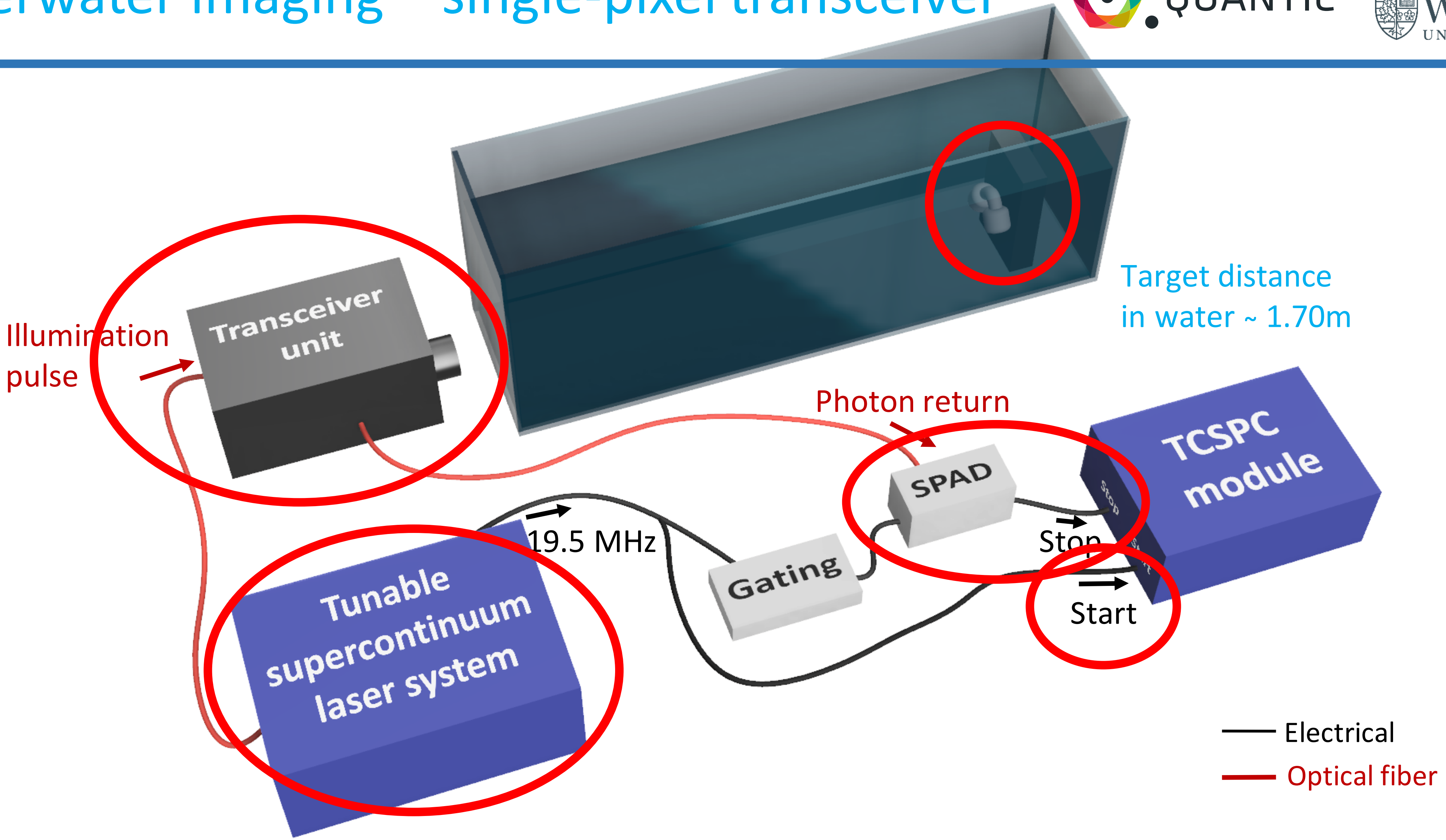


Maalox

- Anti-acid medicine
- Strongly affects scattering

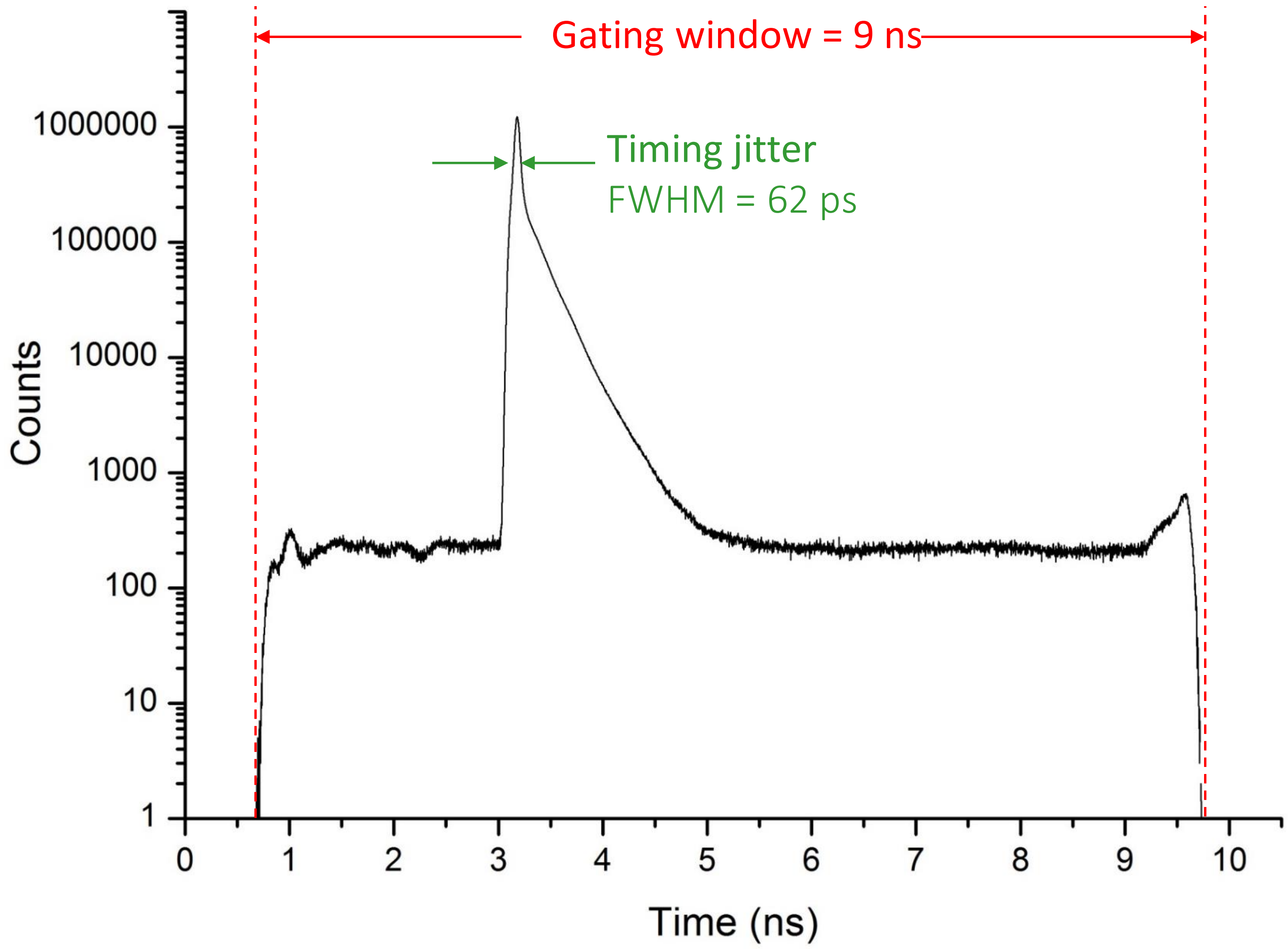
1 attenuation length = distance after which the optical power is attenuated of 1/e of its initial value

Underwater imaging – single-pixel transceiver



A. Maccarone, A. McCarthy, X. Ren, R.E. Warburton, A.M. Wallace, J. Moffat, Y. Petillot, and G. S. Buller, "*Underwater depth imaging using time-correlated single-photon counting*," OPTICS EXPRESS **23**, 26, pp. 33911-33926 (2015).

Underwater imaging – timing histogram



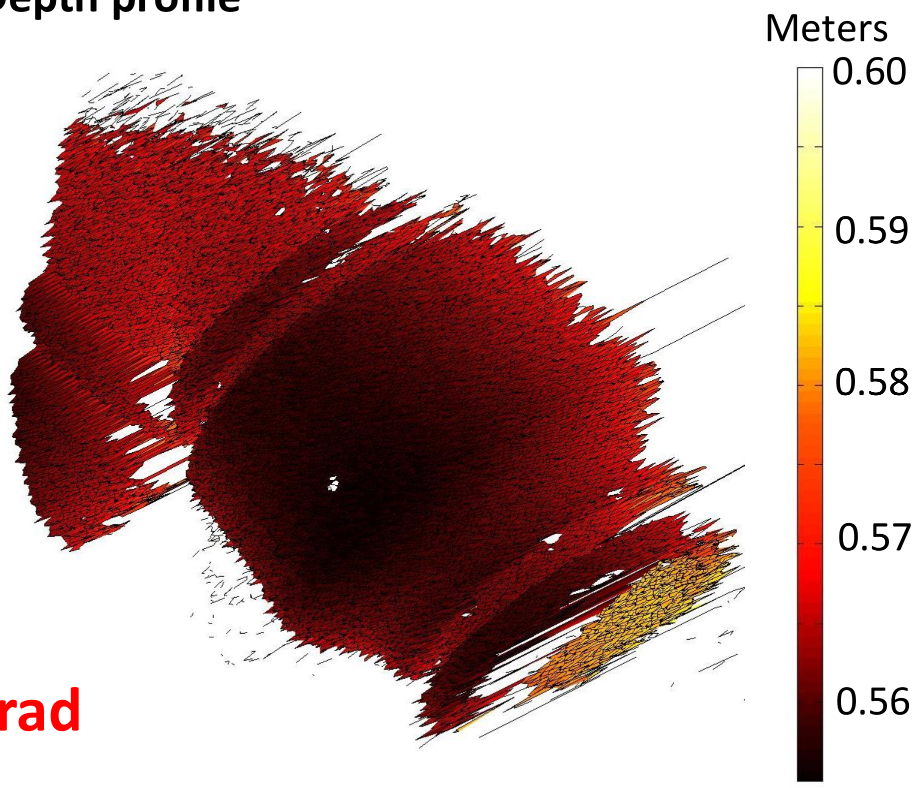
- λ = 690 nm
- Clear water
- Repetition rate =19.5 MHz
- Average optical power ~ 250 nW
- Timing jitter ~ 60 ps

Underwater imaging –8 attenuation lengths

- λ = 675 – 700 nm
- Average power ~ **2.6 mW**
- Pixel format = 240 x 240

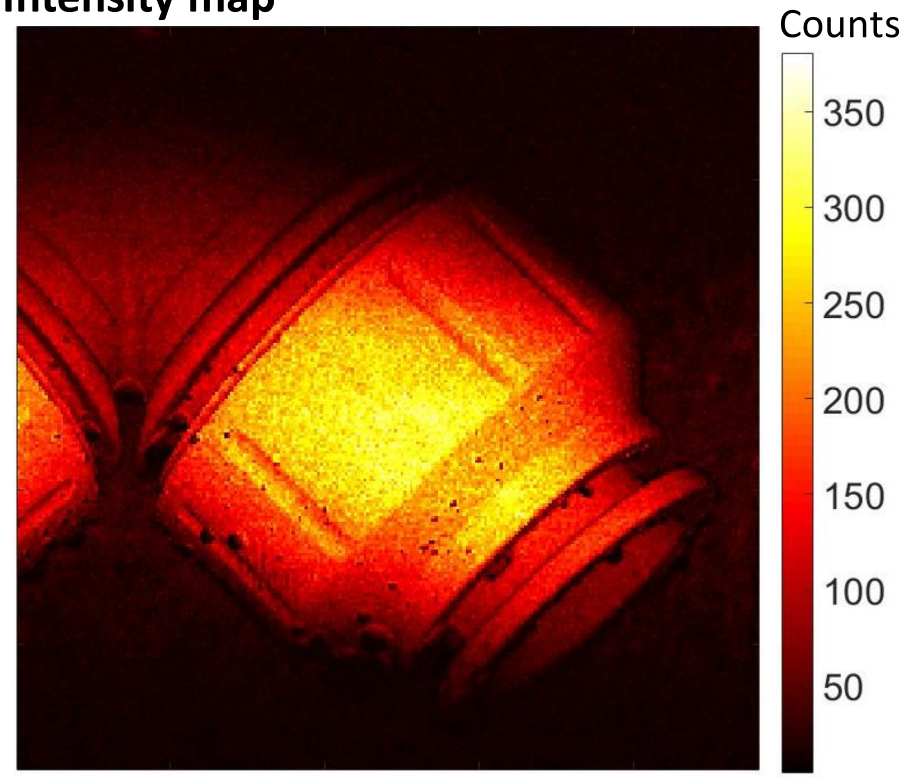
- **8 Attenuation lengths**
- Acquisition time per pixel = **30 ms**
- **Pixel-wise cross-correlation approach**

Depth profile



<60 μrad

Intensity map



Underwater depth profile at 8 attenuation lengths

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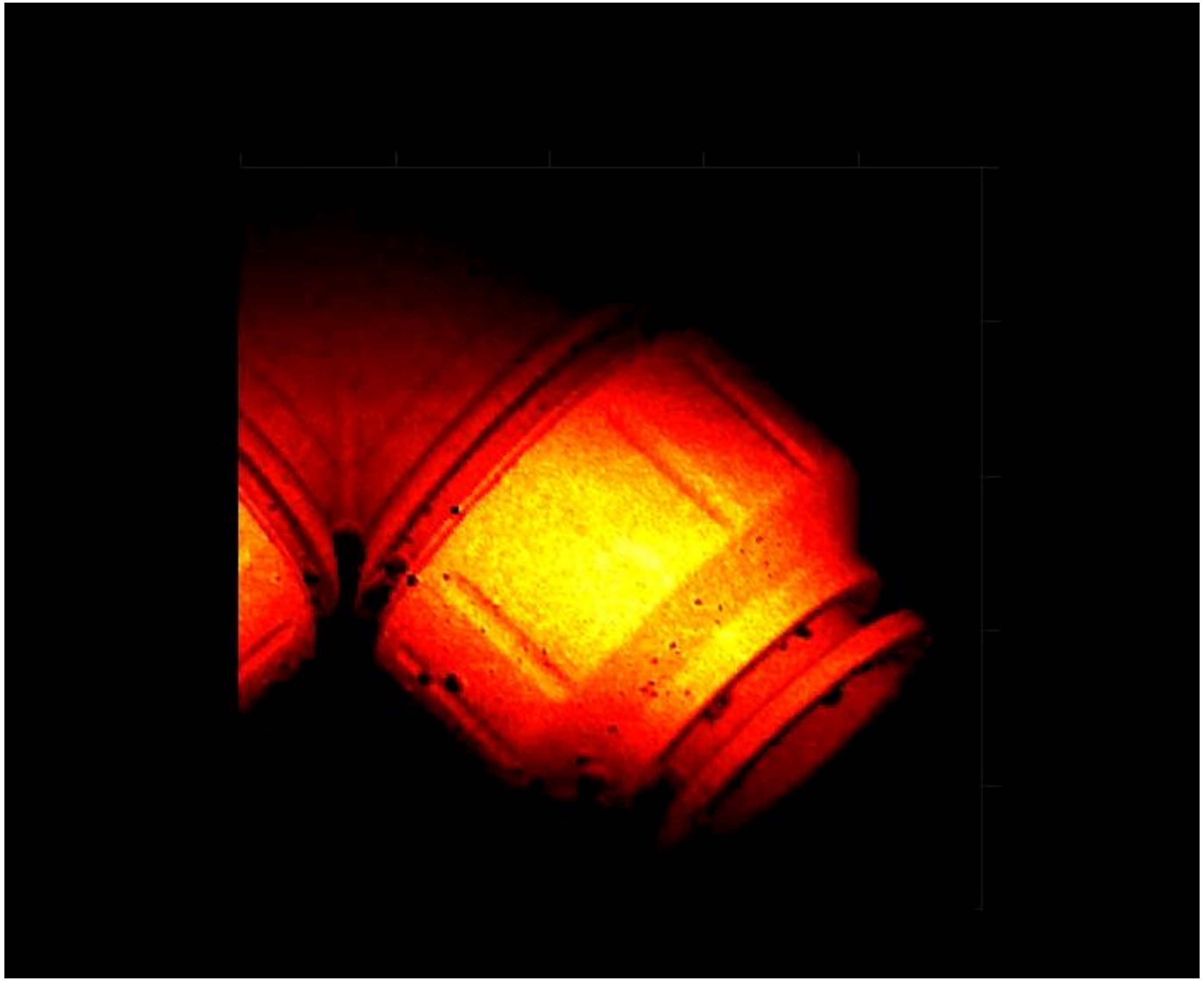
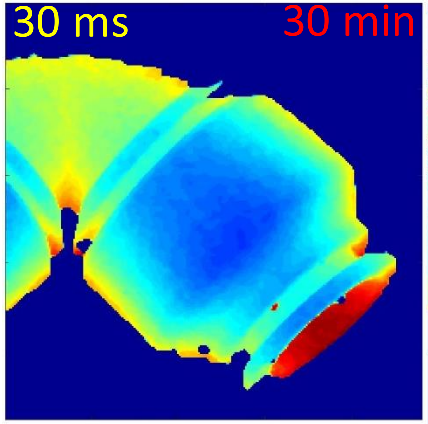
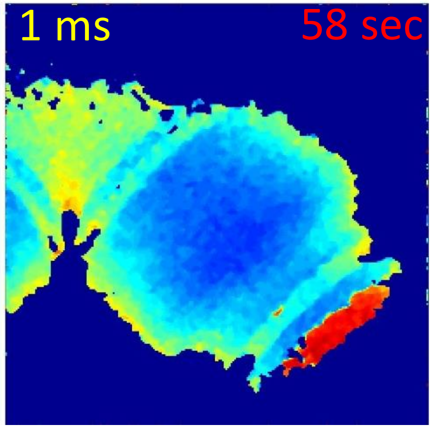


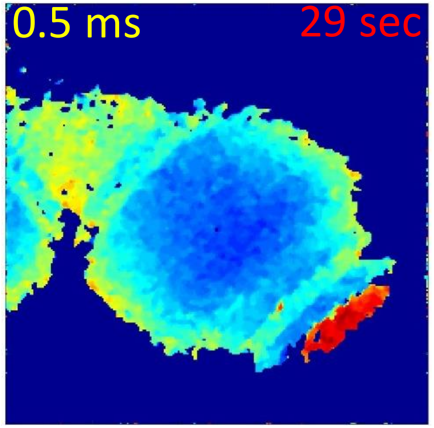
8 AL Depth profiles as acquisition time is reduced



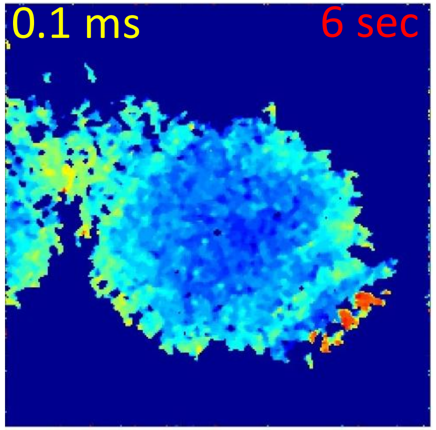
Average photon per pixel = 127.09



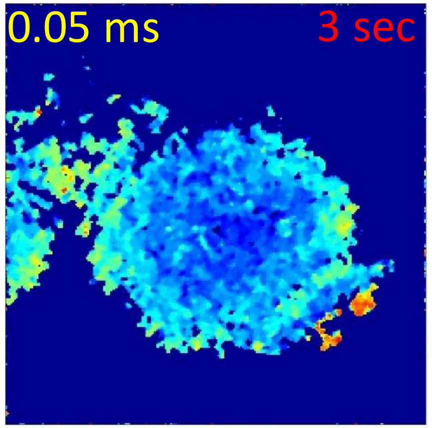
Average photon per pixel = 5.05



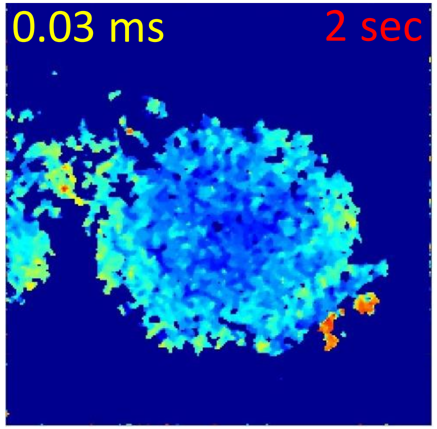
Average photon per pixel = 2.79



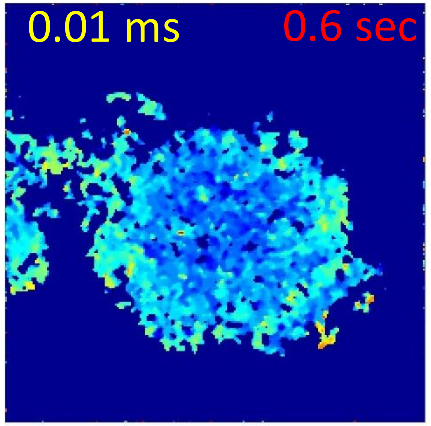
Average photon per pixel = 0.86



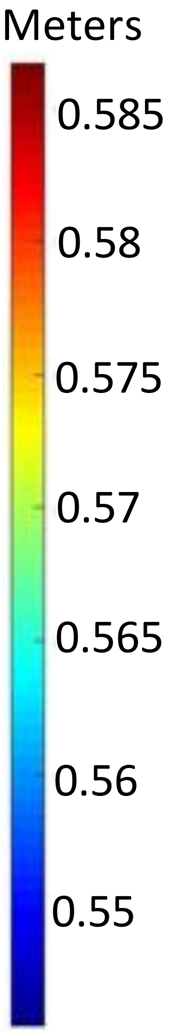
Average photon per pixel = 0.63



Average photon per pixel = 0.54



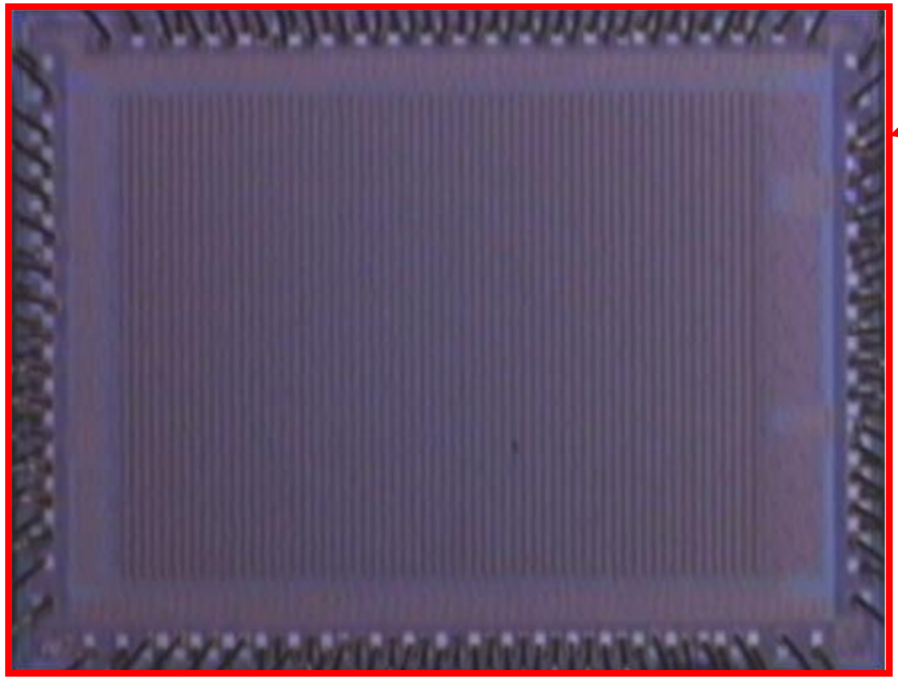
Average photon per pixel = 0.45

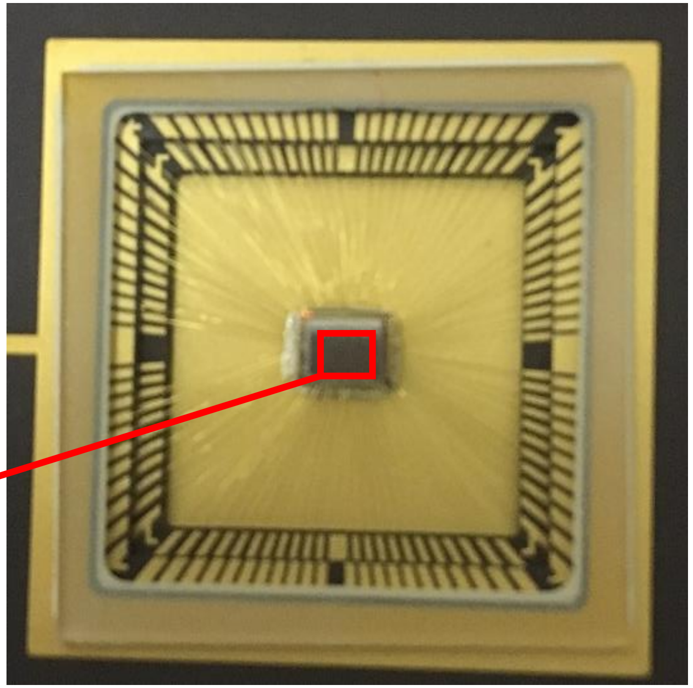


"QuantiCam" – 192 x 128 SPAD array

- 192 × 128 pixels
- TCSPC mode
- 34 ps to 120 ps tunable resolution
- 4096 bins
- 25 Hz Dark Count Rate
- 13% fill factor
- 7% photon detection efficiency at λ = 670nm
- Binary frame:

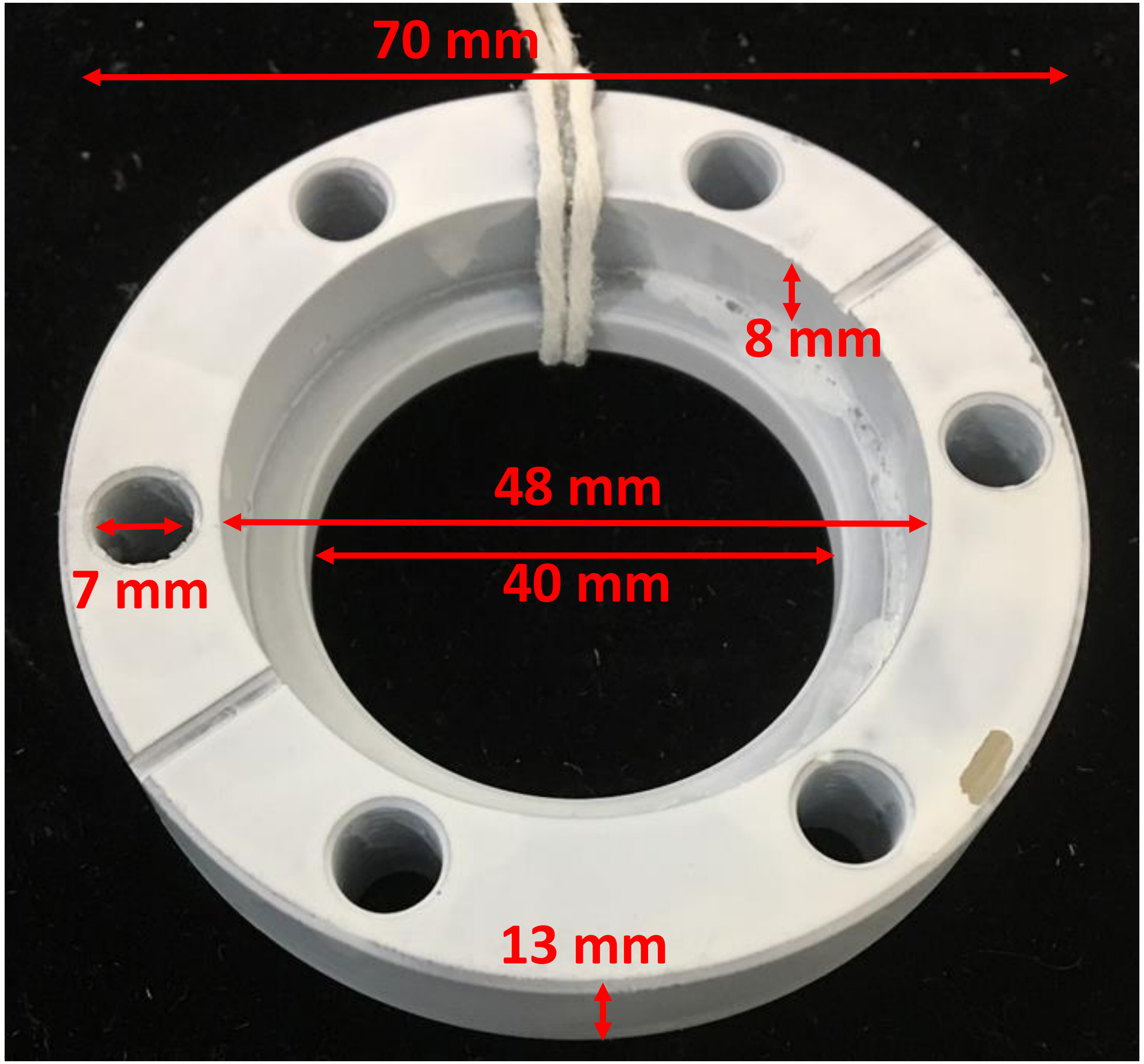
  0 = no event recorded
  1 = event recorded





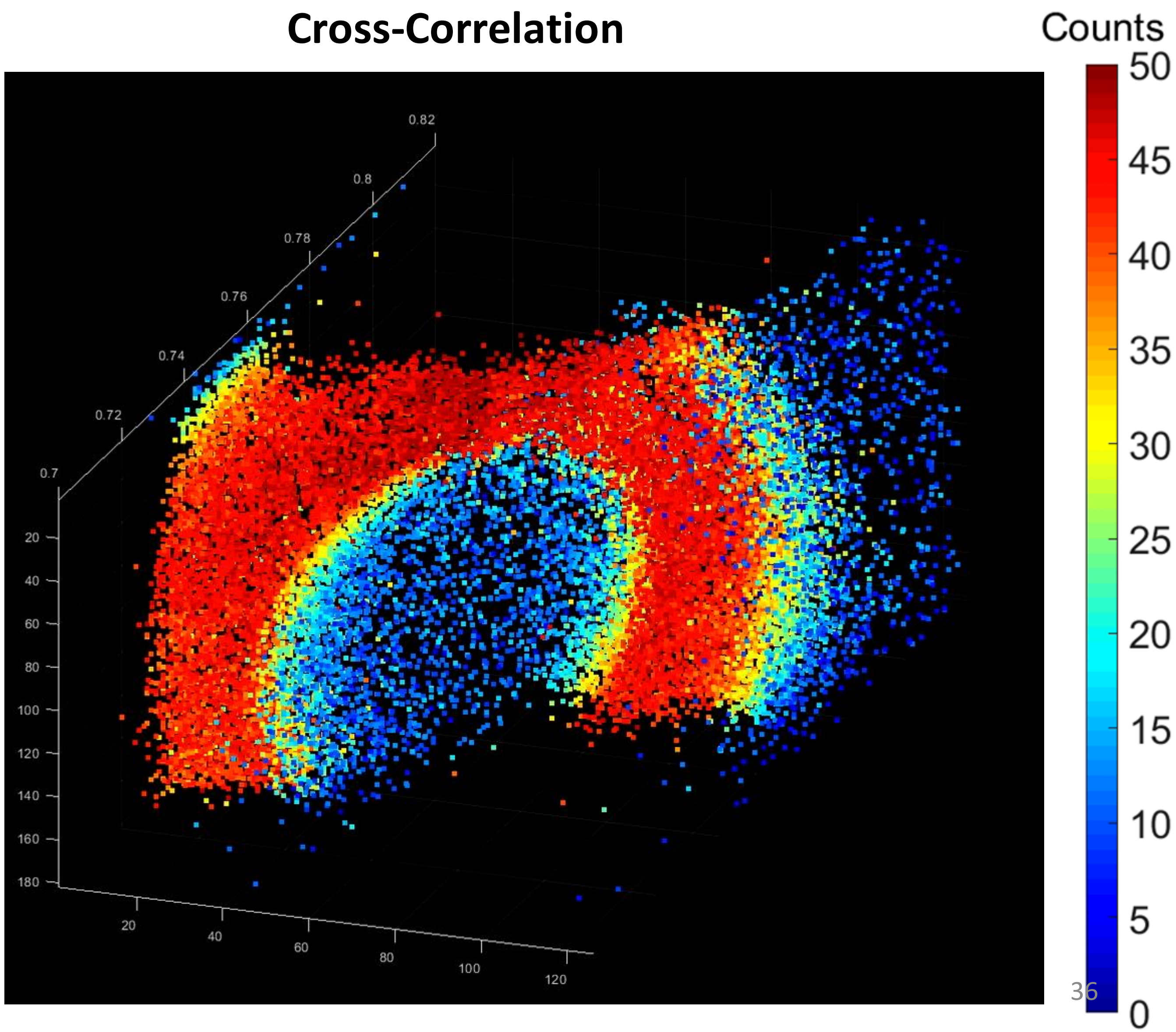
R. K. Henderson, N. Johnston, F. Mattioli Della Rocca, H. Chen, D. Day-Uei Li, G. Hungerford, R. Hirsch, D. McLoskey, P. Yip, and D. J. S. Birch, "*A 192 × 128 Time Correlated SPAD Image Sensor in 40-nm CMOS Technology*," IEEE J. Solid-St. Circ., **54**(7), 1907-1916 (2019).

"QuantiCam" – 192 x 128 SPAD array

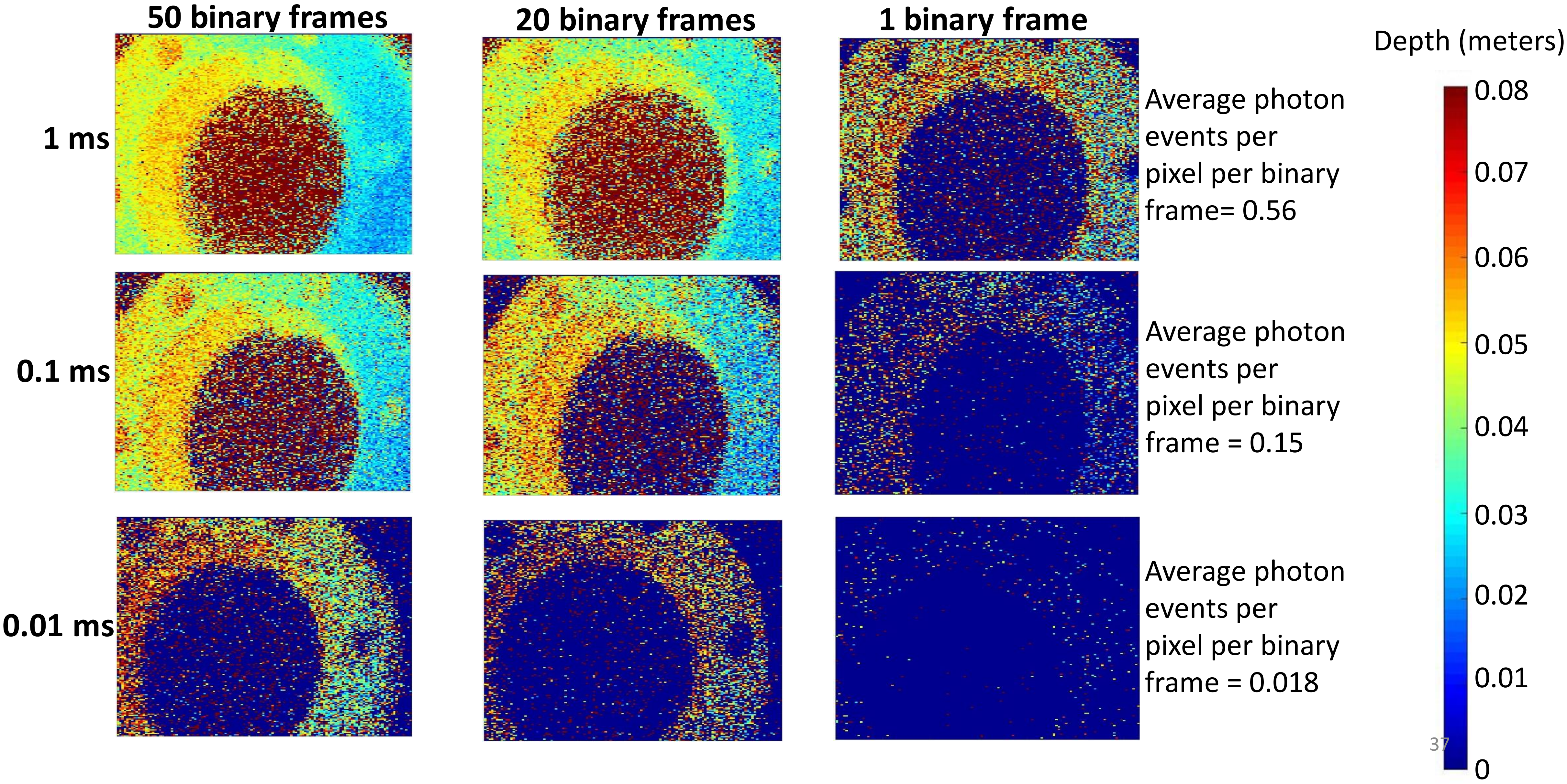


Depth profiles using SPAD array

- Average optical power ~ **0.4 mW**
- **1.2** Attenuation lengths
- Binary frame acquisition time = **1ms**
- Binary frame acquisition rate = **500 Hz**
- **Images obtained with 50 binary frames**



Depth profiles using SPAD array

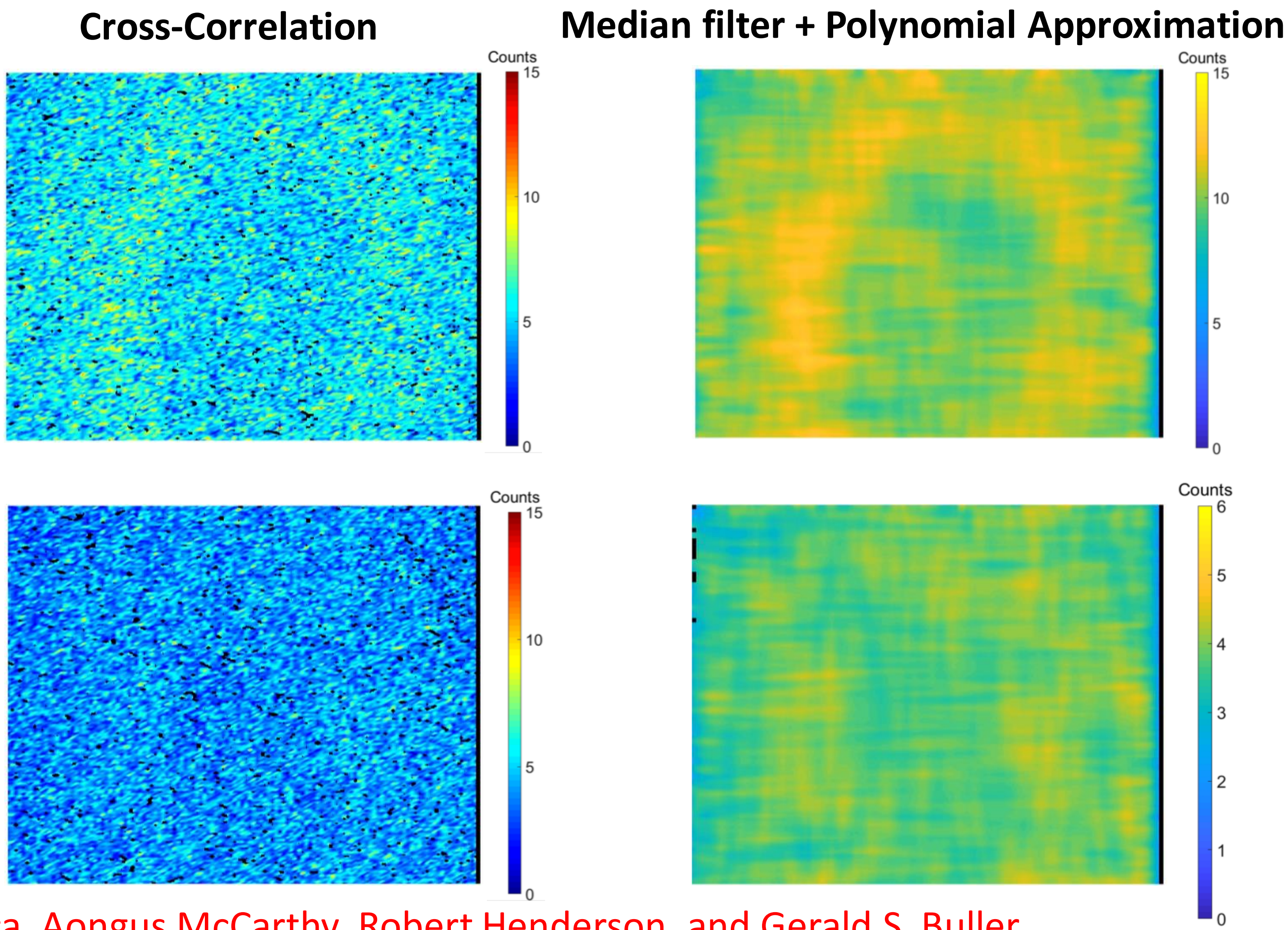


Depth profiles using SPAD array

- Average optical power ~ **8 mW**
- Binary frame acquisition time = **1ms**
- Binary frame acquisition rate = **500 Hz**
- **Images obtained with 50 binary frames**

5.8 AL

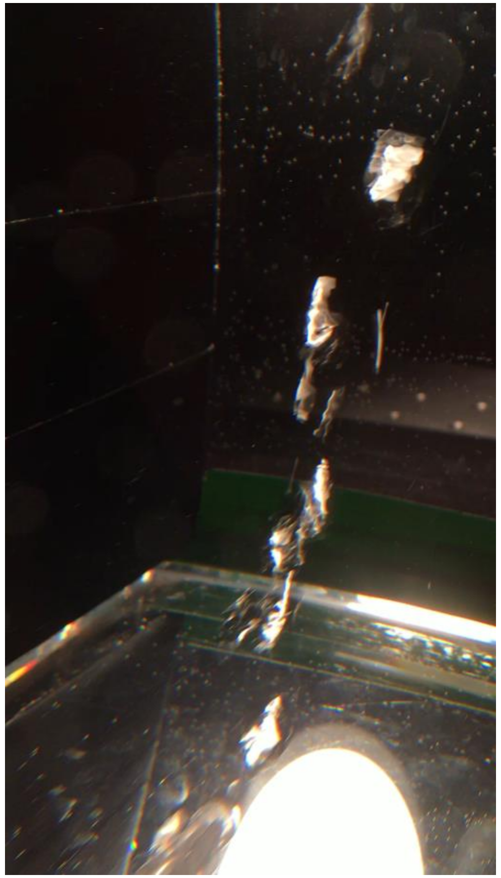
6.7 AL

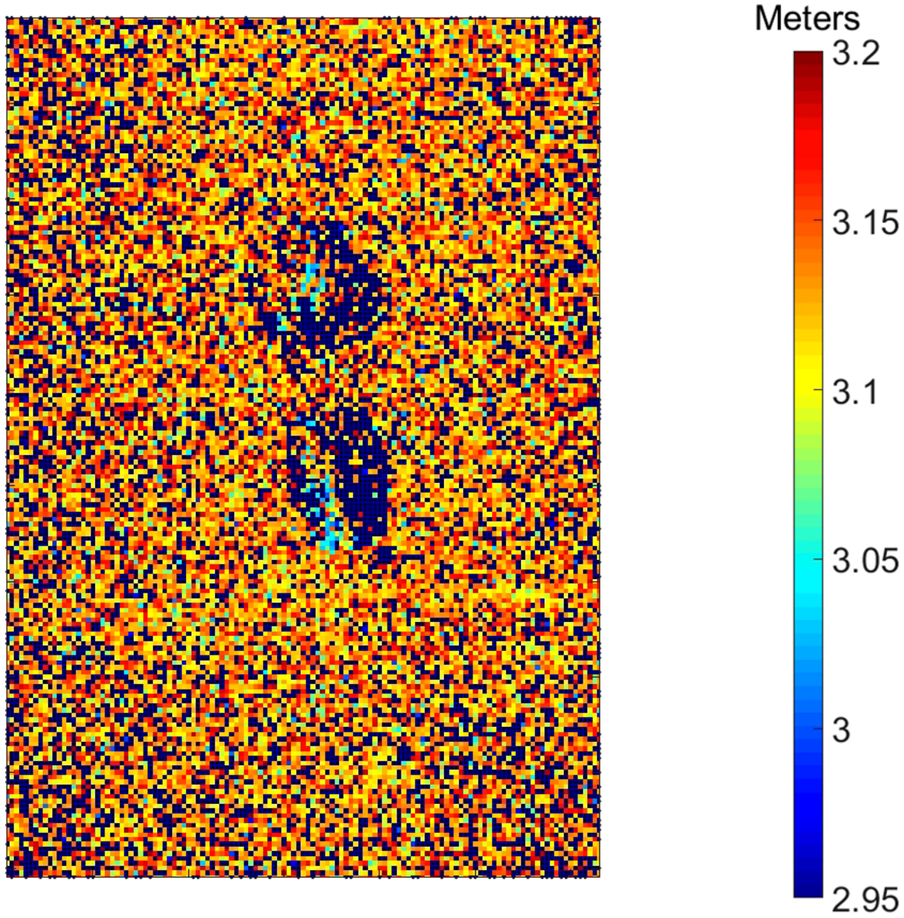


Aurora Maccarone, Francesco Mattioli Della Rocca, Aongus McCarthy, Robert Henderson, and Gerald S. Buller, *"Three-dimensional imaging of stationary and moving targets in turbid underwater environments using a single-photon detector array"*, Optics Express **27**(20), pp. 28437-28456 (2019).

Rapid moving image using SPAD array

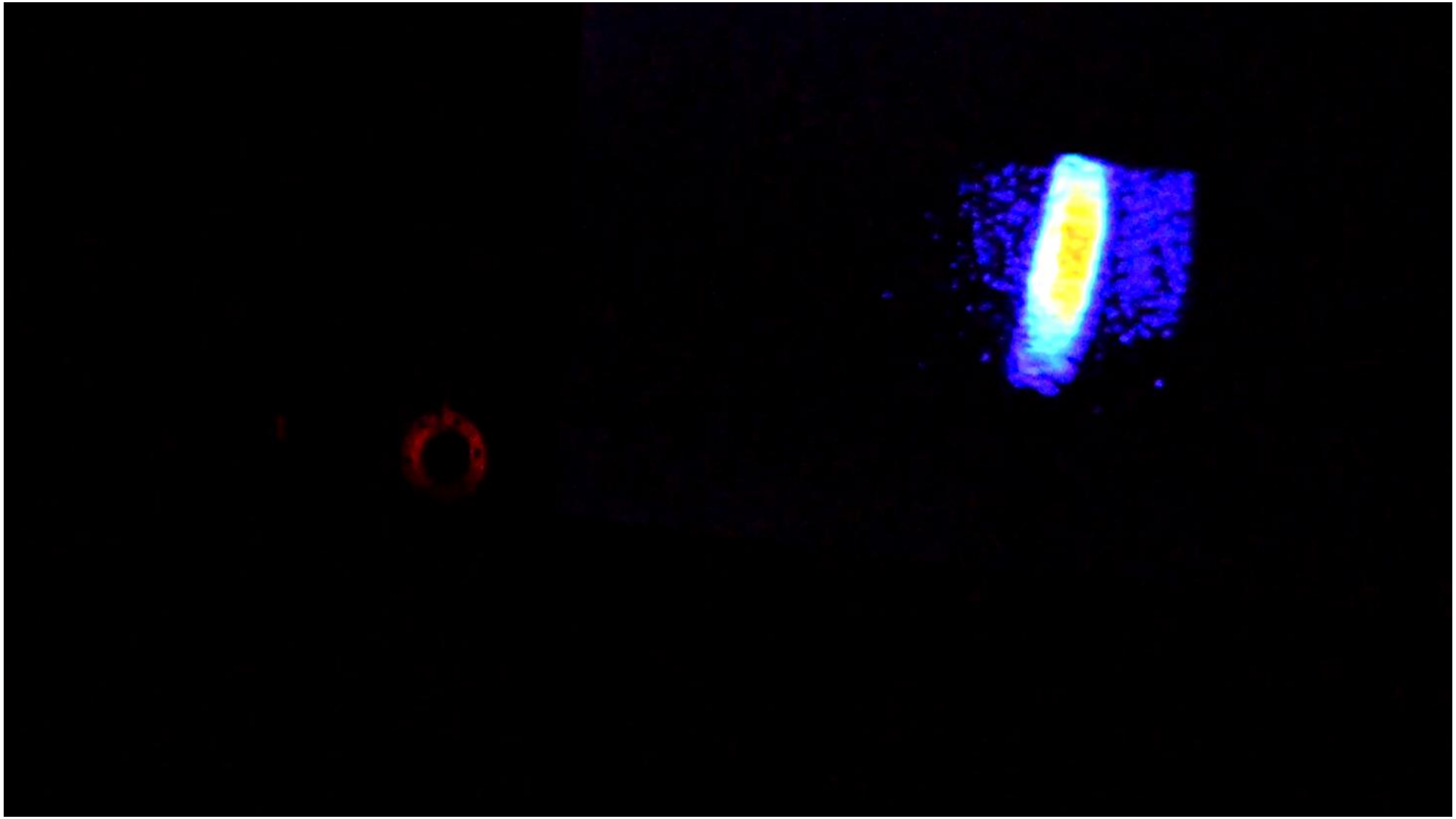
- Average optical power ~ **8 mW**
- **1.2** Attenuation lengths
- Acquisition time per frame = **1ms**
- Acquisition frame rate = **500 Hz**
- Images obtained with single binary frames





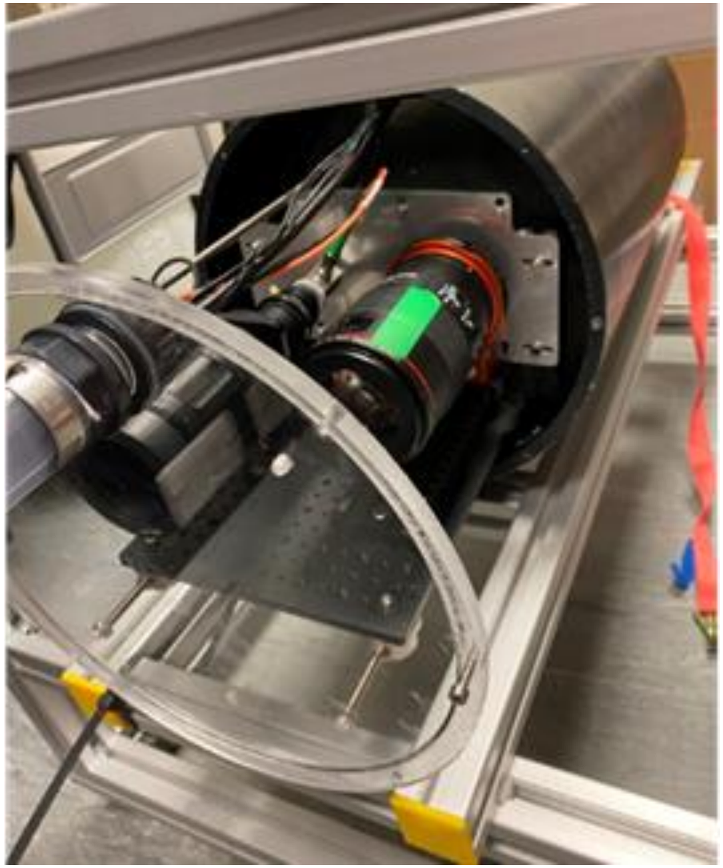
Aurora Maccarone, Francesco Mattioli Della Rocca, Aongus McCarthy, Robert Henderson, and Gerald S. Buller, *"Three-dimensional imaging of stationary and moving targets in turbid underwater environments using a single-photon detector array"*, Optics Express **27**(20), pp. 28437-28456 (2019).

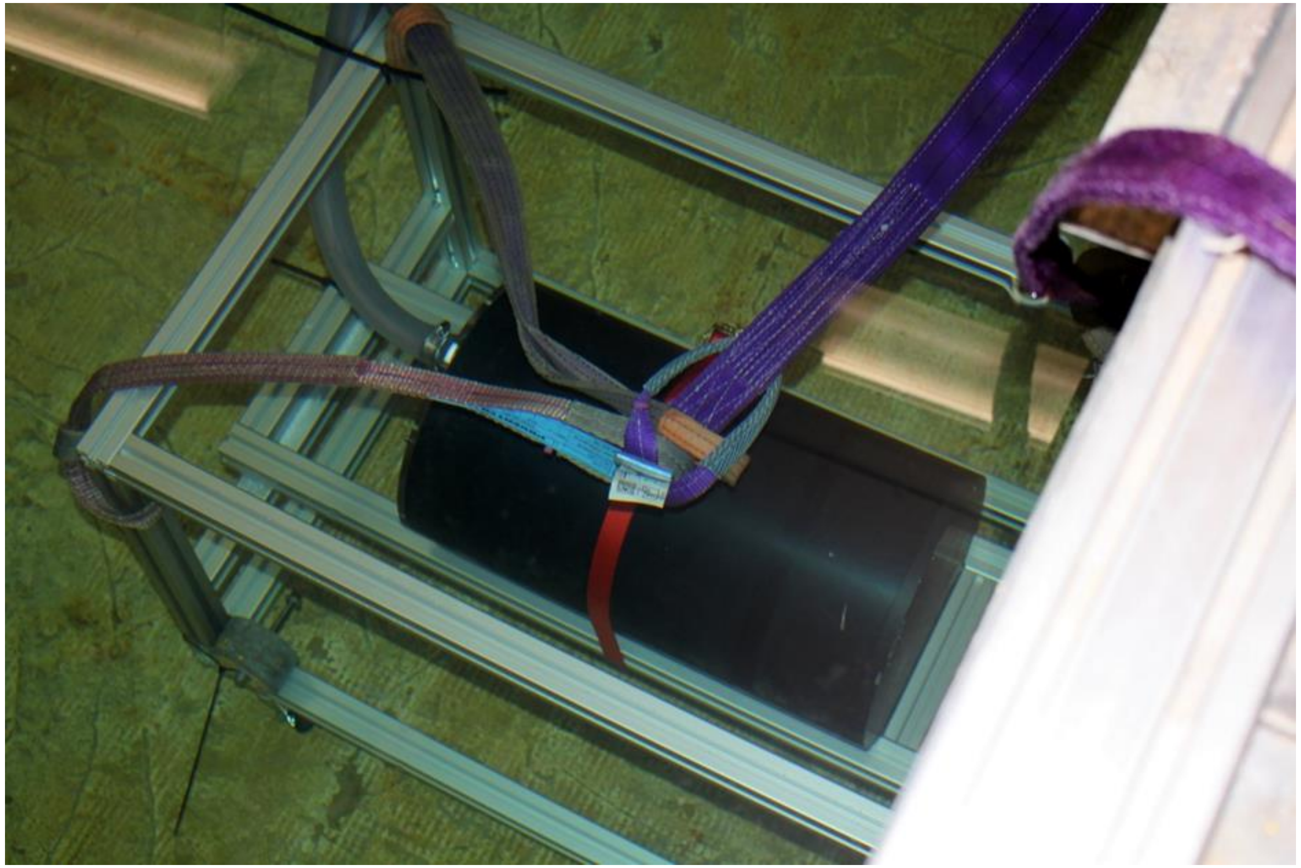
Real-time processing of depth profiles



J. Tachella, Y. Altmann, N. Mellado, A. McCarthy, R. Tobin, G. S. Buller, J.-Y. Tourneret, and S. McLaughlin, "Real-time 3D reconstruction from single-photon lidar data using plug-and-play point cloud denoisers," Nat. Commun. 10(1), 4984 (2019)

Fully submersed transceiver using real-time processing of depth profiles





Summary

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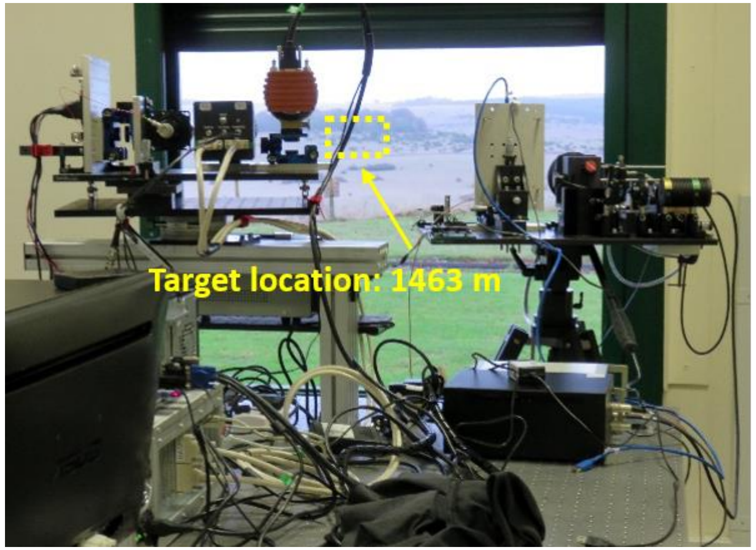
- Time-correlated single-photon counting has been used successfully in several challenging imaging scenarios involving through obscurants. This has developed to “real-time” reconstruction of moving images.

- Longer wavelength SPADs ideal for long-distance free-space imaging through obscurants. > 5 attenuation lengths demonstrated at 150 metres. Work ongoing…

- Si-based SPADs have been used successfully in underwater imaging - depth imaging up to 9.2 attenuation lengths (one way) has been achieved. CMOS SPAD arrays been demonstrated in moving underwater scenes.

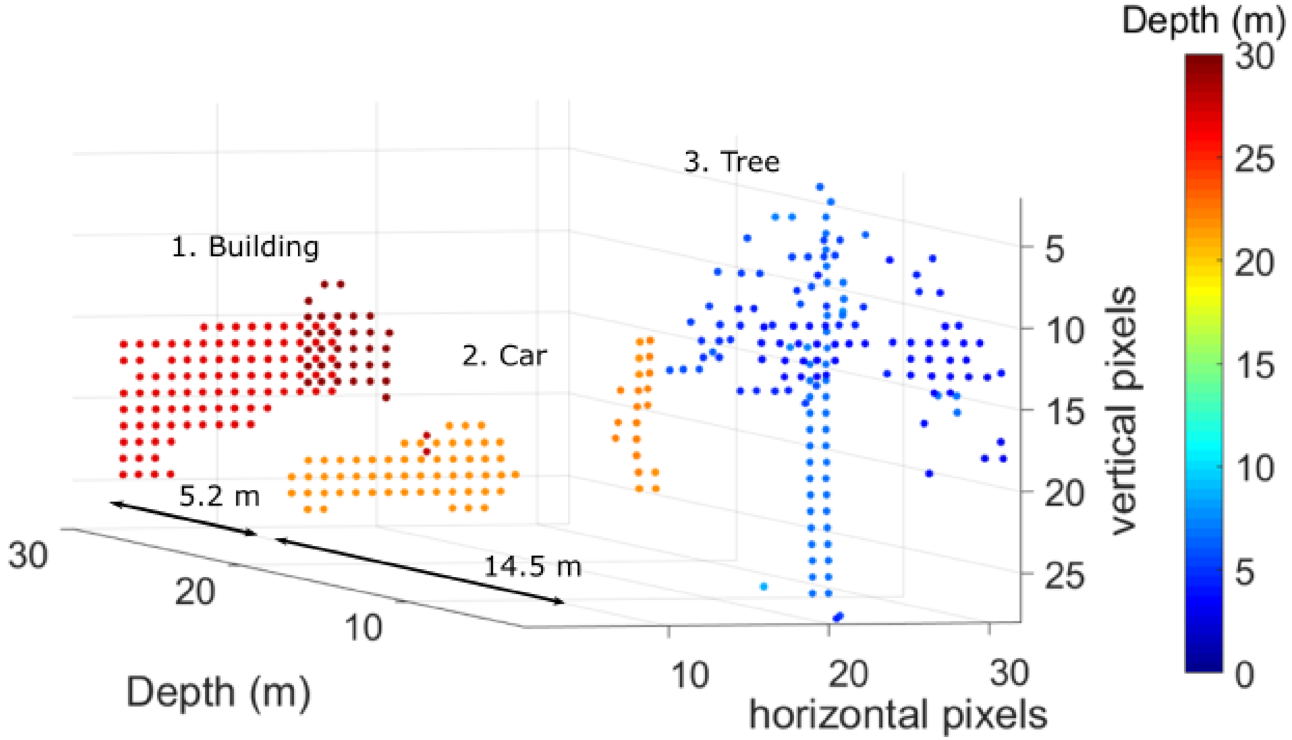
- Field trials on underwater submersible transceivers ongoing.

- All papers available at group web-site www.single-photon.com



Depth imaging at 1.4 km in the presence of high solar background

λ = 1550 nm
Average optical output power level ~ 200 mW



No obscurants used due to on-the-day restrictions

However, neutral density filters used in system transmission channel to simulate reduced signal.

Several data acquisition times also investigated.

- 1 second
- 0.1 seconds
- 0.01 seconds