Underwater time of flight depth imaging using an asynchronous linear single photon avalanche diode detector array

PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Underwater time of flight depth imaging using an asynchronous linear single photon avalanche diode detector array

Maccarone, Aurora, Acconcia, Giulia, Steinlehner, Ulrich, Labanca, Ivan , Rech, Ivan, et al.

Aurora Maccarone, Giulia Acconcia, Ulrich Steinlehner, Ivan Labanca, Ivan Rech, Gerald S. Buller, "Underwater time of flight depth imaging using an asynchronous linear single photon avalanche diode detector array," Proc. SPIE 11540, Emerging Imaging and Sensing Technologies for Security and Defence V; and Advanced Manufacturing Technologies for Micro- and Nanosystems in Security and Defence III, 115400R (14 October 2020); doi: 10.1117/12.2574476

SPIE.

Event: SPIE Security + Defence, 2020, Online Only

Underwater time-of-flight depth imaging using an asynchronous linear single photon avalanche diode detector array

Aurora Maccarone*[1], Giulia Acconcia[2], Ulrich Steinlehner[1], Ivan Labanca[2], Ivan Rech[2], Gerald S. Buller[1]
[1]School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, United Kingdom
[2]Department of Electronics, Information and Bioengineering, Politecnico di Milano, Milano, Italy

ABSTRACT

We investigate three-dimensional profiling of targets in highly scattering underwater environments, obtained using the time-correlated single-photon counting (TCSPC) technique. This approach was implemented in laboratory conditions by using an optical detection system based on a linear array of single-photon detectors and a dedicated TCSPC module. The depth imaging system comprised a single-photon detection module, a TCSPC acquisition system, and a laser diode source in a bi-static transceiver configuration. The laser operated at a wavelength of 670 nm with a pulse duration of 120 ps at a repetition rate of 40 MHz, equivalent to a period of 25 ns. The laser provided a collimated line focus which horizontally illuminated the area of interest. The photon detection module consisted of an array of 16 × 1 silicon single photon avalanche diode (Si-SPAD) detectors built in custom silicon fabrication technology, with each SPAD having a photon detection efficiency of up to 28% at a wavelength of 670 nm. The timing information was measured by a dedicated TCSPC acquisition module, which included four four-channel time to amplitude converter (TAC) arrays. The system acquired time-correlated images with a timing bin duration of 1.6 picoseconds, which was equivalent to 180 μm depth resolution in water. The targets were placed in a 110 liter capacity tank, at a distance of approximately 1.65 meters in several underwater scattering environments, and were moving at a speed of 10 mm/s. These laboratory based experiments demonstrate depth profiles performed in scattering conditions equivalent up to 7.4 attenuation lengths between the transceiver and target, using acquisition times per line of approximately 30 ms, and the pulsed laser had an average optical power of less than 14.6 mW.
Keywords: Single-photon, underwater, scattering, Lidar.

1. INTRODUCTION

Time-correlated single-photon counting (TCSPC) has emerged as a detection approach for high performance lidar and depth profiling due to its high optical sensitivity and excellent surface to surface resolution. The TCSPC technique measures, with picosecond temporal resolution, the timing difference between an optical input pulse and a photon detection event recorded by a single-photon detector [1]. This process is repeated over many laser pulses, and accurate return time, and hence depth information is acquired. This approach has been used to acquire timing information for single-photon depth imaging in challenging environments [2], such as kilometer depth profiling [3], depth imaging of targets hidden behind, camouflage [4] or foliage [5], and depth profiling through fog and smoke [6]. This technique has been recently used also for underwater depth imaging by using an individual silicon single-photon avalanche diode (Si-SPAD) detector [7] and focusing the light on each pixel of the target area. This approach demonstrated three-dimensional underwater imaging up to 9.2 attenuation lengths (AL) [8] – i.e. the distance the light travels in water before being reduce to 1/e of its initial value.

Depth imaging in free space has been achieved with high resolution in several configurations using SPAD detector arrays fabricated in complementary metal-oxide semiconductor (CMOS) [9-15]. Recently, underwater depth imaging using TCSPC was investigated also by using a CMOS Si-SPAD detector arrays [16], which gave the advantage of a large pixel format, and to collect the picosecond resolution timing information for the full-field simultaneously [17]. Generally, CMOS SPAD detector array provide a high degree of parallelization [18-26], however CMOS SPAD detector

Emerging Imaging and Sensing Technologies for Security and Defence V; and Advanced Manufacturing Technologies for Micro- and Nanosystems in Security and Defence III, edited by G. S. Buller, et al, Busse, Proc. of SPIE Vol. 11540, 115400R · © 2020 SPIE · CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2574476

array typically have less optimized performance characteristics when compared to Si-SPAD detector arrays built in custom fabrication technology [27], because of the constraints in the fabrication process.

SPADs made using custom technology have been demonstrated in several applications, such as fluorescence lifetime imaging microscopy [28]. In this paper, we demonstrate a Si-SPAD detector linear array fabricated using custom technology, with dedicated TCSPC electronics [29] for underwater depth imaging. We show preliminary results of depth and intensity profiles of targets in water with different levels of scattering, equivalent up to 7.4 AL one-way between the transceiver and the target.

2. EXPERIMENTAL SETUP

The schematic of the experimental setup is shown in Figure 1. The system comprised a laser diode with central wavelength $\lambda = 670$ nm, operating at the repetition rate of 40 MHz. The output of the laser was a diverging laser line, which was orientated along the horizontal axis at the target position. The target was placed in a water tank of 110 liters capacity, at a distance in water of approximately 1.65 m from the transceiver. During the measurements, the target was moved by a motorized translational stage along the vertical direction. The light scattered by the target was collected with a spherical lens of 150 mm focal length and a clear aperture of approximately 23 mm, which focused the line onto the linear single-photon detector array.

The single-photon detection module consisted of an array of 16×1 silicon single-photon avalanche diode (Si-SPAD) detectors fabricated in custom technology, with single-photon detection efficiency up to 28 % at 670 nm wavelength. Each detector had an active area with a diameter of 50 μm, and the distance between two adjacent detectors was 250 μm from center to center. In order to optimize the performance of the detectors, the SPADs were operated at a temperature of 0 °C.

The timing information was measured by a dedicated TCSPC acquisition module, which included four four-channel time to amplitude converter (TAC) arrays, two eight-channels commercial analog to digital converters (ADC) and a commercial field programmable gate array (FPGA). The TCSPC module was connected to the detector head which provided the start signal for each timing measurement, and to the laser system which provided the stop signal. The system acquired time correlated images from timing bins of 1.6 picosecond duration, equivalent to 180 μm depth resolution in water.

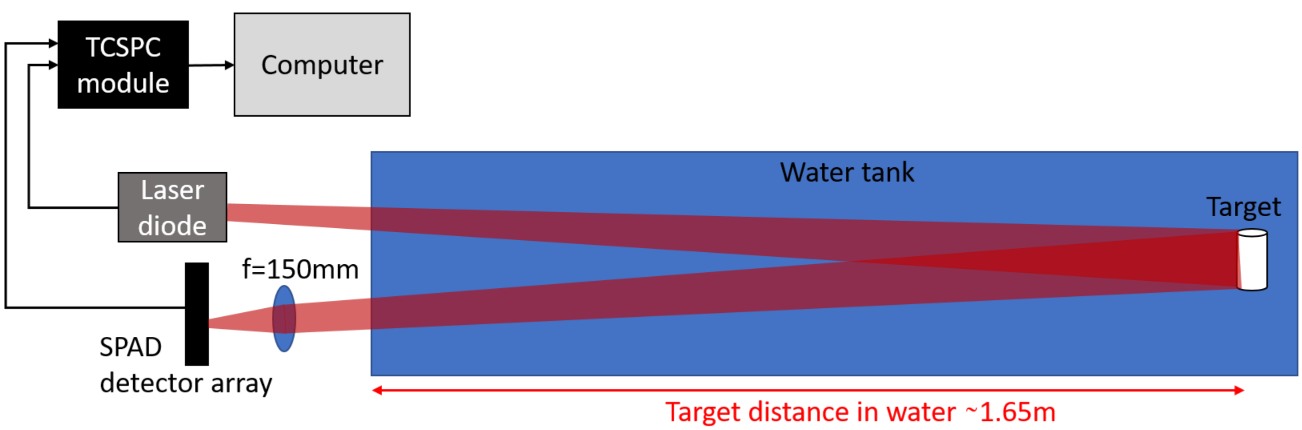

Figure 1. Schematic of the experimental setup. The system comprised a laser diode, a SPAD detector linear array, and a dedicated TSCPC module. A target was placed in water and the scan was performed by moving the target over the vertical direction.

3. RESULTS

The target used was a 3D printed target with three blocks of 15 mm side and depth features of 10 mm, 20 mm, 30 mm, as shown in the schematic in Figure 2.a). Figure 2.b) shows a photograph of the target as viewed from the transceiver.

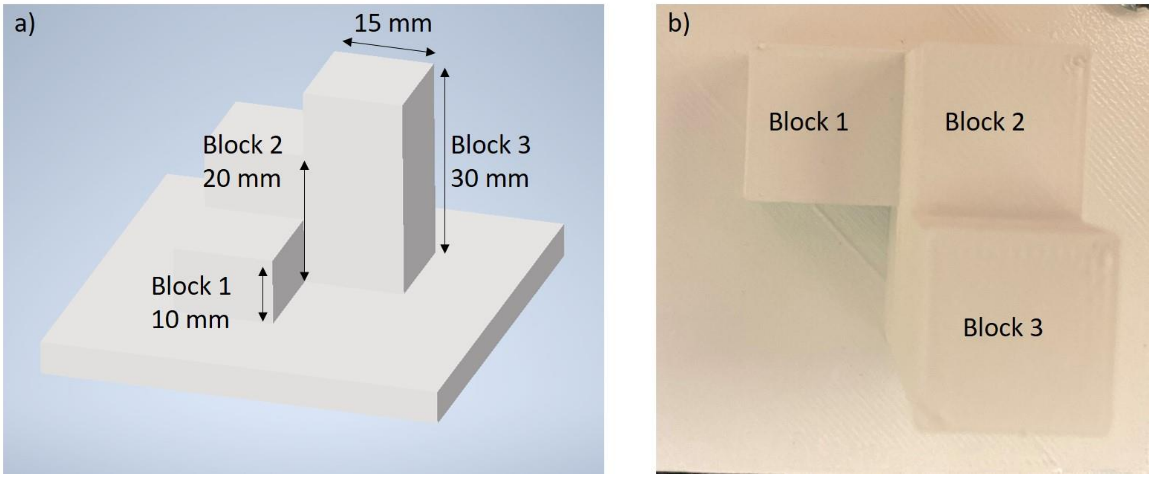

Figure 2. a) schematic of the target used during the experiments. b) Photograph of the target as seen from the system.

During these measurements, the target was moved vertically at a speed of 10 mm/s, and the timing information was acquired asynchronously for the duration of the scan for all the SPAD detectors. This meant that the number of lines of the final image and the acquisition time per line were selected by software during the analysis of the data.

The data presented in this paper were analyzed by selecting 200 lines, with an acquisition time per line of 30 ms, and performing a cross-correlation approach between the histogram recorded and a pre-recorded instrumental response of the system. The instrumental response was obtained by measuring the timing information from a stationary Lambertian scatterer target in unfiltered tap water, using a long acquisition time of approximately 40 seconds. The maximum value of the cross-correlation was used to estimate the depth information for each pixel, and the intensity was obtained by counting the number of events in a 150 bins window around the maximum of the cross-correlation, which was equivalent to 240 ps timing window.

Several depth and intensity profiles measurements were performed in unfiltered tap water and different concentrations of scattering agent, equivalent to an attenuation of up to 7.8 AL between the system and the target. The average optical power of the laser for each scan was adjusted depending on the level of scattering in water, and it was varied from 3 μW in unfiltered tap water up to 14.6 mW for high levels of attenuation of the propagation medium.

Figure 3 shows the intensity maps obtained with the pixel-wise cross-correlation approach in several underwater environments. The intensity map is not affected up to 5.4 AL, however in more attenuating environments the intensity quickly degrades with no information available above 6.8 AL, and the target cannot be identified because of the high level of scattering.

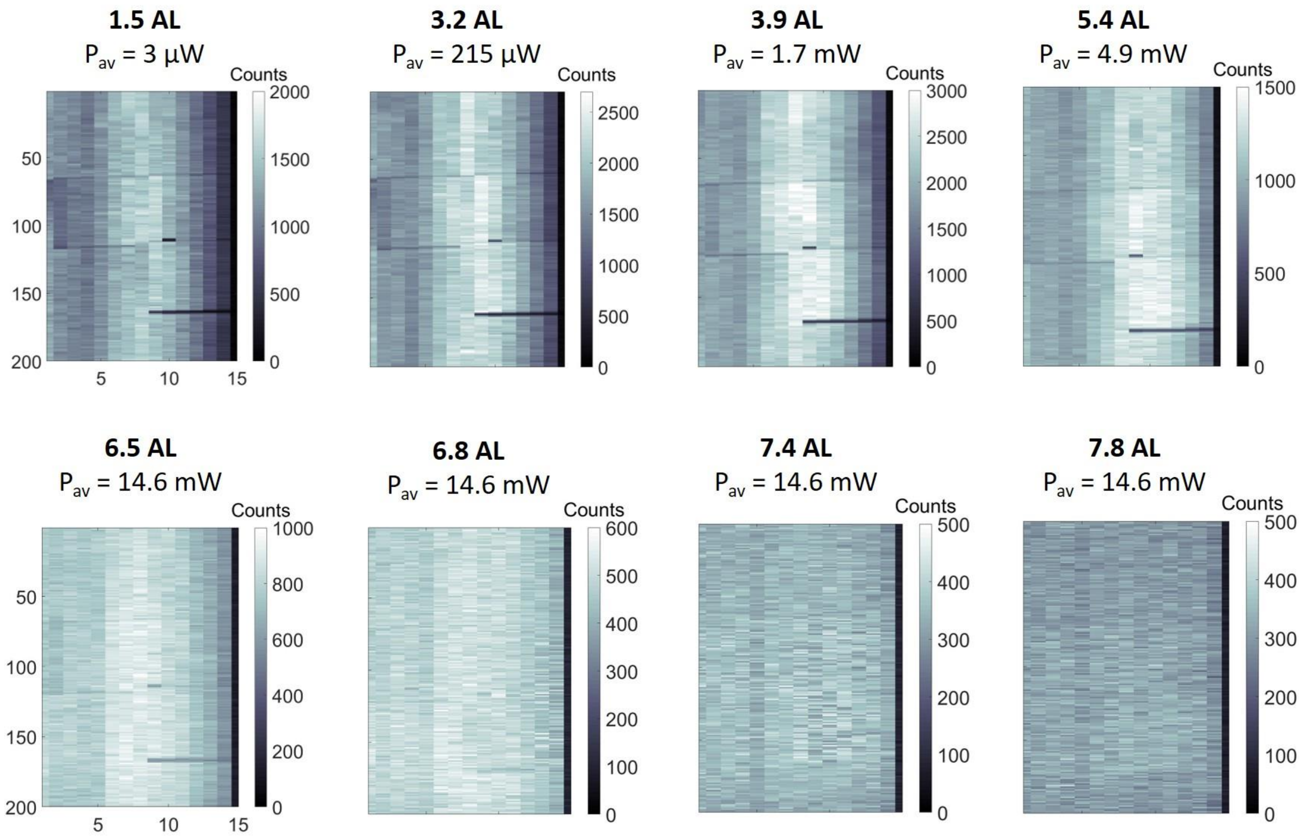

Figure 3. Intensity map of the target in several scattering environments. The average optical power entering the tank was adjusted depending on the level of scattering of the water.

However, the timing information allowed us to detect and identify the target in high levels of scattering in water. This can be seen in Figure 4, which shows the depth maps in several scattering conditions obtained with the cross-correlation approach. In this case, the timing information allows to identify the target up to 7.4 AL and to detect it at 7.8 AL between the transceiver and the target. However, further investigation is needed in order to establish the achievable depth resolution in highly scattering environments.

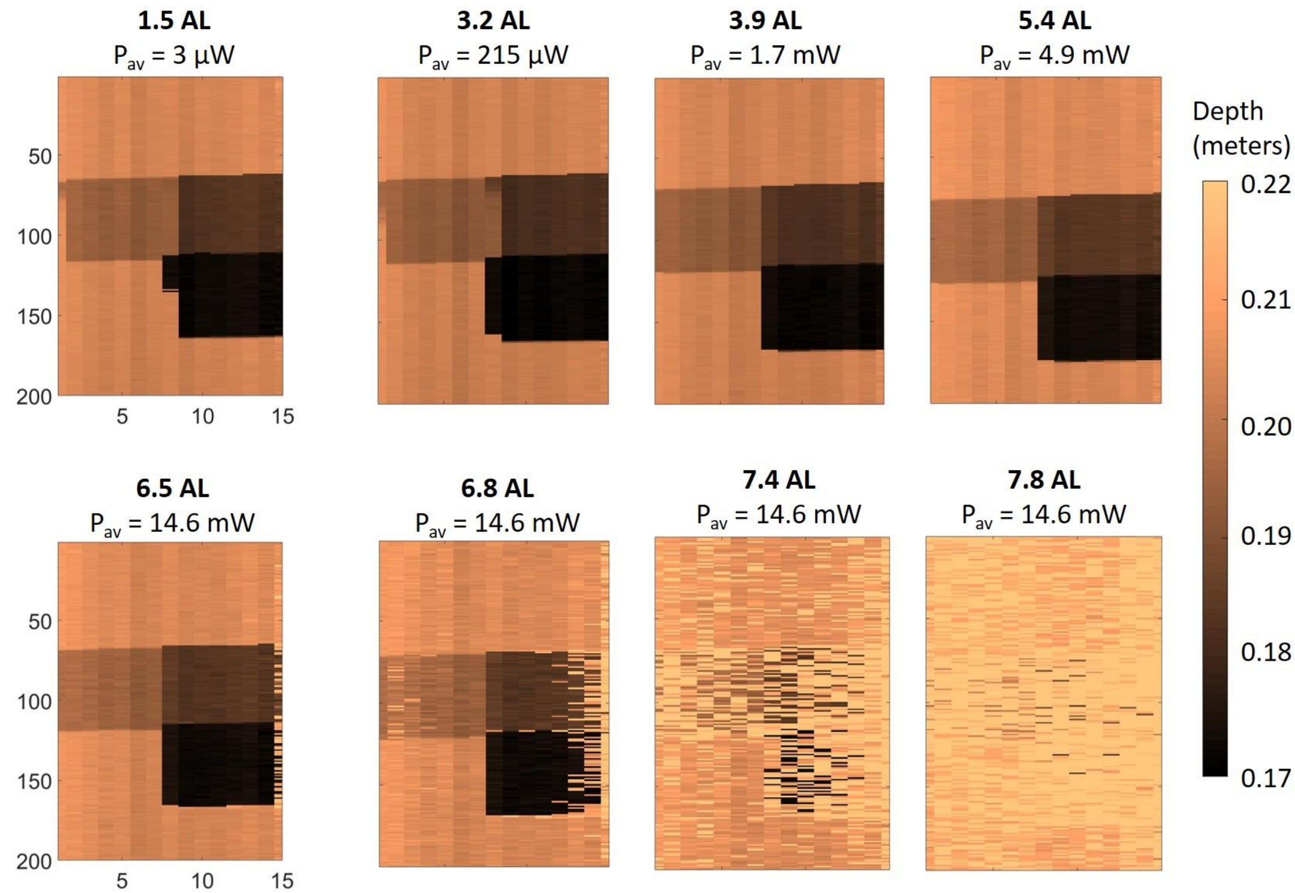

Figure 4. Intensity map of the target in several scattering environments. The average optical power entering the tank was adjusted depending on the level of scattering of the water.

4. CONCLUSIONS

Preliminary results were presented on underwater depth imaging using a single-photon detection system based on a linear array Si-SPAD detectors fabricated from custom technology, with a dedicated time-correlated single-photon counting (TCSPC) module.

Depth and intensity maps were obtained with a pixel-wise cross-correlation approach in several underwater scattering scenarios. These depth results show potential for target identification in highly scattering underwater environments equivalent up to 7.4 attenuation lengths between the system and the target, and target detection in attenuating environments equivalent to 7.8 attenuation lengths. At the same time, the corresponding intensity maps showed that the intensity map is not affected by scattering up to 5.4 attenuation lengths, but it degrades quickly in higher levels of scattering.

Further experiments will be performed in order to establish how the scattering affects the achievable depth and spatial resolution of this single-photon system and to investigate reduced acquisition times per line.

ACKNOWLEDGEMENTS

The authors acknowledge the support of UK Engineering and Physical Sciences Research Council (EPSRC) projects EP/T00097X/1 and EP/N003446/1.

REFERENCES

[1] W. Becker, [Advanced Time-Correlated Single Photon Counting Techniques], Chemical Physics, Springer (2005).

[2] D. Shin, F. Xu, D. Venkatraman, R. Lussana, F. Villa, F. Zappa, V. K. Goyal, F. N. C. Wong, and J. H. Shapiro, "Photon-efficient imaging with a single-photon camera", Nat. Commun., 7, 12046 (2016).

[3] Y. Kang, L. Li, D. Liu, D. Li, T. Zhang, and W. Zhao, "Fast Long-Range Photon Counting Depth Imaging With Sparse Single-Photon Data", IEEE Photonic J., 10(3), (2018).

[4] R. Tobin, A. Halimi, A. McCarthy, X. Ren, K. J. McEwan, S. McLaughlin, and G. S. Buller, "Long-range depth profiling of camouflaged targets using single-photon detection", Opt. Eng., 57(3), 031303 (2017).

[5] M. Henriksson, H. Larsson, C. Grönwall, and G. Tolt, "Continuously scanning time-correlated single-photon-counting single-pixel 3-D lidar", Opt. Eng., 56(3), 031204, (2016).

[6] R. Tobin, A. Halimi, A. McCarthy, M. Laurenzis, F. Christnacher, and G. S. Buller, "Three-dimensional single-photon imaging through obscurants", Opt. Express, 27(4), 4590-4611 (2019).

[7] 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", Opt. Express, 23(26), 33911-33926 (2015).

[8] A. Maccarone, A. McCarthy, A. Halimi, R. Tobin, A. M. Wallace, Y. Petillot, and G. S. Buller, "Depth imaging in highly scattering underwater environments using time correlated single photon counting", Proc. SPIE 9992, Emerging Imaging and Sensing Technologies, 99920R (2016).

[9] Robert K. Henderson, Nick Johnston, Sam W. Hutchings, Istvan Gyongy, Tarek Al Abbas, Neale Dutton, Max Tyler, Susan Chan, and J. Leach, "A 256×256 40nm/90nm CMOS 3D-Stacked 120dB Dynamic-Range Reconfigurable Time-Resolved SPAD Imager", in IEEE International Solid-State Circuits Conference (2019).

[10] C. Niclass, A. Rochas, P. A. Besse, and E. Charbon, "Design and characterization of a CMOS 3-D image sensor based on single photon avalanche diodes", IEEE J. Solid-State Circuits, 40(9), 1847-1854 (2005).

[11] F. Guerrieri, S. Tisa, A. Tosi, and F. Zappa, "Two-dimensional SPAD imaging camera for photon counting", IEEE Photonics J., 2(5), 759-774 (2010).

[12] E. Charbon, "Single-photon imaging in complementary metal oxide semiconductor processes". Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2012), 20130100 (2014).

[13] M. Perenzoni, L. Pancheri, and D. S. Toppa, "Compact SPAD-Based Pixel Architectures for Time-Resolved Image Sensors", Sensors, 16(5), 745 (2016).

[14] D. Portaluppi, E. Conca, and F. Villa, "32× 32 CMOS SPAD imager for gated imaging, photon timing, and photon coincidence", IEEE J. Sel. Top. Quant., 24(2),1-6 (2017).

[15] S. Bellisai, D. Bronzi, F. Villa, S. Tisa, A. Tosi, and F. Zappa, "Single-photon pulsed-light indirect time-of-flight 3D ranging", Opt. Express, 21(4), 5086 - 5098 (2013).

[16] A. Maccarone, F. Mattioli Della Rocca, A. McCarthy, R. Henderson, and G. S. Buller, "Three-dimensional imaging of stationary and moving targets in turbid underwater environments using a single-photon detector array", Opt. Express, 27(20), 28437-28456 (2019).

[17] R. K. Henderson, N. Johnston, F. Mattioli Della Rocca, H. Chen, D. Day-Uei Li, G. Hungerford, R. Hirsch, D. McLoskey, P. Yip, 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).

[18] C. Veerappan, J. Richardson, R. Walker, D. Li, M. W. Fishburn, Y. Maruyama, D. Stoppa, F. Borghetti, M. Gersbach, R. K. Henderson, and E. Charbon, "A 160 x 128 single-photon image sensor with on-pixel 55ps 10b time-to-digital converter", in ISSCC Tech. Dig. Papers. IEEE San Francisco. p. 312-314 (2011).

[19] F. Villa, D. Bronzi, S. Bellisai, G. Boso, A. Bahgat Shehata, C. Scarcella, A. Tosi, F. Zappa, S. Tisa, D. Durini, S. Weyers, and W. Brockherde, "SPAD imagers for remote sensing at the single-photon level", Proc. SPIE 8542, Electro-Optical Remote Sensing, Photonic Technologies, and Applications VI, 85420G (2012).

[20] M. Perenzoni, N. Massari, D. Perenzoni, L.Gasparini, D. Stoppa, "A 160×120 Pixel Analog-Counting Single-Photon Imager With Time-Gating and Self-Referenced Column-Parallel A/D Conversion for Fluorescence Lifetime Imaging", IEEE J. Solid-St. Circ., 51(1), 155-167 (2016).

[21] C. Niclass, C. Favi, T. Kluter, M. Gersbach, and E. Charbon, "A 128 x 128 single-photon image sensor with column-level 10-bit time-to-digital converter array", IEEE Journal of Solid-State Circuits, 43(12), 2977-2989 (2008).

[22] A. C. Ulku, C. Bruschini, I. M. Antolovic´, Y. Kuo, R. Ankri, S. Weiss, X. Michalet, and E. Charbon, "A 512× 512 SPAD image sensor with integrated gating for widefield FLIM", IEEE J. Sel. Top. Quant., 25(1), 6801212 (2019).

[23] F. Villa, R. Lussana, D. Bronzi, S. Tisa, A. Tosi, F. Zappa, A. Dalla Mora, D. Contini, D. Durini, S. Weyers, and W. Brockherde, "CMOS Imager With 1024 SPADs and TDCs for Single-Photon Timing and 3-D Time-of-Flight", IEEE J. Sel. Top. Quantum Electron., 20(6), 3804810 (2014).

[24] F. Mattioli Della Rocca, H. Mai, S. Hutchings, T. Al Abbas, K. Buckbee, A. Tsiamis, P. Lomax, I. Gyongy, N. Dutton, and R. Henderson, "A 128 × 128 SPAD Motion-Triggered Time of Flight Image Sensor with In-Pixel Histogram and Column-Parallel Vision Processor", IEEE J. Solid-St. Circ., 55(7), 1762-1775 (2020).

[25] C. Niclass, M. Soga, H. Matsubara, M. Ogawa, and M. Kagami, "A 0.18- m CMOS SoC for a 100-m-Range 10-Frame/s 200 96-Pixel Time-of-Flight Depth Sensor", IEEE J. Solid-St. Circ., 49(1), 315 - 330 (2013).

[26] D. Bronzi, F. villa, S. Tisa, A. Tosi, F. Zappa, D. Durini, S. Weyers, and W. Brockherde, "100 000 Frames/s 64 × 32 Single-Photon Detector Array for 2-D Imaging and 3-D Ranging", IEEE J Sel. Top. Quant., 20(6), 3804310 (2014).

[27] G. Acconcia, A. Cominelli, M. Ghioni, and I. Rech, "Fast fully-integrated front-end circuit to overcome pile-up limits in time-correlated single photon counting with single photon avalanche diodes", Opt. Express, 26(12), 15398-15410 (2018).

[28] P. Peronio, I. Labanca, G. Acconcia, A. Ruggeri, A. A. Lavdas, A. A. Hicks, P. P. Pramstaller, M. Ghioni, and I. Rech, "32-channel time-correlated-single-photon-counting system for high-throughput lifetime imaging", Rev. Sci. Instrum., 88, 083704 (2017).

[29] A. Cuccato, S. Antonioli, M. Crotti, I. Labanca, A. Gulinatti, I. Rech, and M. Ghioni, "Complete and Compact 32-Channel System for Time-Correlated Single-Photon Counting Measurements", IEEE Photonic J., 5(5), (2013).