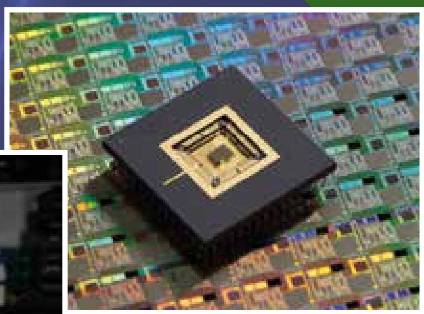
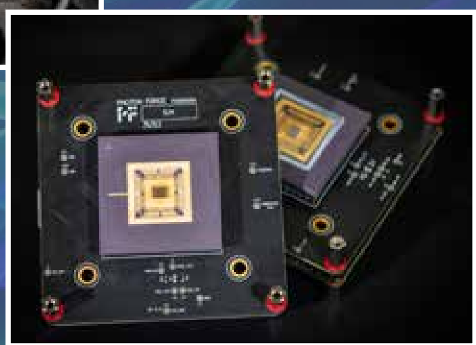
PHOTON FORCE

Single-Photon Sensitive Cameras, Sensors and Modules

The highest throughput, fastest time-resolved single-photon counting technology on the market





Photon Force offers
SPAD array cameras and sensors
with the ability to timestamp
500,000,000 photons per second

Our technologies are accelerating
progress in multiple areas
including photonics, quantum optics,
biophotonics, and research in other
scientific and engineering fields

Quantum Optics

Research

Photonics

About Photon Force

Dr Richard Walker co-founded Photon Force in 2015, after 7 years in the renowned CMOS Sensors & Systems Group at the University of Edinburgh led by Professor Robert Henderson.

As part of the image sensing community, Photon Force has built on over a decade of successful research experience in time-resolved imaging to provide innovative, high quality and accurate sensor technology that facilitates scientific, academic and commercial research.

Our Belief

We believe the research community should have access to powerful tools for faster scientific progress. Through our technology, we bring an order-of-magnitude acceleration to single-photon imaging and data processing, and we support our customers with a wide variety of processing challenges to enable further enhanced techniques.

We believe that time-resolved single-photon imaging has the ability to revolutionise a wide range of fields, from energy production to biomedical research. We aim to help bring about that revolution through the mass manufacture of single-photon avalanche diode (SPAD) sensors. By making our detectors widely available to researchers and companies, we are enabling them to develop applications and technological advancements that have not previously been possible.

Our Innovation

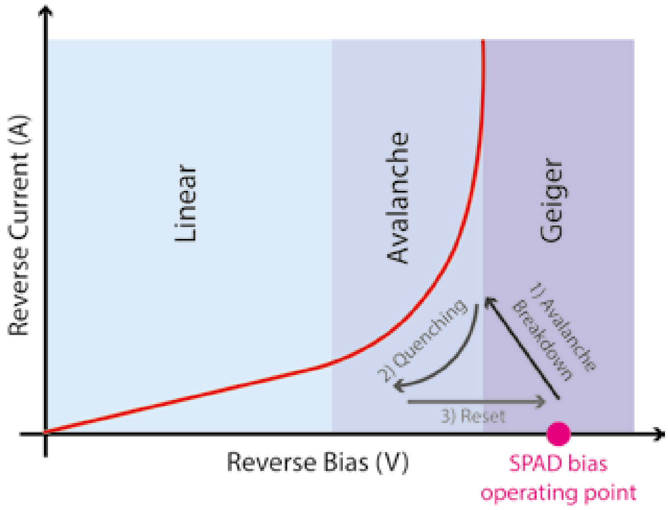
Our PF32 time-resolved camera product range offers the highest throughput single-photon-counting cameras on the market. Since the launch of our initial camera range, we have continued to innovate, developing and launching new products and services that build on our market-leading technology.

We also work with umbrella organisations such as Innovate UK to play a role in crucial R&D projects aimed at creating next-generation technologies with impact.

What is a SPAD?

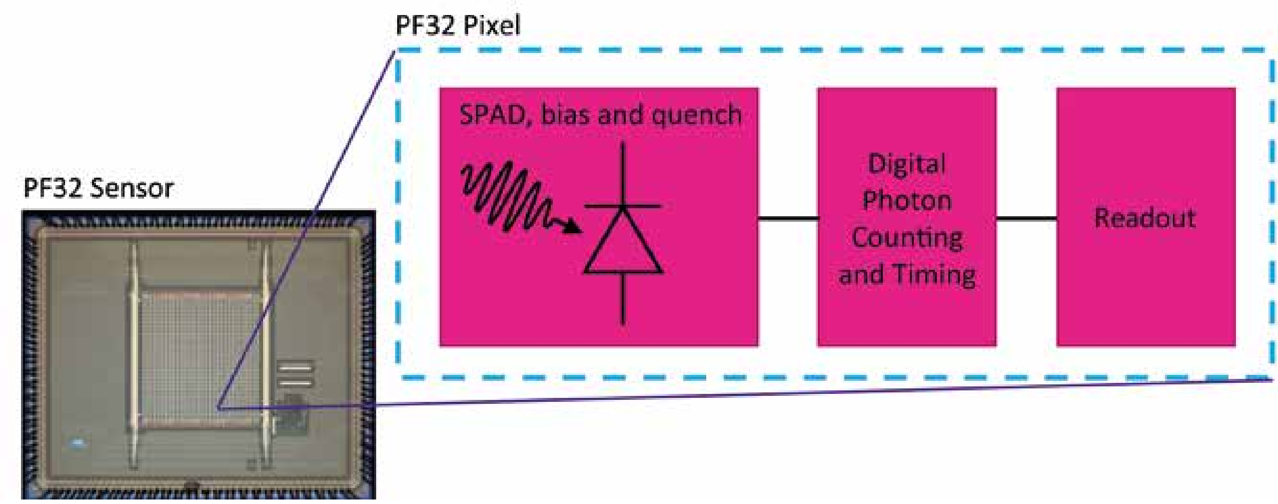
A Single-Photon Avalanche Diode (SPAD) is a photodiode that has been specifically designed to be operated beyond its reverse breakdown voltage, in the so-called "Geiger mode". While a conventional photodiode would immediately break down if biased in this region, a SPAD can sit stably in this configuration for a period of time, until disturbed by an incoming photon or other noise source.

When a photon is absorbed within the device, creating an electron-hole pair, the resulting avalanche due to impact ionisation provides a rush of current, easily detectable by the surrounding circuitry. The SPAD therefore provides digital detection of a single photon.



Unparalleled Integration – The CMOS Advantage

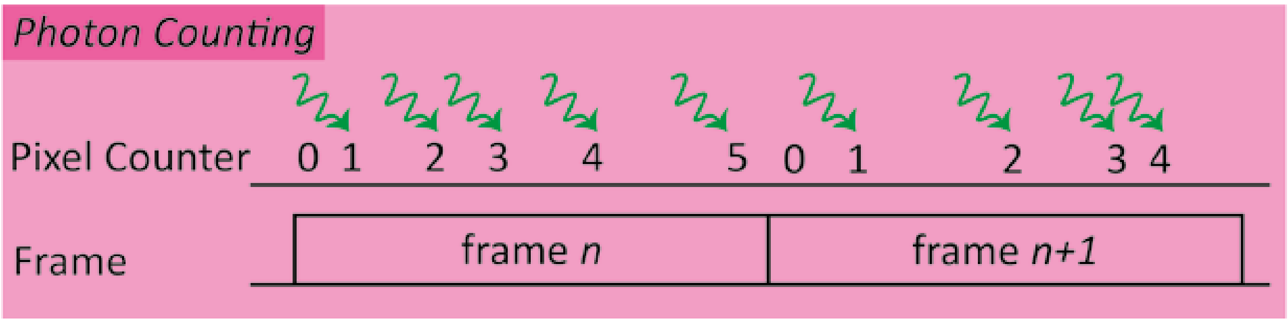
Photon Force sensors utilise advanced CMOS manufacturing technologies to combine a SPAD along with bias/quench, photon counting/timing and readout electronics into a compact pixel. This pixel is then replicated to form an imaging array. Since every pixel provides self-contained photon detection and counting/timing, our arrays offer unparalleled throughput of up to 500M photons/s*.
**Subject to model and operating mode.*



Digital Photon Counting and Timing

Photon Counting:

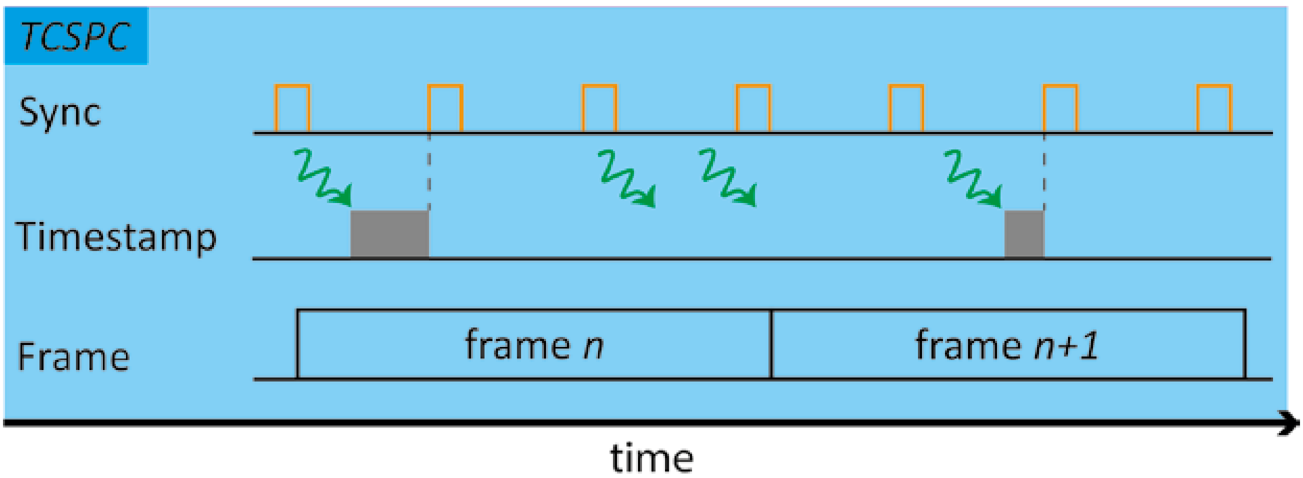
SPADs allow true digital single photon counting, with no analogue read noise. Every detected photon increments the in-pixel counter. Photon Force cameras allow for flexible, ultra-high speed readout - crucial for applications such as diffuse correlation spectroscopy.



Time-Correlated Single Photon Counting (TCSPC):

SPADs are unique in providing time information for every detected photon, directly into the digital domain - ideal for integration with timing and readout circuitry. With Photon Force sensors, the first photon detected in every frame can be timestamped with a resolution of just 55ps with respect to a synchronization reference. Combined with high speed readout, our technology delivers time-tagged data with unprecedented throughput, providing up to half a billion single-photon timestamps per second!

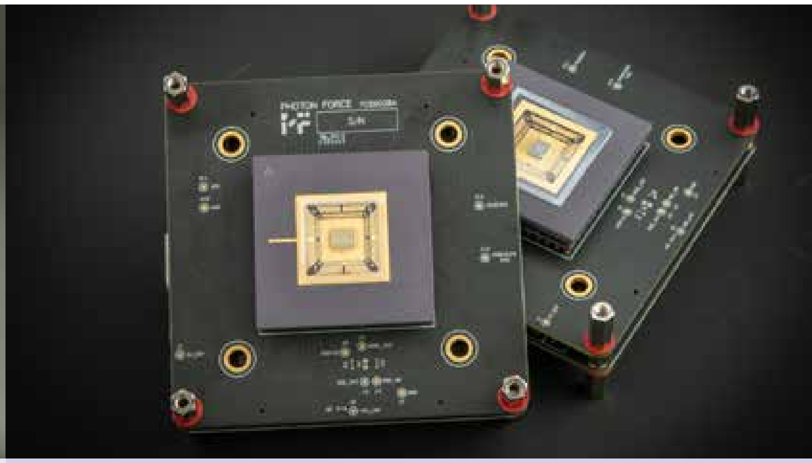
Read on to learn about the range of applications our sensors and cameras have been applied to.



Our Products and Services

Photon Force offers a range of products and services all aimed at the acceleration of scientific and commercial research and product development that incorporates single-photon counting and timing.

Our camera range currently includes six PF32 models. The PF32-Lite offers an entry-level unit, the PF32-Core is ideal for almost all TCSPC application, then the PF-Ultra offers extreme speed for applications that require flexibility in readout modalities. All three models are available with a microlens option, offering a higher fill factor and increased sensitivity.



PF32 Cameras

The Photon Force range of PF32 cameras are the highest throughput SPAD array cameras on the market today.

- 32×32 TCSPC pixel array
- 55 picosecond resolution
- Six models; Lite, Core and Ultra , each available with or without microlens option
- Two modes; TCSPC and photon counting
- Up to 500,000,000 photons timestamped per second

PF32 Module

The PF32 range is now also available in a module format, as shown in the image above. This smaller size, weight, and power solution eases integration of our sensors into larger systems. The data connection to the host has been upgraded to PCIe, offering unparalleled speed and consistency.

Full specs of both the PF32 camera and module can be found towards the end of the brochure.

Firmware

We are developing a firmware library of standard functions to accelerate your research and development programme by performing data analysis within the camera itself. These functions includes a correlator function, histogramming, and X-Y scanner synchronisation routines. These functions increase throughput rates or ease of data interpretation from the camera to a host computer and speed up system software development.

Sensors & ROICs

We offer a design and manufacturing service to provide custom sensors and readout integrated circuits (ROICs) spanning resolution, size and architecture options.

Software

Our off-the-shelf software provides a flexible API for easy integration with other applications. Common programming languages that we link with include MatLab, LabView, Python, C and C++.

Where are Photon Force technologies used?

Photon Force products and technologies are used across a wide range of sectors to enable ultrafast, Time-Correlated Single Photon Counting with the ability to timestamp half a billion photons per second.

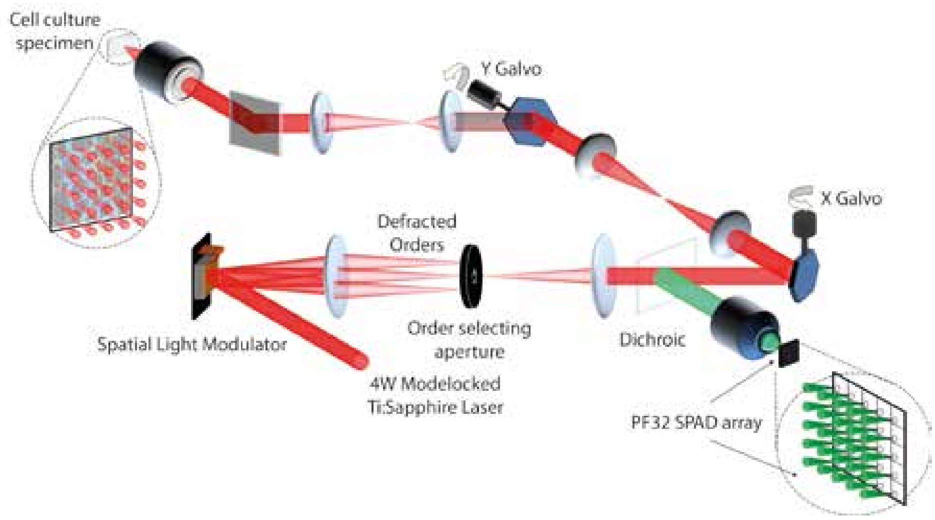
The PF32 was originally designed for use in Fluorescence Lifetime Imaging Microscopy (FLIM), an example of this work is shown below. Since then, our cameras and sensors have been used in the fields of photonics, quantum optics and other scientific research to enable next generation technologies and products in a wide range of industries, spanning neuroscience, energy, communications, automotive, and beyond.

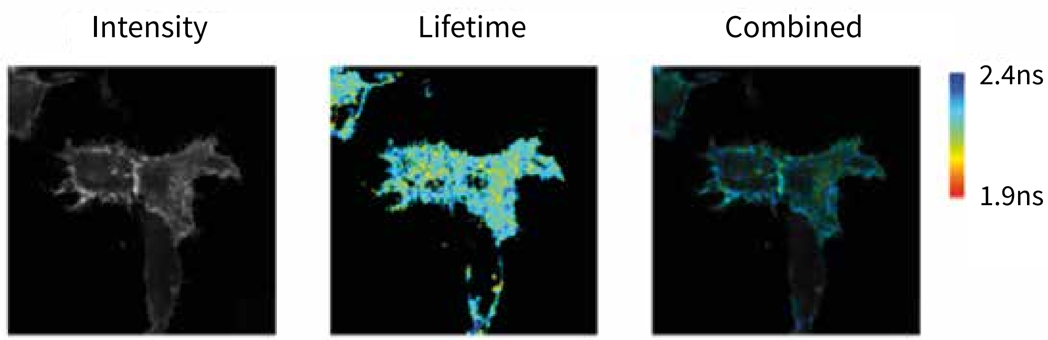
Fast Fluorescence Lifetime Imaging Microscopy (FLIM)

The PF32 family can be used as widefield FLIM cameras, imaging 1,024 independent TCSPC spatial points simultaneously at high speed. Alternatively, the camera can be used as a 'bucket' detector for high-speed scanning systems, with the advantage of all 1,024 pixels being able to simultaneously detect and timestamp photons.

While confocal microscopes are the workhorses of biomedical imaging laboratories, setting the goldstandard in image contrast and quality, the acquisition of an image point by point is inherently slow. To break through this speed barrier, Photon Force customers have used the PF32 to build the pioneering multibeam confocal microscope architecture: replacing the single beam and pinhole of a typical confocal microscope with an array of beamlets to rapidly scan the image plane. The returning points are aligned with the photosensitive areas of the SPAD array, which act as virtual pinholes, rejecting out of focus light. Since each beamlet and SPAD array pixel pair are fully independent and operate in parallel, the resulting system can accelerate confocal fluorescence lifetime microscopy by orders of magnitude.

As with conventional confocal microscopes, the output image resolution is dependent on the scan parameters and optics (and not the number of pixels of the sensor), allowing customers to capture stunning high-fidelity images at record speed.

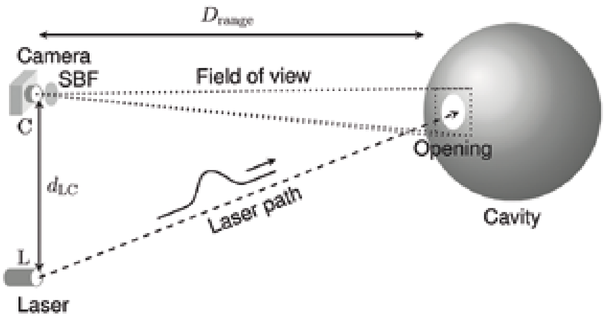




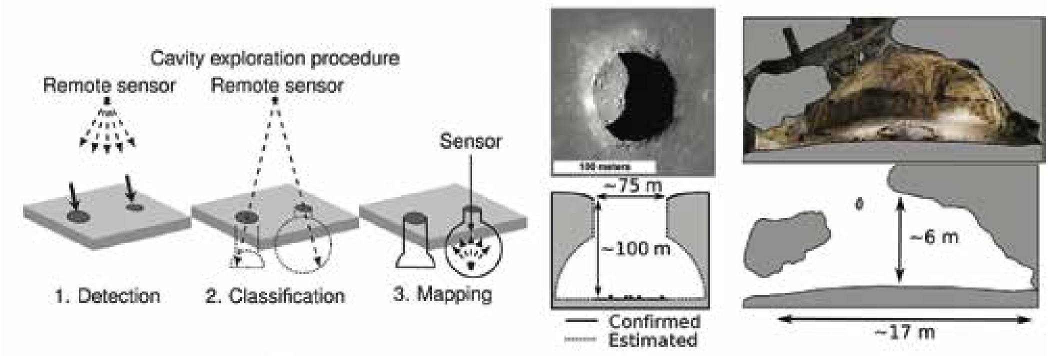
"A high speed multifocal multiphoton fluorescence lifetime imaging microscope for live-cell FRET imaging," Simon Poland *et al.*, Biomedical Optics Express, 6 (2), 277-296, 2015.

LiDAR and associated applications

With its ps accuracy timing, single photon sensitivity and high frame rate, the PF32 is an ideal sensor for LiDAR and other associated applications such as imaging through scattering media and non-line-of-sight (NLOS) imaging. In this section we share selected works from our customers who have published in these fields.



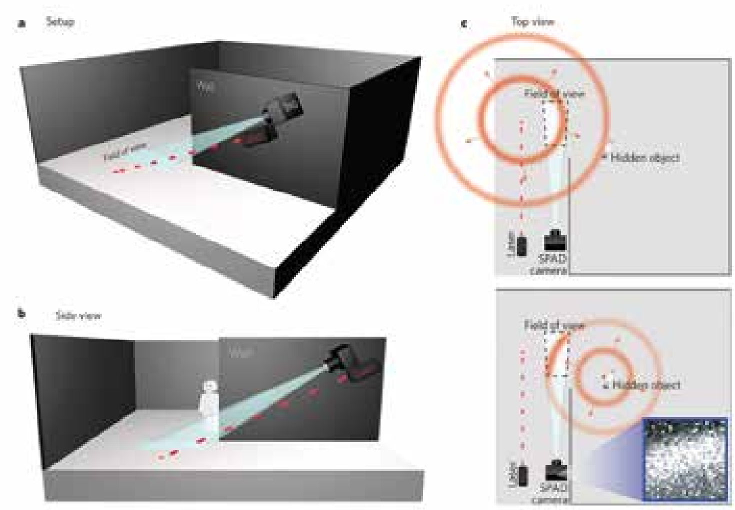
Imagine exploring new terrain and discovering what is hidden within a cavity without actually having to venture inside! Our friends at ISL wrote a fascinating paper on methods to do exactly this using time-correlated photon counting data. It relies on recording the arrival times of photons that exit after bouncing multiple times around the cavity, then using reconstructive techniques to form an estimate of cavity dimensions.



"Time-correlated single photon counting for evaluation of cavity dimensions with multibounce photons"
Martin Laurenzis *et al.* Journal of Applied Remote Sensing, Vol. 17, Issue 2, 024503 (April 2023).

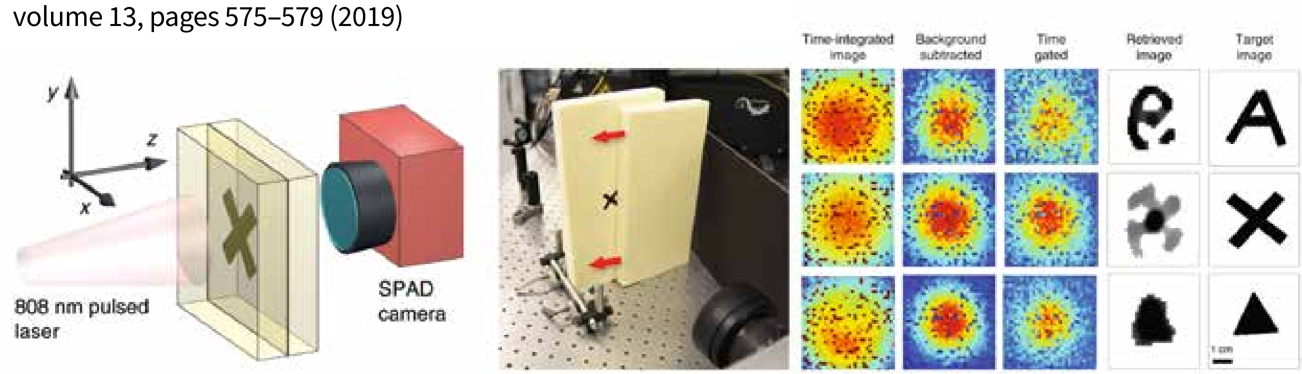
Photons that are detected after multiple bounces are also the key to tracking objects around corners and non-line-of-sight imaging. In the adjacent diagram the methodology is presented - a pulsed laser impinges on the floor where it is scattered in a spherical wave. This bounces back from the hidden object across the field of view of the camera, and the triplescattered photons are detected and timestamped by the PF32, allowing an accurate estimate of the object's position and motion in real time.

More recently, the PF32 has been used by researchers at Tsinghua University in a paper authored by Chengquan Pei *et al.* entitled "Dynamic nonline-of-sight imaging system based on the optimization of point spread functions" in Optics Express, Vol 29, issue 20 (2021).

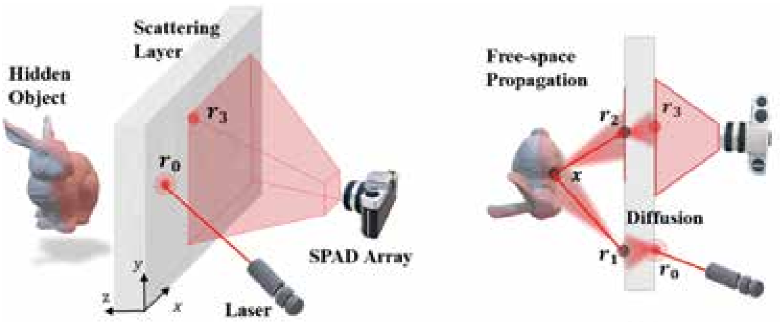


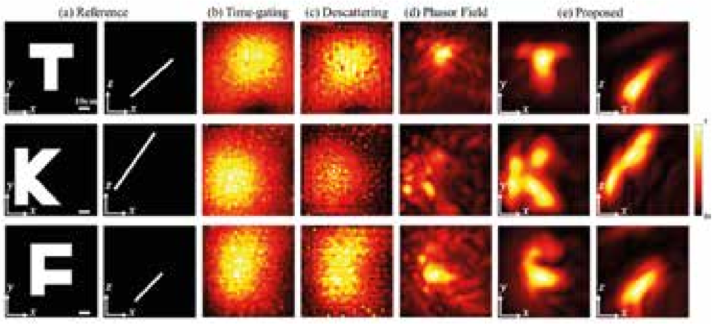
G. Gariepy *et al.*, "Detection and tracking of moving objects hidden from view" Nature Photonics, Volume 10, pages 23–26 (2016)

Computational techniques can exploit data to reveal the shape and form of objects concealed within solid materials, as demonstrated by researchers at the University of Glasgow. The shapes are placed between two highly-scattering materials. They were then able to reconstruct the shapes using the techniques detailed in "Computational time-of-flight diffuse optical tomography" by A. Lyons *et al.*, Nature Photonics volume 13, pages 575–579 (2019)



When measuring transmission is not possible, researchers at Tsinghua University have demonstrated methods to reconstruct 3D forms behind a scattering layer based on reflected TCSPC data with the PF32. You can read more about it in "Scan-free timeof-flight-based three-dimensional imaging through a scattering layer" by Rujia Deng *et al.* in Optics Express, volume 31, issue 14 (2023).





“Towards photography through realistic fog,” G. Satat *et al.*, 2018 IEEE International Conference on Computational Photography (ICCP), 2018, pp. 1-10.

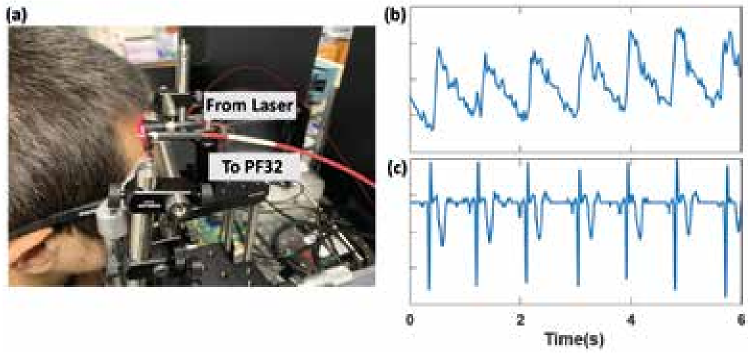
Researchers at MIT utilised the measurement capability of the PF32 camera to computationally remove inclement weather conditions such as fog, and produce a photo and depth map as if there were no fog present, with contrast improved by 6.5x in dense fog conditions.

Using the Photon Force PF32 to increase sensitivity for Diffuse Correlation Spectroscopy (DCS)

At Duke University, Wenhui Liu *et al.* use the Photon Force PF32 SPAD camera's high frame rates and photon counting mode to record single-photon images at over 300kfps.

The Duke University experiment showed real-time measurement of blood flow in human tissue. Image (a) shows the set up for the in vivo forehead blood flow and image (b) demonstrates the results using the Photon Force PF32. Image (c) validates the results by comparing them to results from a commercial electrocardiogram monitor.

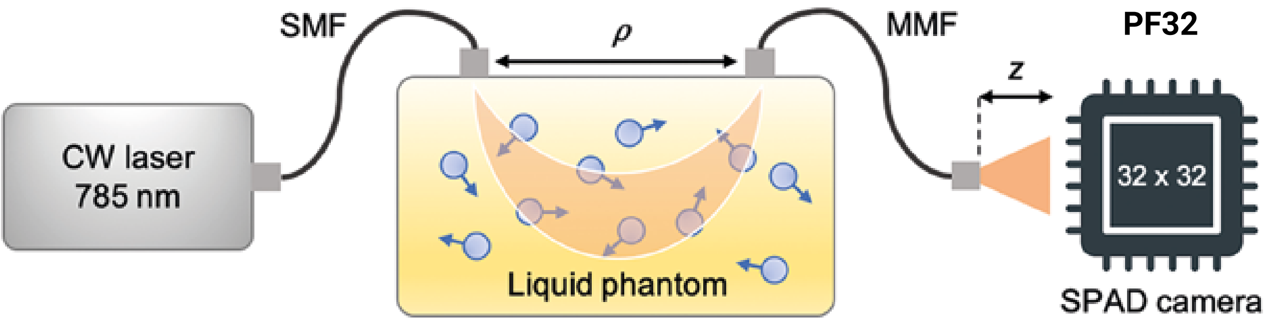
"Fast sensitive diffuse correlation spectroscopy with a SPAD array," W. Liu *et. al.*, in Biophotonics Congress: Biomedical Optics 2020 (Translational, Microscopy, OCT, OTS, BRAIN), OSA Technical Digest (Optical Society of America, 2020), paper SM3D.3.

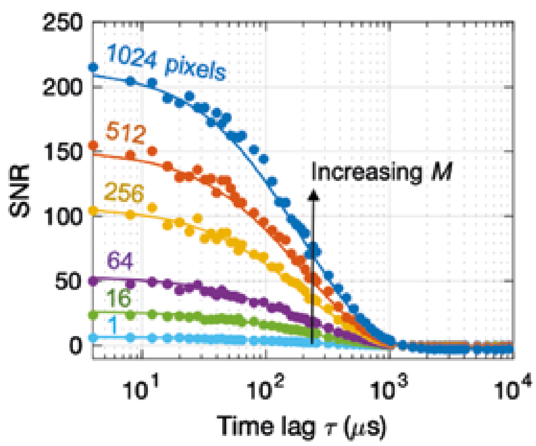


Can your brain communicate directly with a computer?

At Facebook Reality Labs, the team used the Photon Force PF32 camera, our customised firmware and multispeckle Diffuse Correlation Spectroscopy in an attempt to answer this question through their research on Brain-Computer Interfaces.

With a requirement to develop a scalable method of monitoring cerebral blood flow and measuring cortex functional activation tasks, the Facebook team turned to Photon Force for help with increasing the Signal-to-Noise Ratio (SNR). Using the Photon Force PF32 camera achieved this; facilitating a 32-fold increase to SNR. The ultimate goal is to create a brain/computer interface. You can read more about their work in the journal publication by E. Sie *et al.* in Neurophotonics, issue 7 (035010) from 2020.





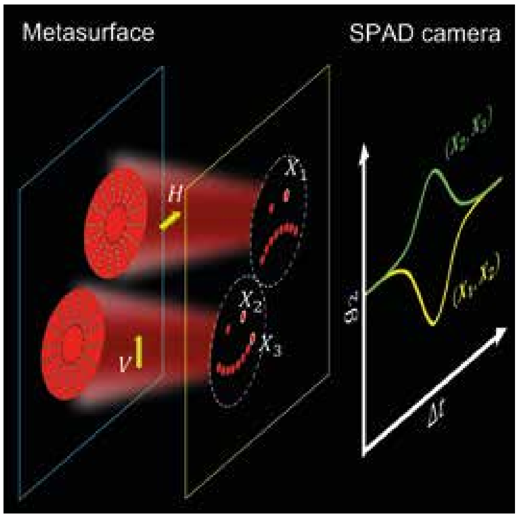
The PF32 in Quantum applications

Single photons are the fundamental building blocks enabling many quantum applications. From assessing multiple single-photon sources simultaneously (quantum dots or defects in diamonds) and quantum random number generation to quantum key distribution and quantum correlations, the PF32 can help advance and accelerate your research.

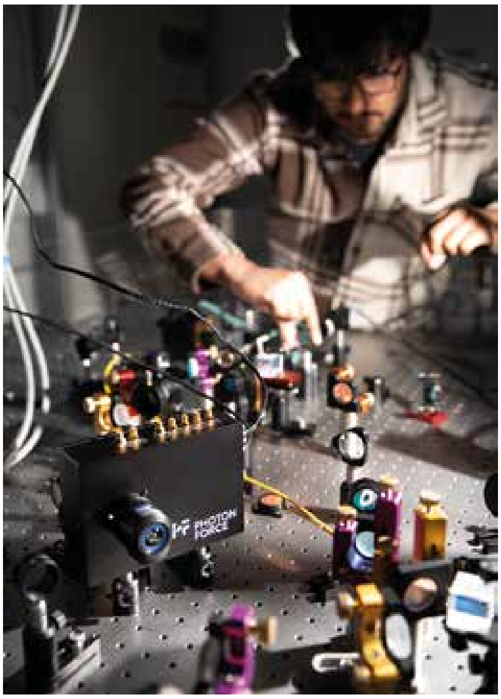
We have worked closely with researchers at Heriot-Watt University in Edinburgh where they are using the PF32 to perform free space optical quantum key distribution. You can read about their work by Cameron Simmons *et al.* entitled "An investigation of jamming in free-space quantum key distribution" in the proceedings of Quantum Technology: Driving Commercialisation of an Enabling Science III (2023).

HERIOT WATT UNIVERSITY

香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY



Researchers at the Hong Kong University of Science and Technology used the PF32 for their paper "Polarization coincidence images from metasurfaces with HOM-type interference", written by Tsz Kit Yung *et al.*, iScience vol. 25 (2022).



"Breaking the diffraction limit using fluorescence quantum coherence", by authors Wenwen Li *et al.*, Optics Express, 25 (2022) was fascilitated by the PF32's spatial and temporal TCSPC capabilities and is another demonstration of Photon Force products enabling new quantum measurements.

中國科学院
CHINESE ACADEMY OF SCIENCES

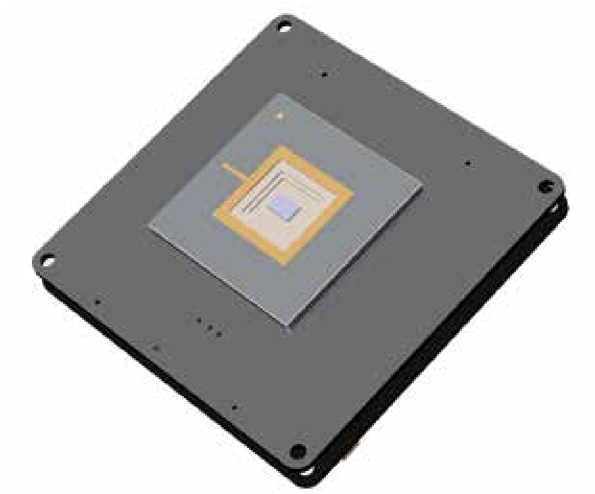
How can we help YOU in your single-photon sensing application?

PF32 Module for OEM Integration

Photon Force introduces new module-level products for use in OEM applications. Until now, Photon Force has sold SPAD camera technology solutions to customers in camera form, more suited to the R&D laboratory environment. Photon Force modules will allow system developers the opportunity to use a compact bare board solution with control over the configuration of the optical path to the sensor and direct connection to the host control system, such as a board level computer.

The module incorporates the sensor and a high capability FPGA, on a stacked pair of PCBs, and connection via an Oculink Connector (PCIe four lane interface).

Developers will normally use the PF32 camera as the first lab develoment vehicle for their projects and then move to implementation of a production solution once core performance criteria are met. Photon Force will work closely with customers to help optimise cost and the distribution of functionality between the camera subsystem and the host application computer and interface system, finding best utilisation of the module's FPGA and the sensor's control system.



KEY SPECS (MODULE)

	PF32
General:	
Form Factor	Dual PCB Stack
Sensor PCB	CPGA Sensor PCB
Comms/Processing PCB	FPGA for processing and host connectivity
On-Module Processing	Histogramming of sensor data
Connectivity	PCIe (Gen 2, x4) via Oculink Connector (SFF-8611)
Timing Signals	UF.L Connector for TCSPC Syncronisation
Host Connectivity Bandwidth	16 Gbps
Power	12V @ 650mA Max over dedicated power connector
Mechanical	Module Dimensions 80mm x 80mm x 25mm Mounting Holes: M3 x4
Optical	Option for mounting lens on sensor PCB
In-module histogramming parameters:	
Histogramming channels	1,024 (one per pixel)
Bins per channel	1024 bins
Bin depth	Between 6 to 48, Application dependent

PF32 Camera Specifications

Sensor Dimensions

Array Size	32 × 32 pixels 1.6 × 1.6mm
SPAD active area (diameter)	6.95µm
Pixel pitch	50µm
Optical fill factor	1.5%
MLA Optical fill factor	Up to 20%

Optical/Electrical Performance

Photodetection efficiency	Peak 28% at 500nm
Dark count rate	<100cps for more than 80% of pixels
Afterpulsing	<0.02%
Optical/Electrical crosstalk	None
Timing jitter	≤200ps FWHM

Photon Counting Mode

Photon counting	7 bit in-pixel 16 bit in firmware
Maximum count rate per pixel	20Mcps

Time Correlated Mode

Temporal bin	55ps
Temporal range	55ps - 57ns
TDC resolution	10 bit
Maximum laser sync frequency	100MHz
Laser sync input amplitude	User programmable
Laser sync input polarity	User programmable
Laser sync output amplitude	3.3V

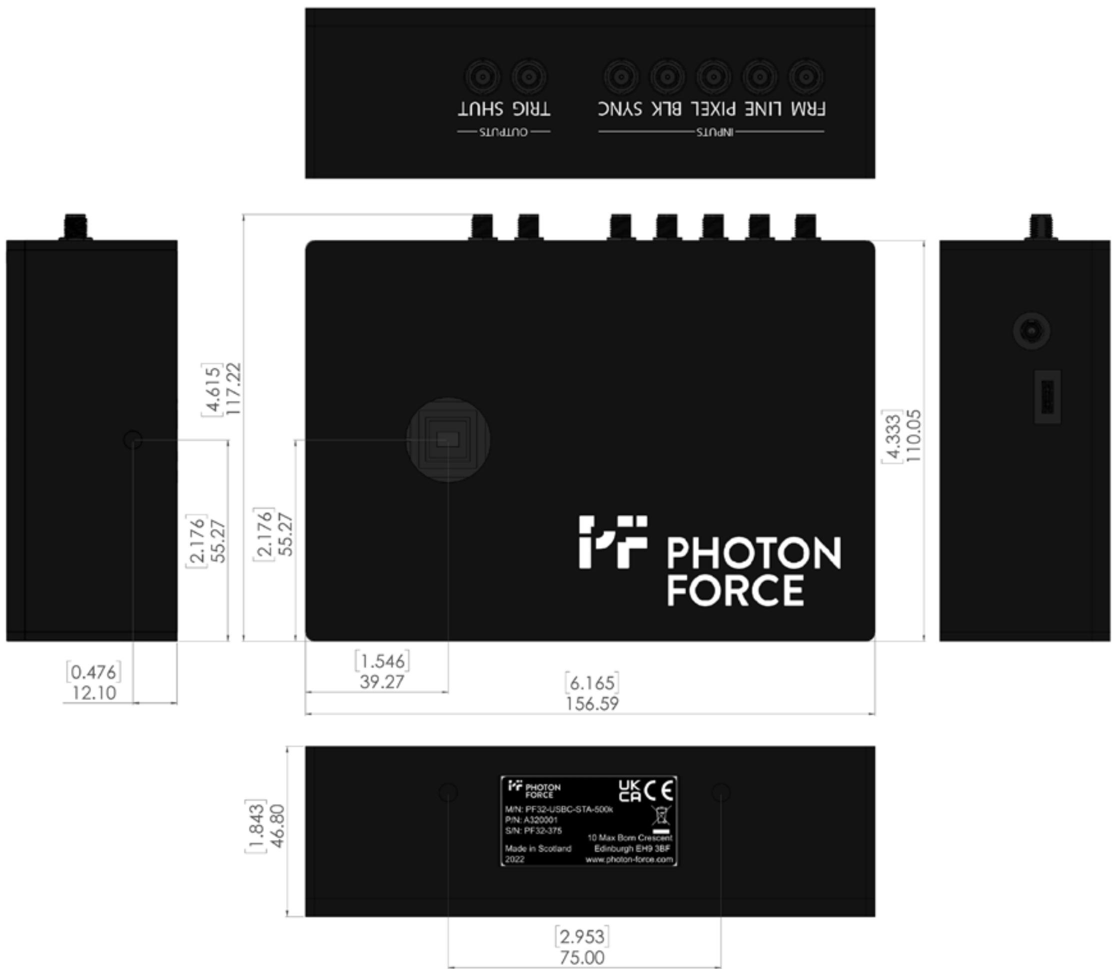
Readout & Control

Raw data streaming rate to PC	
PF32-Lite	50kfps
PF32-Core	150kfps
PF32-Ultra (*export licence controlled*)	Up to 714kfps
Inter-frame dead time	<50ns
X/Y scanner sync input signals	Pixel, line and frame clock
Exposure sync signals	Blanking (3.3V / 5V input) Shutter (3.3V output)

Camera is supplied with: manual, test data sheet, USB cable, power supply and aluminium travel case.

PF32 Order Codes

	Standard	Microlensed
Lite	PF32-USBC-STA-Lite	PF32-USBC-MLA-Lite
Core	PF32-USBC-STA-Core	PF32-USBC-MLA-Core
Ultra	PF32-USBC-STA-Ultra	PF32-USBC-MLA-Ultra



What our clients say:

"The camera is truly a transformative technology that has allowed us to use the picosecond timing resolution to take ultrafast imaging and LiDAR applications to the next level."
- Prof. Daniele Faccio, University of Glasgow

"A paradigm shift in the acquisition of fluorescence lifetime data... There is no longer a need to compromise between accuracy, speed, and spatial resolution."
- Dr. Simon Poland, King's College London

"The high temporal resolution of the SPAD camera by Photon Force makes it a unique tool to explore new science and technology in a single-photon LiDAR, non-line-of-sight imaging and so forth."
- Prof. Feihu Xu, University of Science and Technology of China

"The PF32 SPAD array's single-photon sensitivity and high frame readout opens up new and exciting possibilities for deep-tissue biophotonic measurement. The array's thousand plus detectors greatly enhances standard methods of diffusive light measurement, such as diffuse correlation spectroscopy, and takes biomedical optical measurement to the next level."
- Prof. Roarke Horstmeyer, Duke University

Customers and Partners

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