Applications of depth imaging based on time-correlated single-photon counting

HERIOT WATT UNIVERSITY

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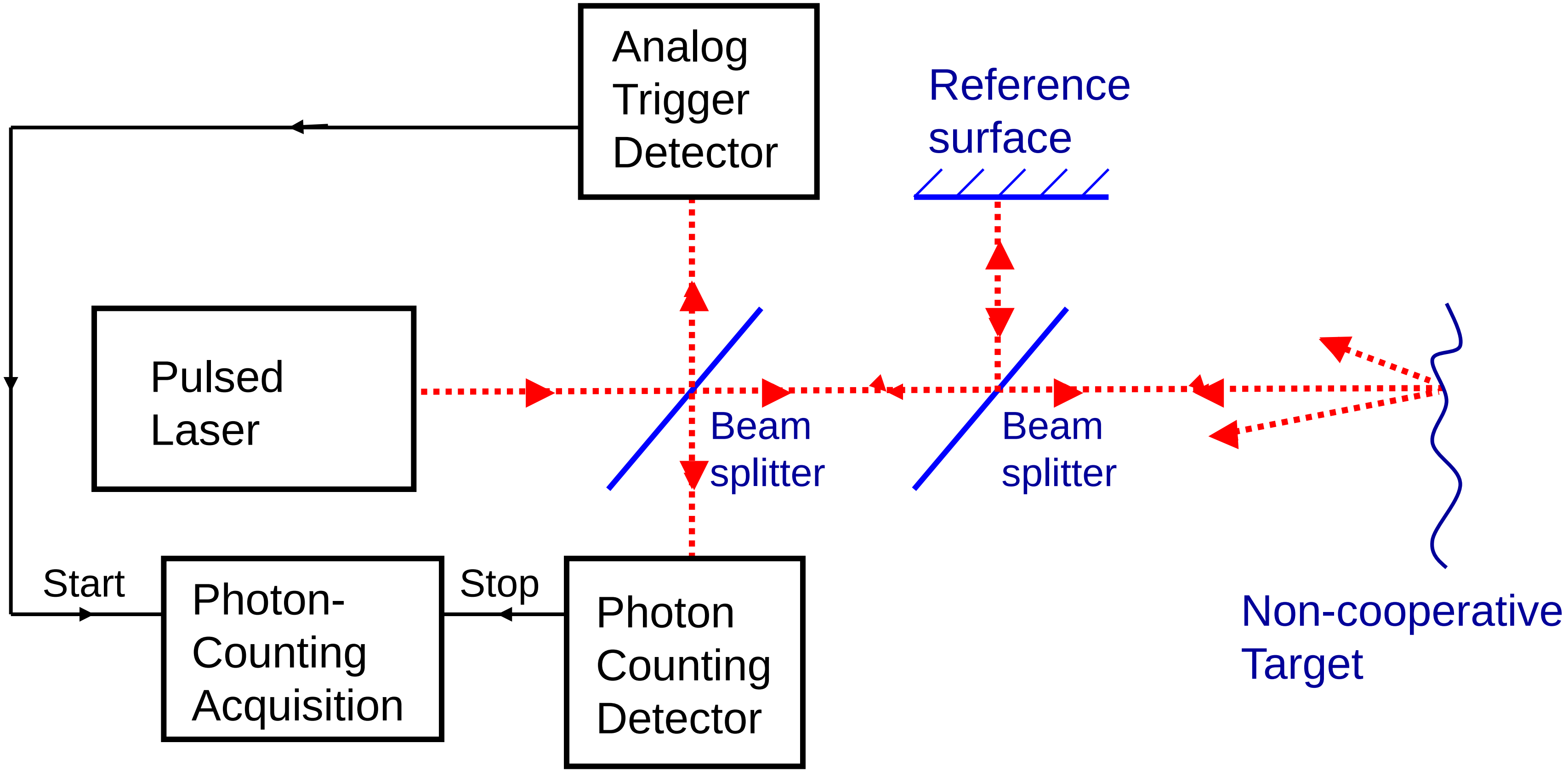
Introduction

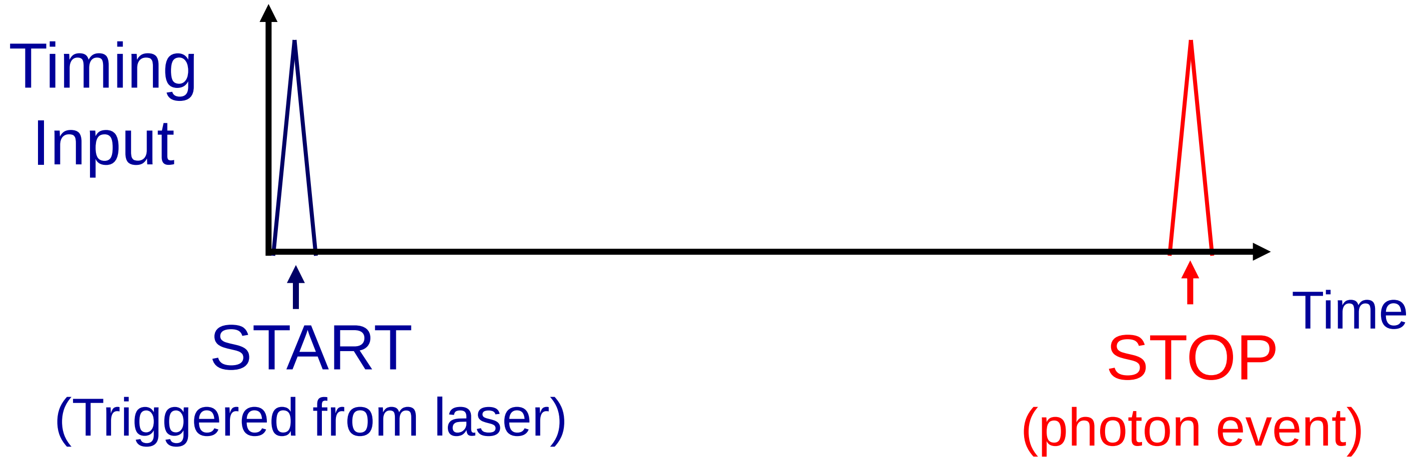
- Photon counting time-of-flight principles
- Scanning photon-counting depth imagers (λ ~ 850nm)
- λ ~ 1550nm photon-counting depth imaging using SNSPDs and InGaAs/InP SPAD detectors
- Multiple wavelength depth imaging
- Imaging using arrayed detectors

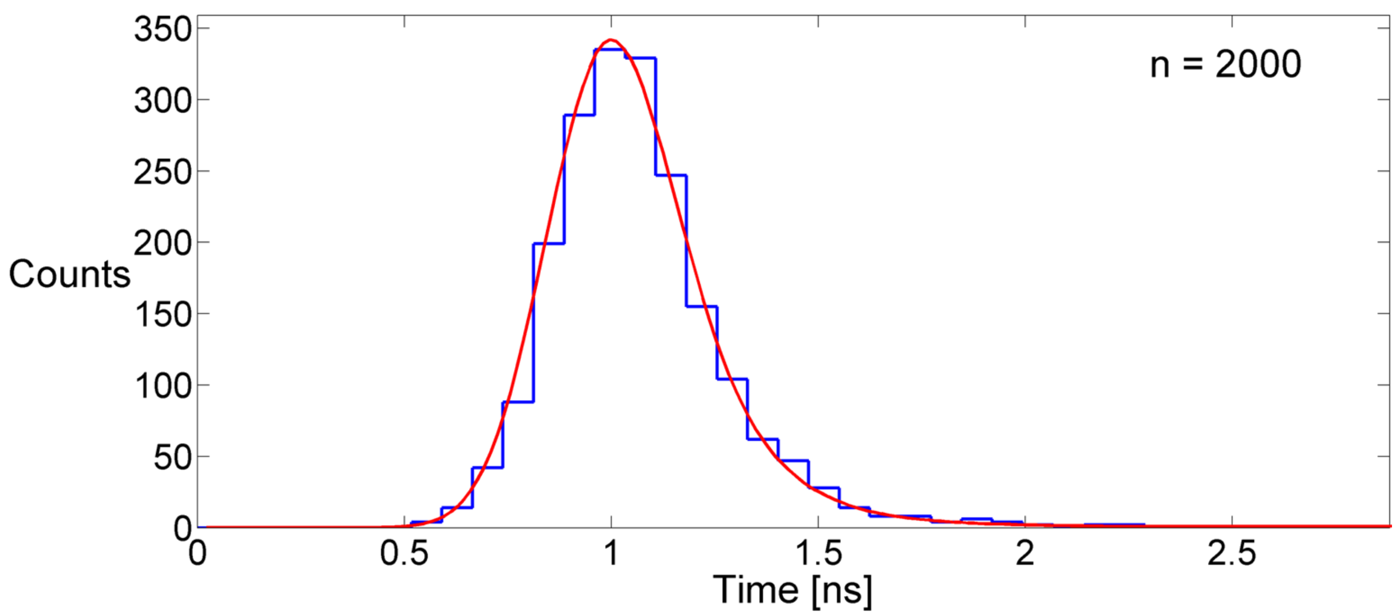
Time-of-Flight Measurements using Time-Correlated Single-Photon Counting



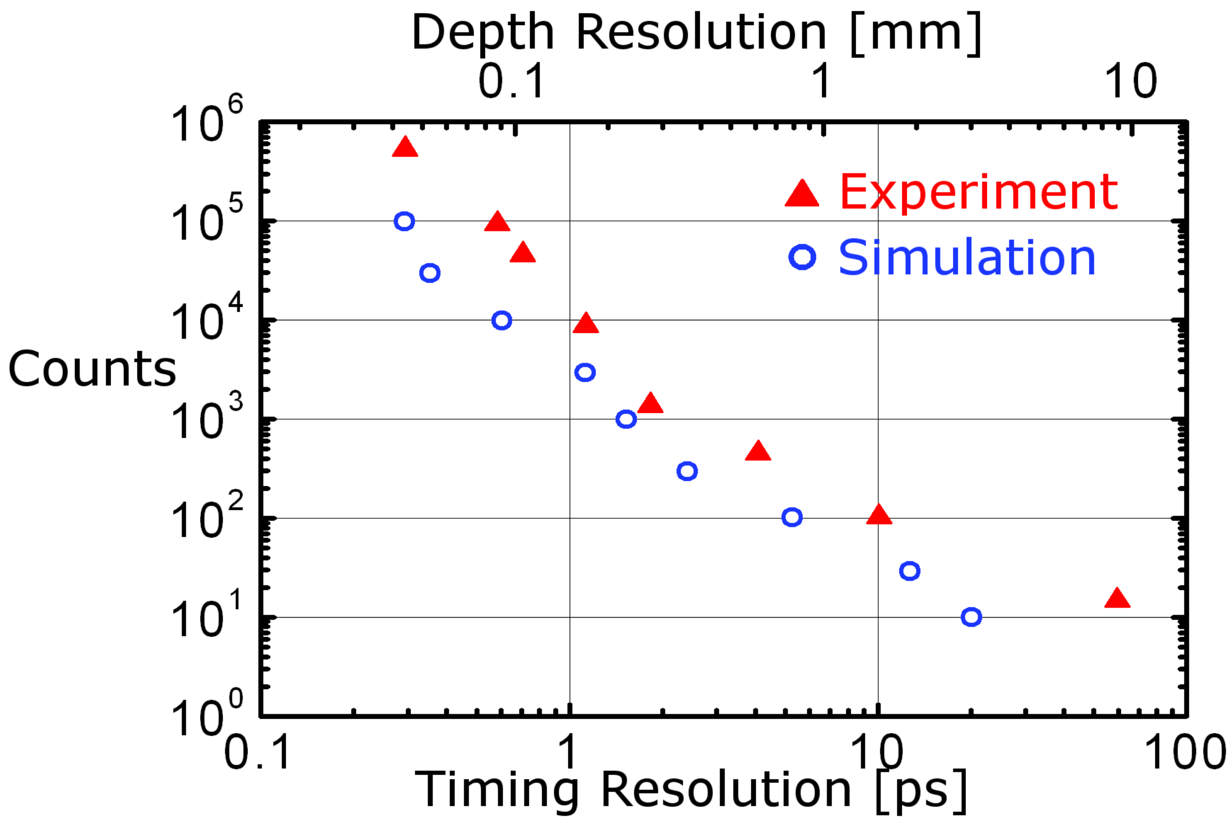
JS Massa, AM Wallace, GS Buller, SJ Fancey and AC Walker "*Laser depth measurement based on time-correlated single photon counting*" Optics Letters, **22**, p543 (1997)

Time-Correlated Single-Photon Counting





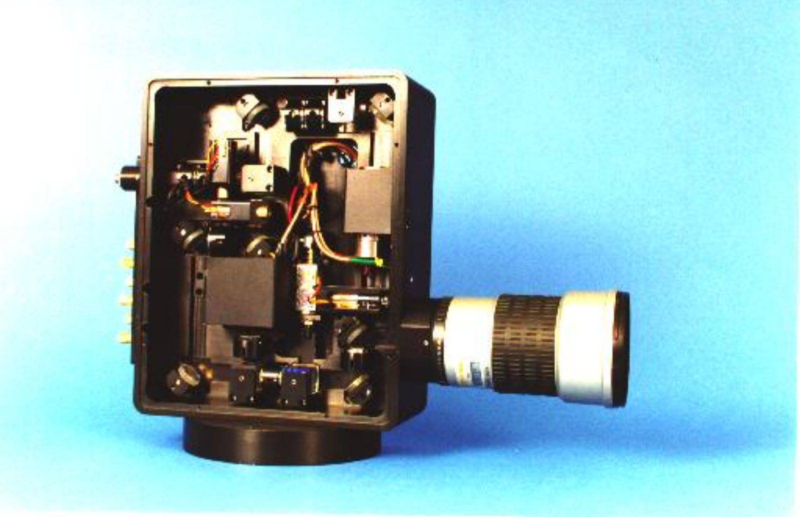
Depth Resolution of Time-Correlated Single-Photon Counting



- System Jitter: 50 ps
- Range: 30 metres (indoors)

S. Pellegrini, G.S. Buller, J.M. Smith, A.M. Wallace, S. Cova "*Laser-based distance measurement using picosecond resolution time-correlated single-photon counting*" Measurement Science and Technology, **11**, (6) pp712-716 (2000)

First Photon-counting Depth Imaging System Indoor, Short-range (1997-2002)



- Short range (< 50 metres)
size 250 x 200 x 100mm

- λ ~ 850nm, 25MHz rep. rate
passively Q-switched
semiconductor laser, ~pJ per pulse

- Shallow-junction Si-SPAD.
Instrumental response ~ 50-75ps FWHM

- Optical head weighed 5kg and included laser, detector, input/output lenses and all routing optics.

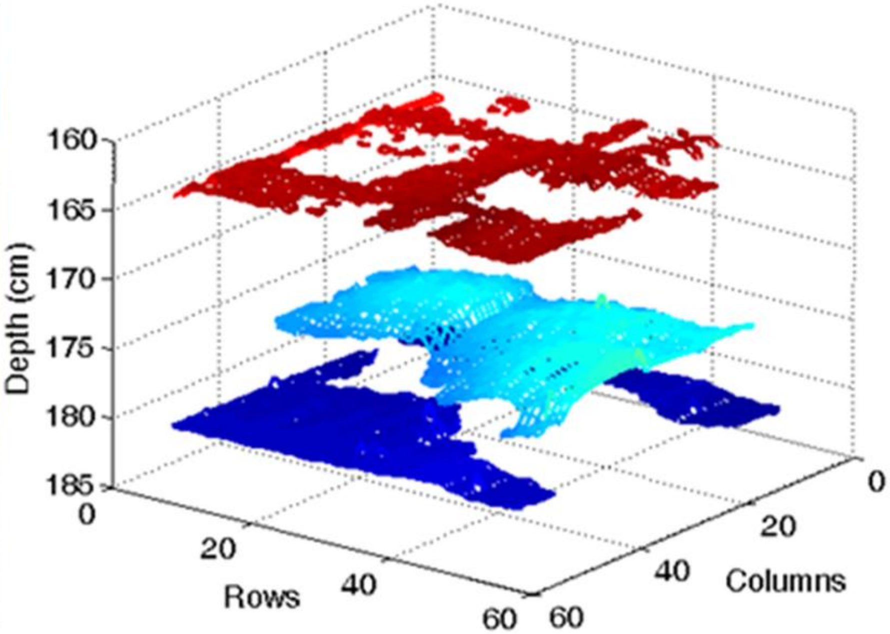
- Tested in aerospace manufacture, in partnership with Sowerby Research Centre, British Aerospace

J.S.Massa, G.S. Buller, A.C. Walker, S. Cova, M. Umasuthan, and A.M. Wallace
Time-of-Flight Optical Ranging System Using Time-Correlated Single Photon Counting
Applied Optics, **37**, pp7268-7304 (1998)

Why Photon Counting Depth Imaging?

Multi-surface resolution / Imaging through clutter

Example – cat in a perspex box (2 metres range)

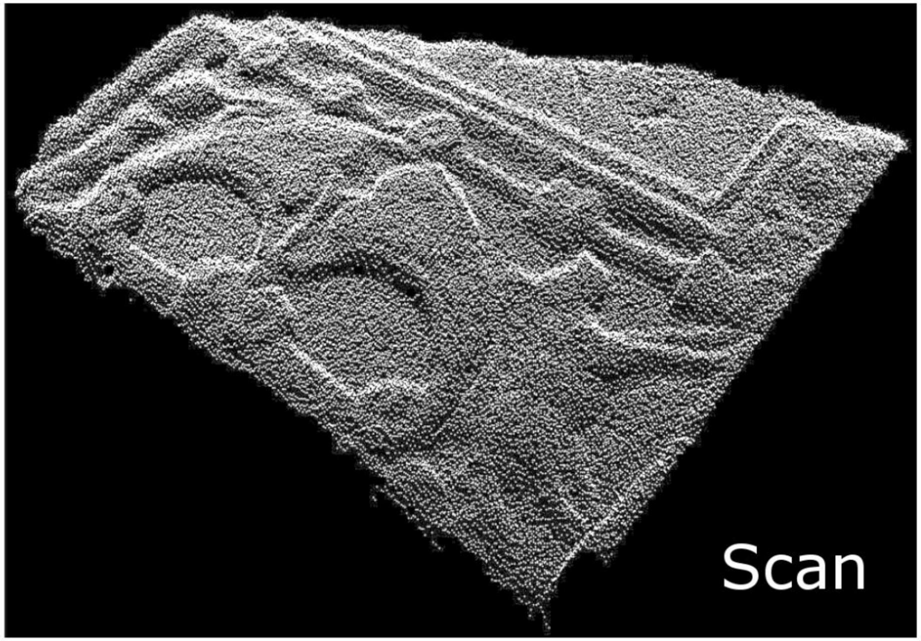


G.S. Buller and A.M. Wallace, "*Recent advances in Ranging and Three-Dimensional imaging using time-correlated single-photon counting*", Journal of Selected Topics in Quantum Electronics, **13**, pp1006-1015, (2007)

Why Photon Counting Depth Imaging?

Depth precision at low light levels – few µW's average power

example Roman frieze (National Museum of Scotland, Edinburgh)

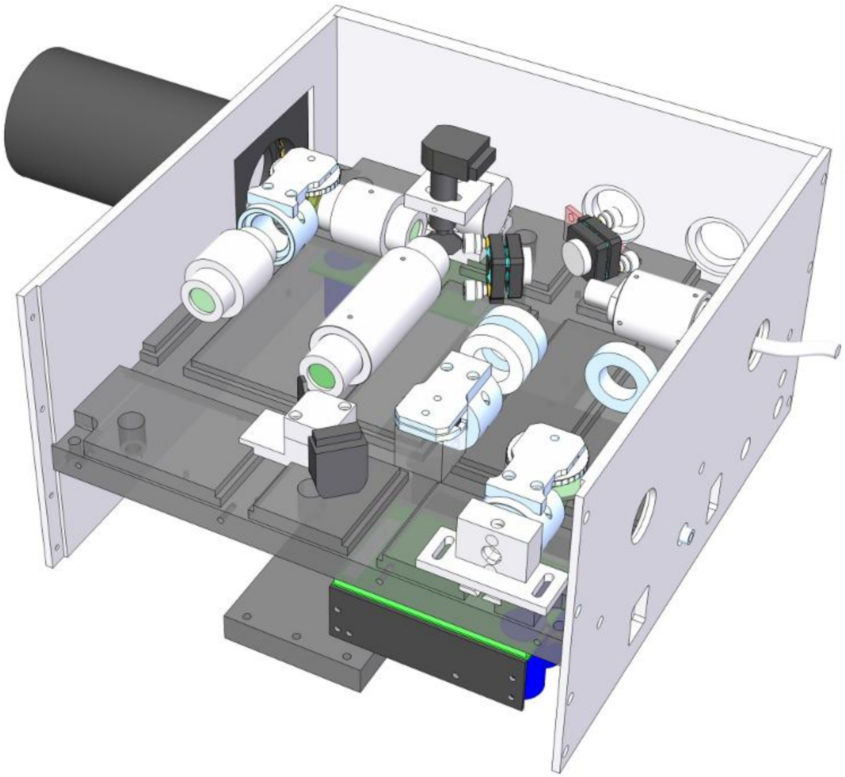


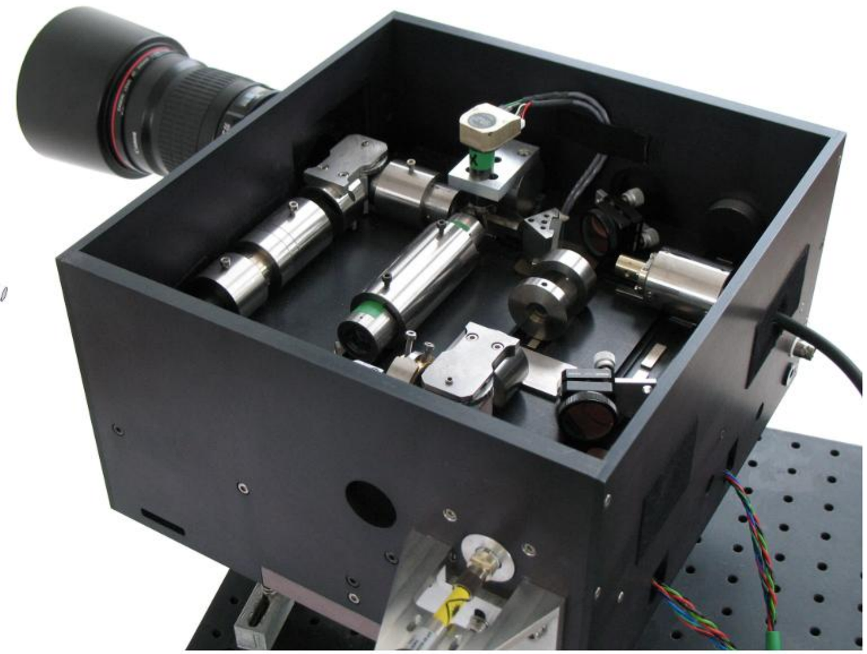
► Depth resolution: 50 µm, Spatial resolution: ~60 µm, Range: 2 metres

G.S. Buller and A.M. Wallace, "*Recent advances in Ranging and Three-Dimensional imaging using time-correlated single-photon counting*", Journal of Selected Topics in Quantum Electronics, **13**, pp1006-1015, (2007)

Long-distance scanning depth imaging system

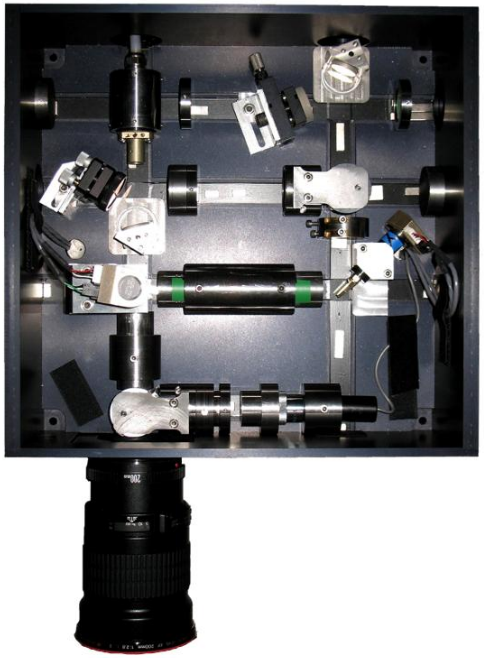
Transceiver (275×275×170 mm)

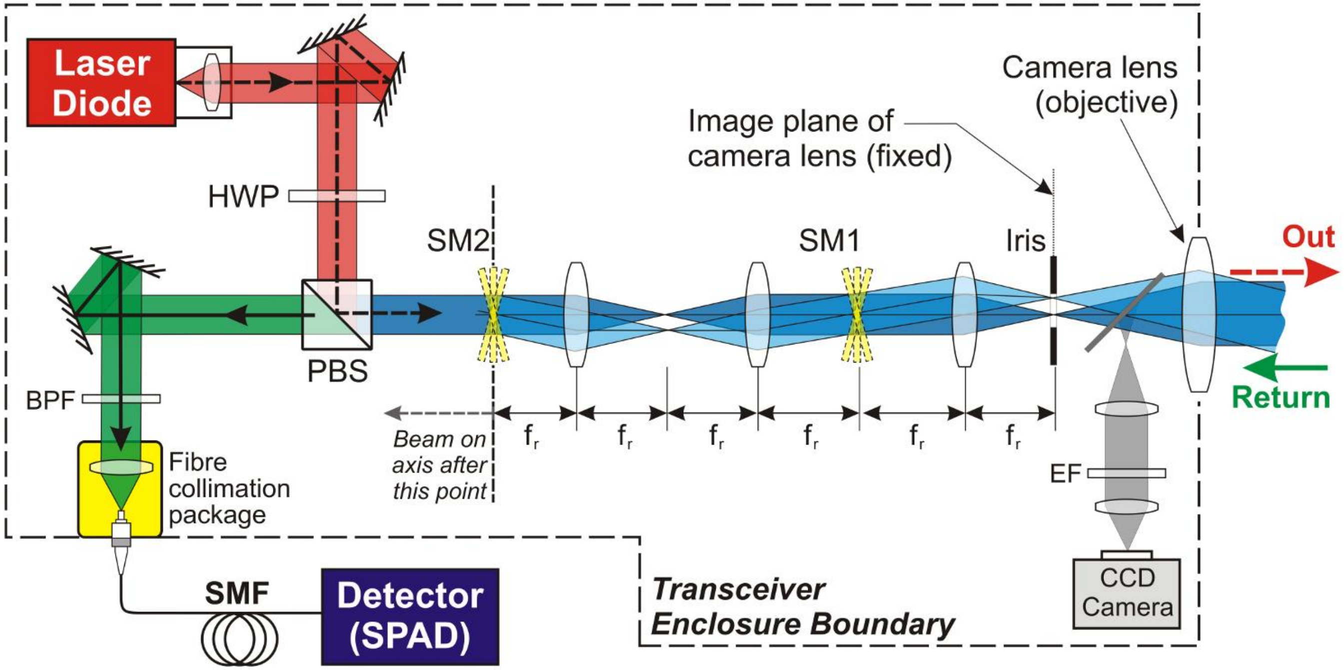




► Modular system – testbed for new components.

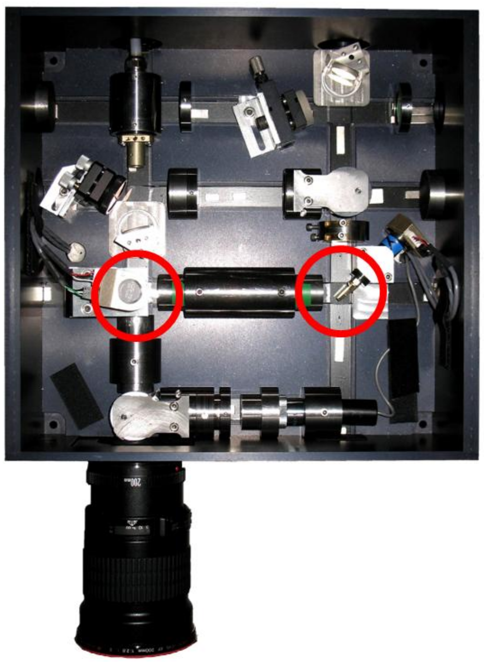
Depth imager optical layout for λ ~ 850nm

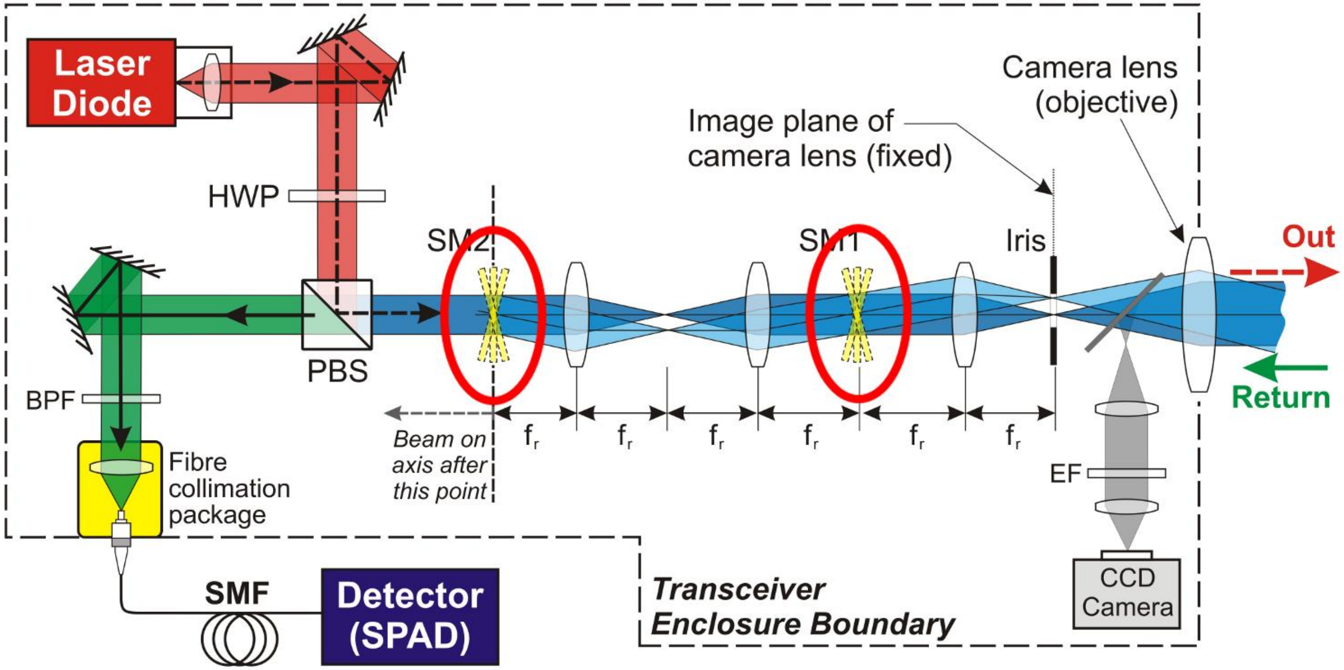




A. McCarthy, R.J. Collins, N.J. Krichel, V. Fernández, A.M. Wallace and G.S. Buller, "*Long-range Time-of-flight Scanning Sensor based on High-speed Time-correlated Single-photon Counting*" Applied Optics, **48**, pp. 6241–6251 (2009)

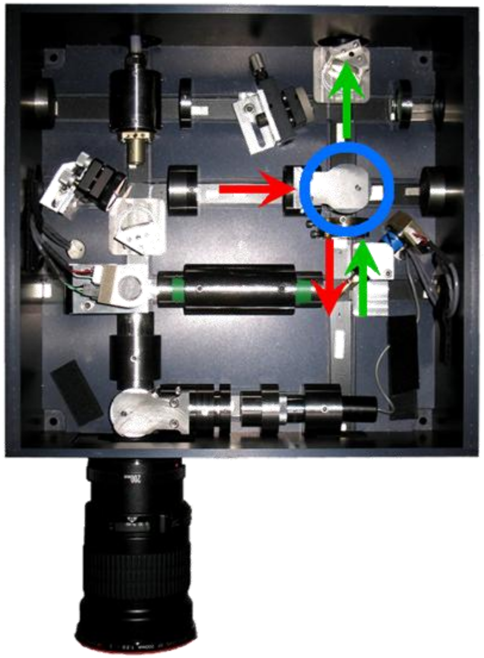
Depth imager optical layout for λ ~ 850nm

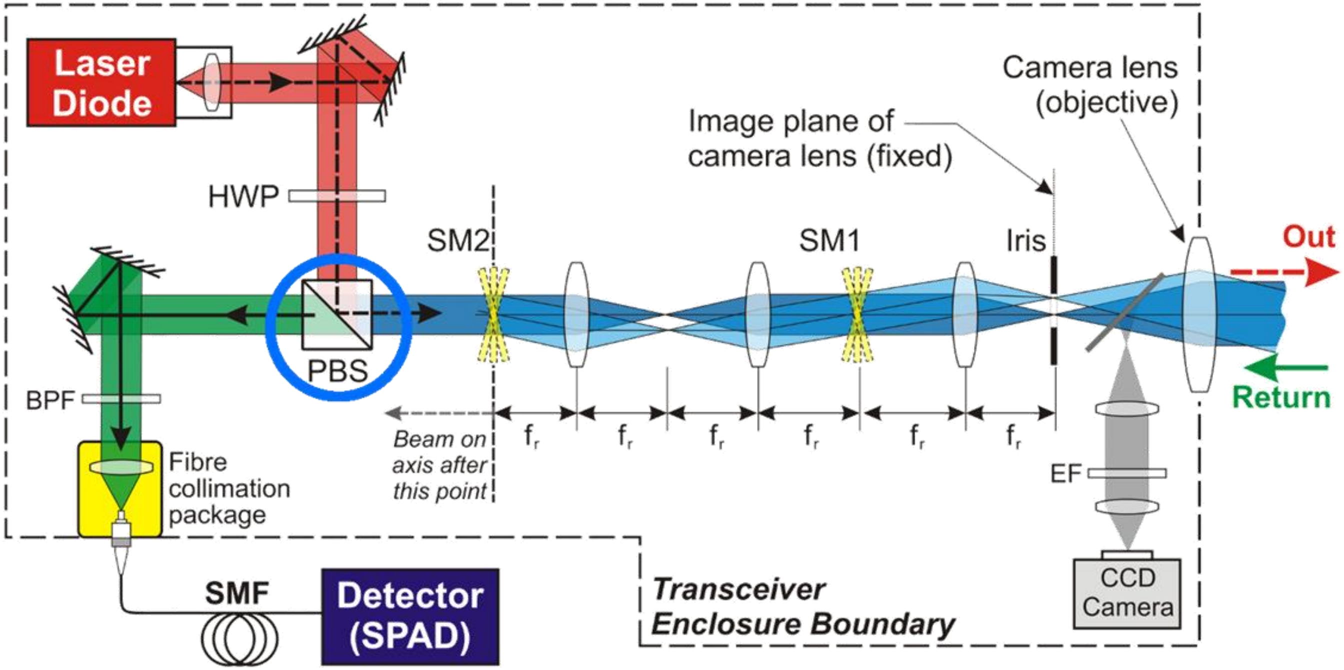




► Galvanometer mirrors steer common transmit and receive beam path

Depth imager optical layout for λ ~ 850nm

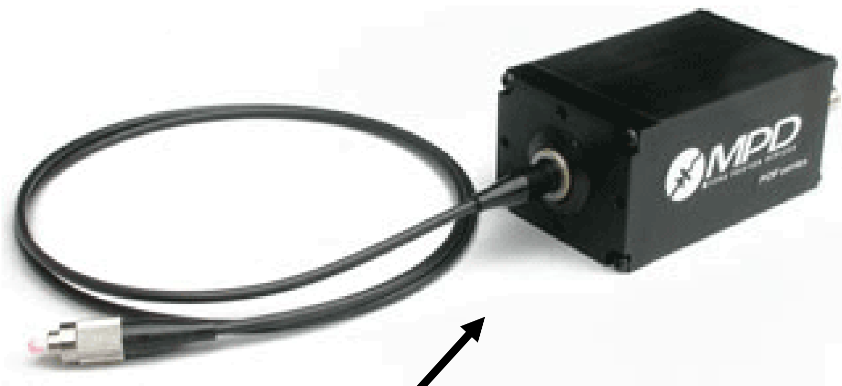




► Galvanometer mirrors steer common transmit and receive beam path.

► Polarising optics split channels

Silicon Single-photon Avalanche Diode (SPAD) detectors (500nm < λ < 1000nm)

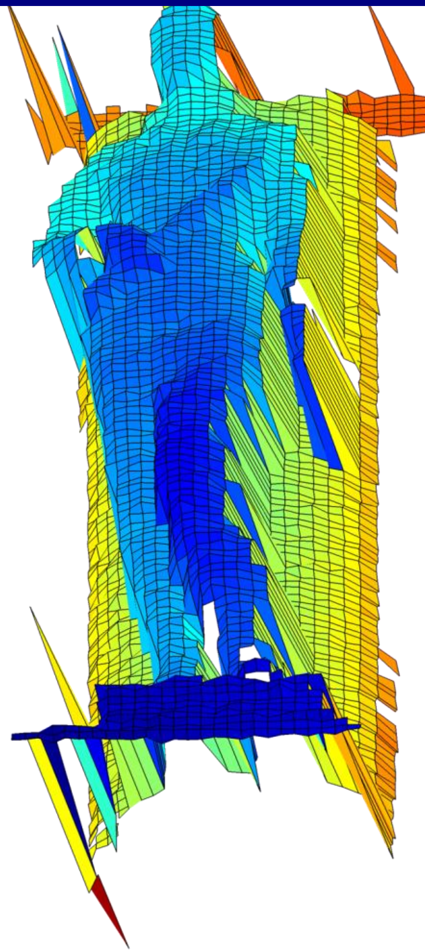


Thin Junction Si-SPAD
(active area ~50µm)

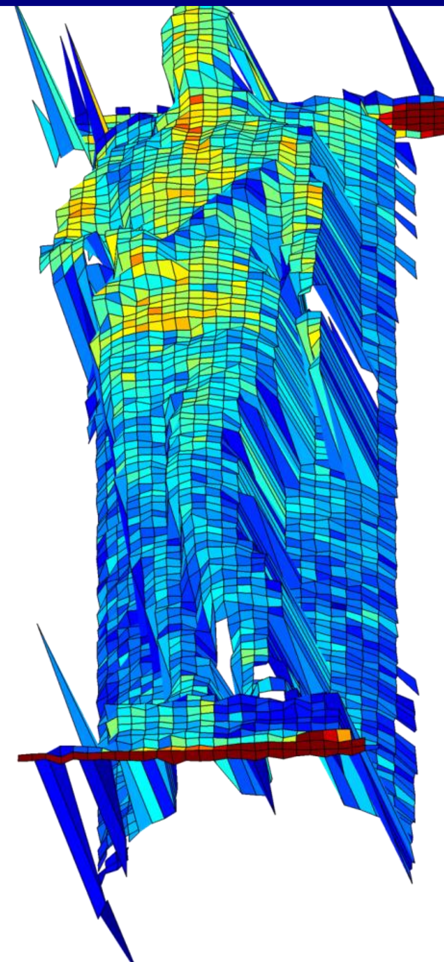
Thick Junction Si-SPAD
(active area ~180µm)

http://optoelectronics.perkinelmer.com/content/Datasheets/DTS_SPCMAQRH.pdf
http://www.micro-photon-devices.com/

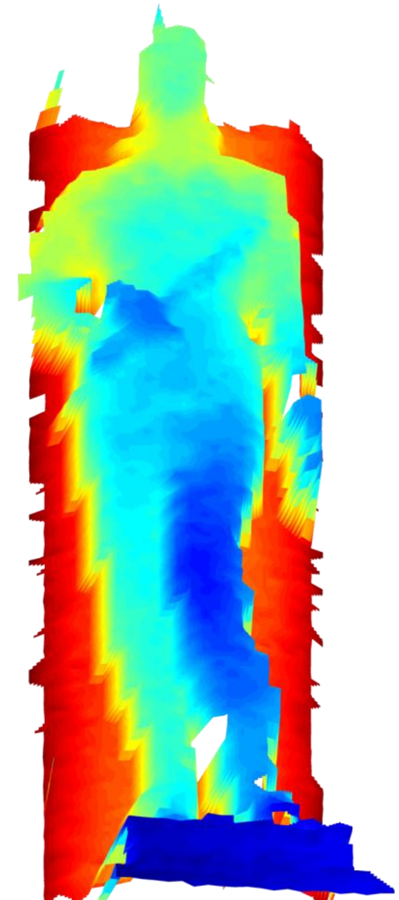
Mannequin Scan at 325 metres for λ ~ 850nm (32 x 128 scan, 2.5 mrad x 5.5 mrad)



Colour = Depth



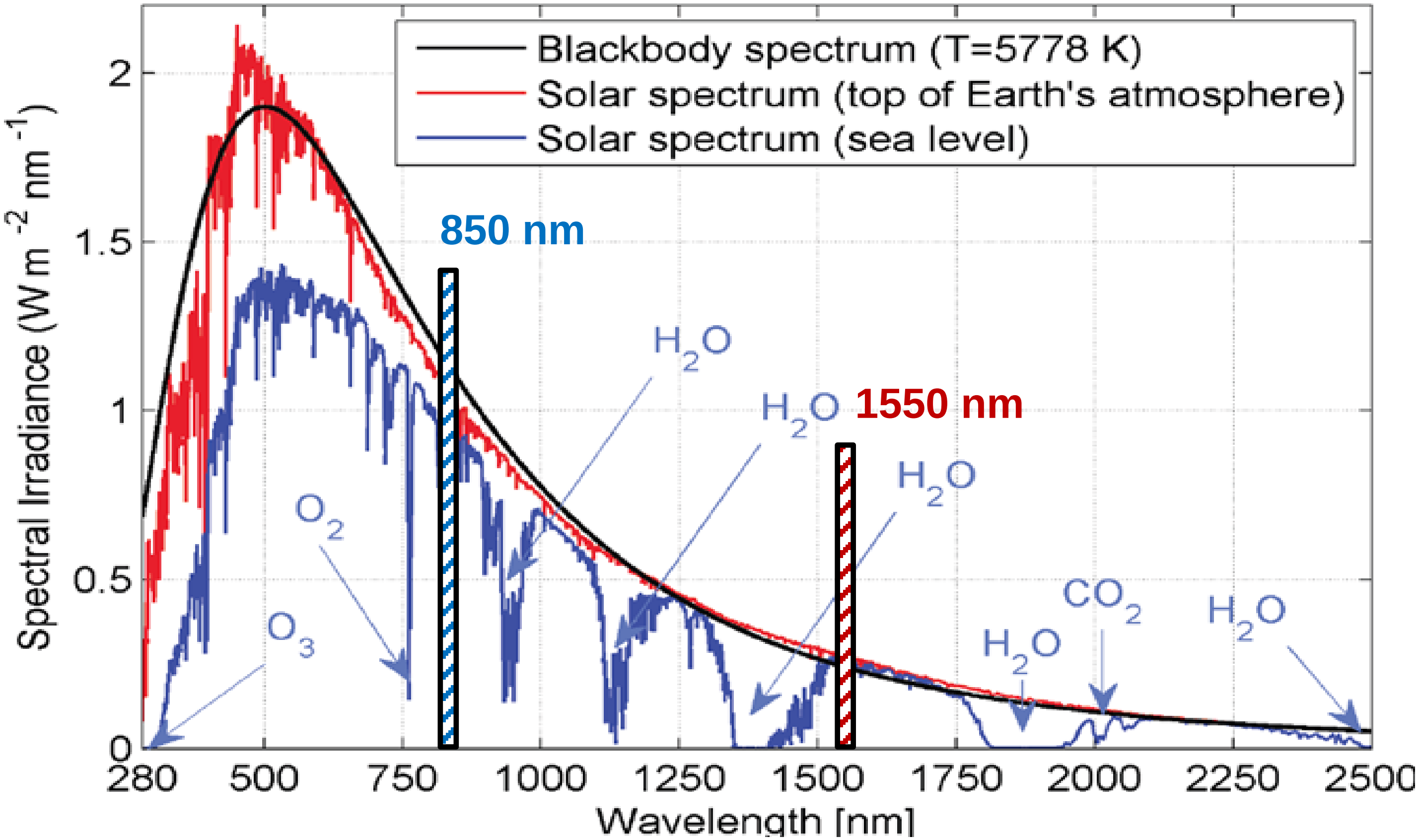
Colour = Intensity



Spatial interpolation colour = depth

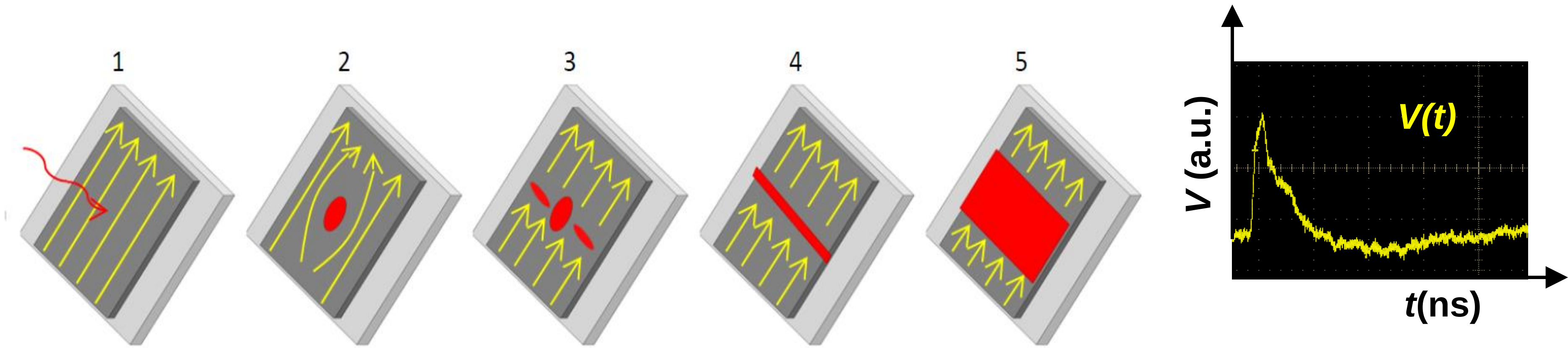
A. McCarthy, R.J. Collins, N.J. Krichel, V. Fernández, A.M. Wallace and G.S. Buller, "*Long-range Time-of-flight Scanning Sensor based on High-speed Time-correlated Single-photon Counting*" Applied Optics, **48**, pp. 6241–6251 (2009)

Wavelength considerations - solar background spectrum

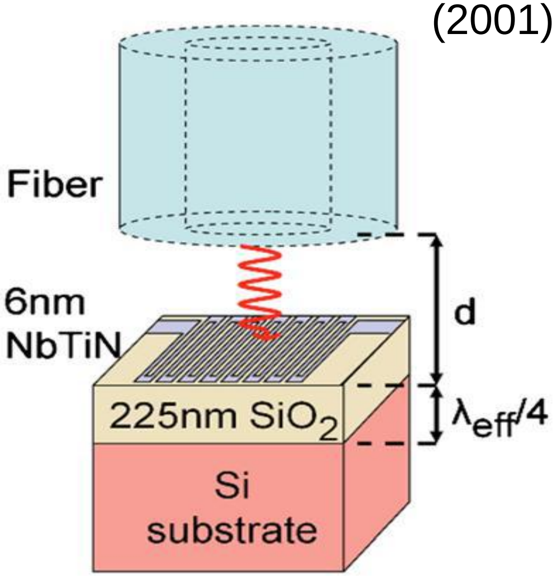


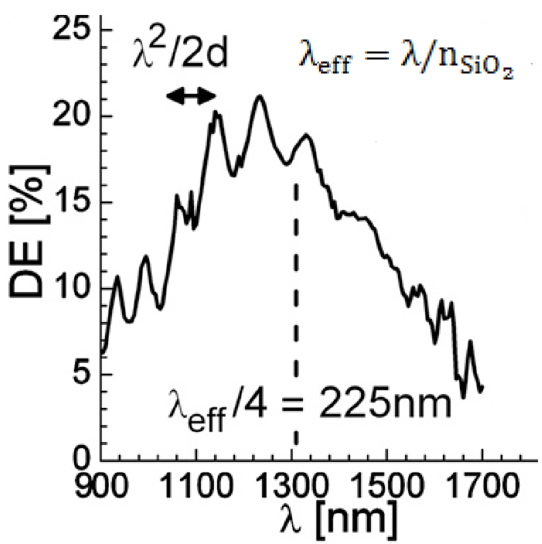
Operational wavelength is chosen to take account of detector efficiency, solar background and atmospheric attenuation

Superconducting Nanowire Single-Photon Detectors (operate at ~3K, λ ~ 1550nm)



Gol'tsman, G. N. *et al* Appl. Phys. Lett. **79**, 705 (2001)



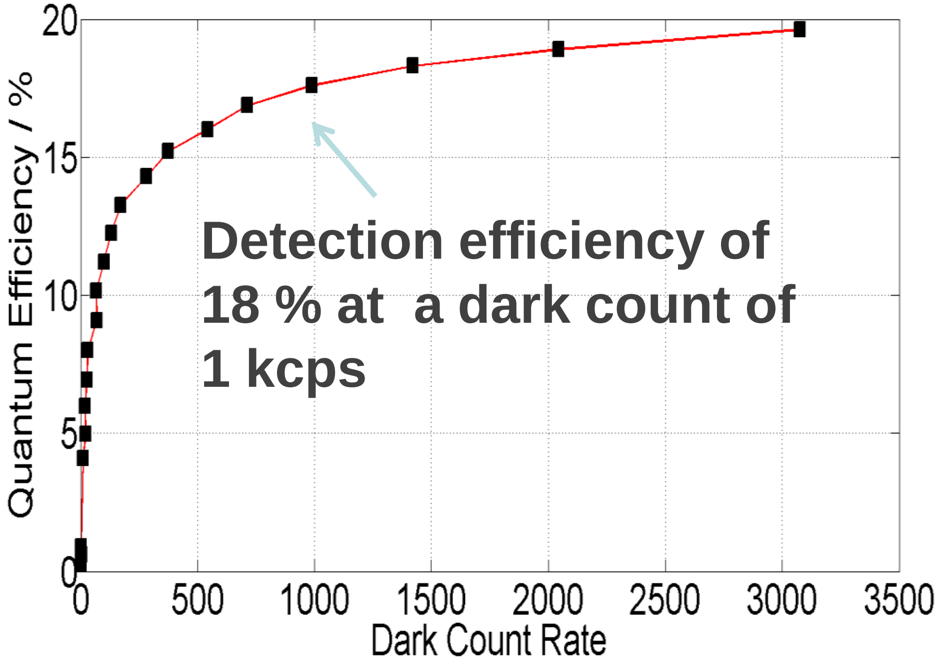


- Optical structure designed for enhancement of short infrared wavelength operation
- SNSPDs provided by TU Delft
- Packaged at Heriot-Watt

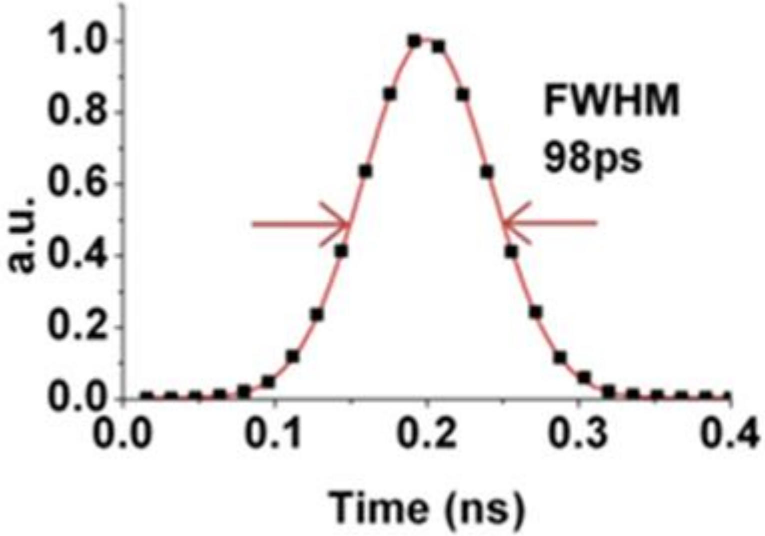
NbTiN Superconducting Nanowire Single-Photon Detectors

- High single-photon detection efficiency at λ = 1560 nm
- Low dark count rate

- Free running (not electrically-gated)
- Low timing jitter with an almost Gaussian temporal profile



System Temporal Response



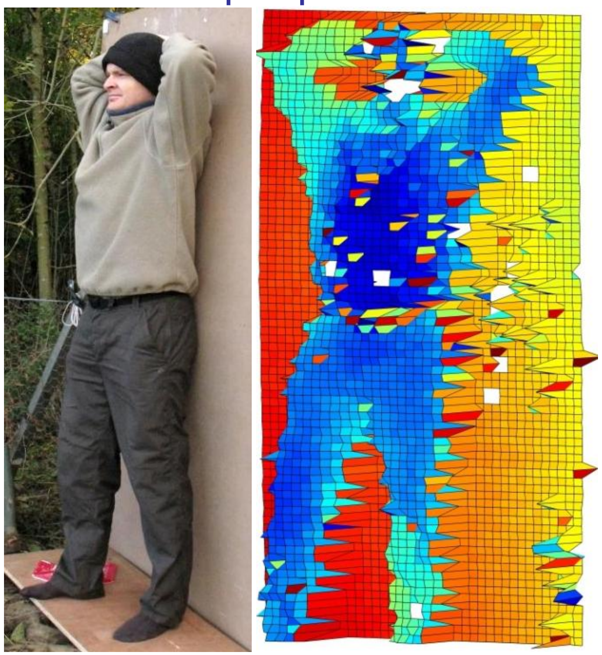
Hadfield, R.H. Nature Photonics **3**,696 (2009)

Chandra M. Natarajan *et al.* Supercond. Sci. Technol. **25**, 063001 (2012)

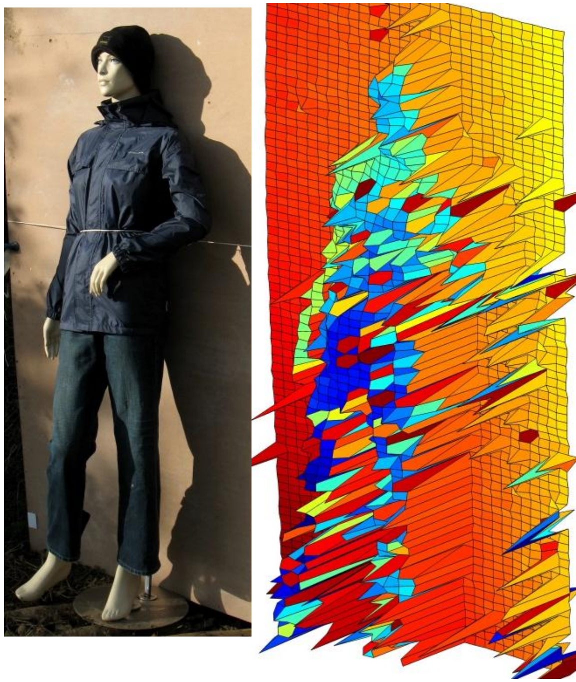
Depth profile at a stand-off distance of 910 metres using SNSPD
(average laser power < 250µW, λ ~ 1560nm)

Dwell time per pixel of **50 ms**

Dwell time per pixel of **10 ms**



Dwell time per pixel of **5 ms**



A pixel-to-pixel spacing of ~25 mm in x and y

A scan of a retro-reflective flat panel, using a per-pixel acquisition time of 10 ms resulted in a depth uncertainty of 1.1 mm (i.e. timing resolution: 7.3 ps)

A. McCarthy, N.J. Krichel, N.R. Gemmell, X. Ren, M.G. Tanner, S.N. Dorenbos, V. Zwiller, R.H. Hadfield and G.S. Buller, “*Kilometer-range, high resolution depth imaging via 1560 nm wavelength single-photon detection”,* Optics Express, **21**, No. 7, pp 8904-8915 (2013)

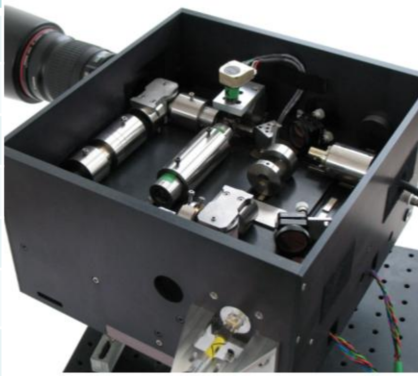
Gated InGaAs/InP SPAD Detector (operates at ~ 230K, λ ~ 1550nm)

Electrically gated InGaAs/InP SPAD module

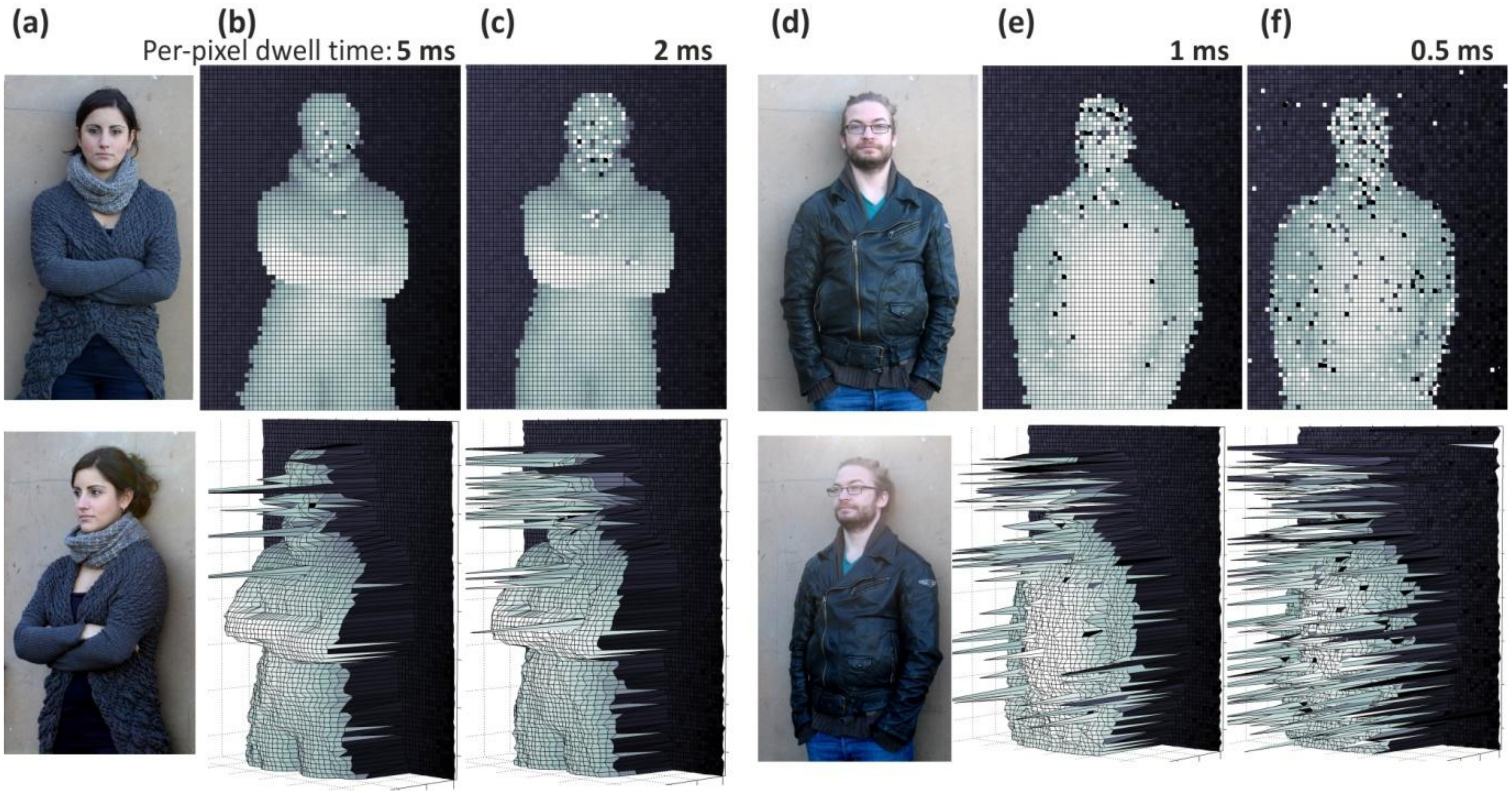
- Fibre-pigtailed detector
- Active area 25μm diameter
- Cooled to 230K
- 26% single-photon detection efficiency at 16 kcps dark count rate
- Nanosecond detector gating at up to 133MHz (40MHz repetition rate used in these experiments)

Single-photon scanning system

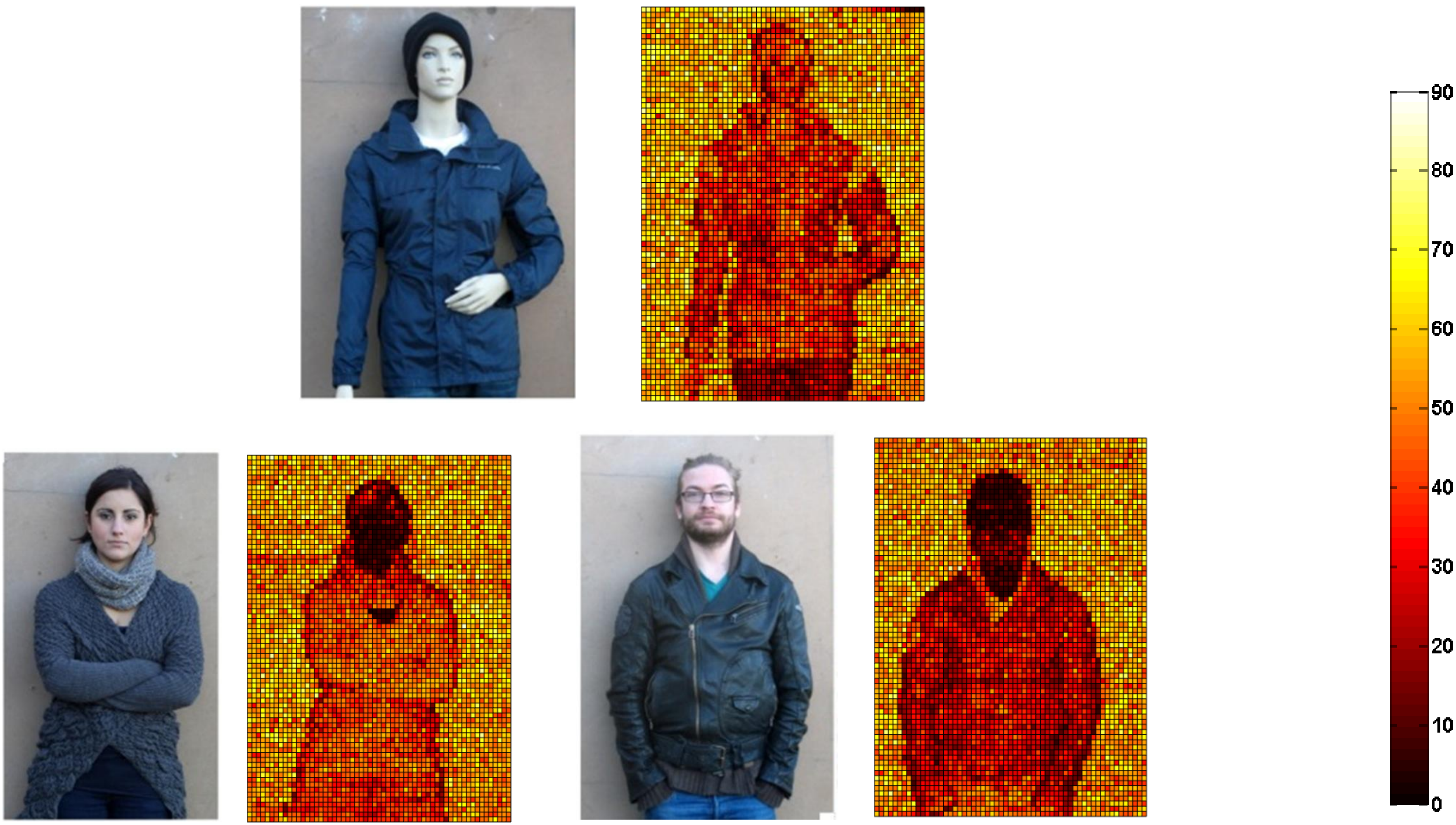
Detector	NbTiN SNSPD (resonant cavity)	InGaAs/InP SPAD
Laser	Mode locked fibre laser	Supercontinuum laser
Repetition rate	50MHz	40MHz
Wavelength	1560nm	1550nm
Average optical power	<250μW	<600μW
Detector collection fibre	9μm core diameter	9μm core diameter
Objective lens	500mm FL; 80mm ϕ	500mm FL; 80mm ϕ
x-y spatial resolution	50μrad	50μrad
Data acquisition	Picoharp 300	Picoharp 300
Single photon detection efficiency	18%	26%
Dark count rate	1000 counts per second	16,000 counts per second
Temporal response	98ps	144ps
Detector operating temp.	3K	230K



Depth imaging using InGaAs/InP SPAD (Daylight conditions, range 325 metres, average optical power < 600µW, λ ~ 1550nm)



Plots indicating photon number per pixel range 325 metres, average optical power < 600µW, λ ~ 1550nm, pixel acquisition time = 5ms



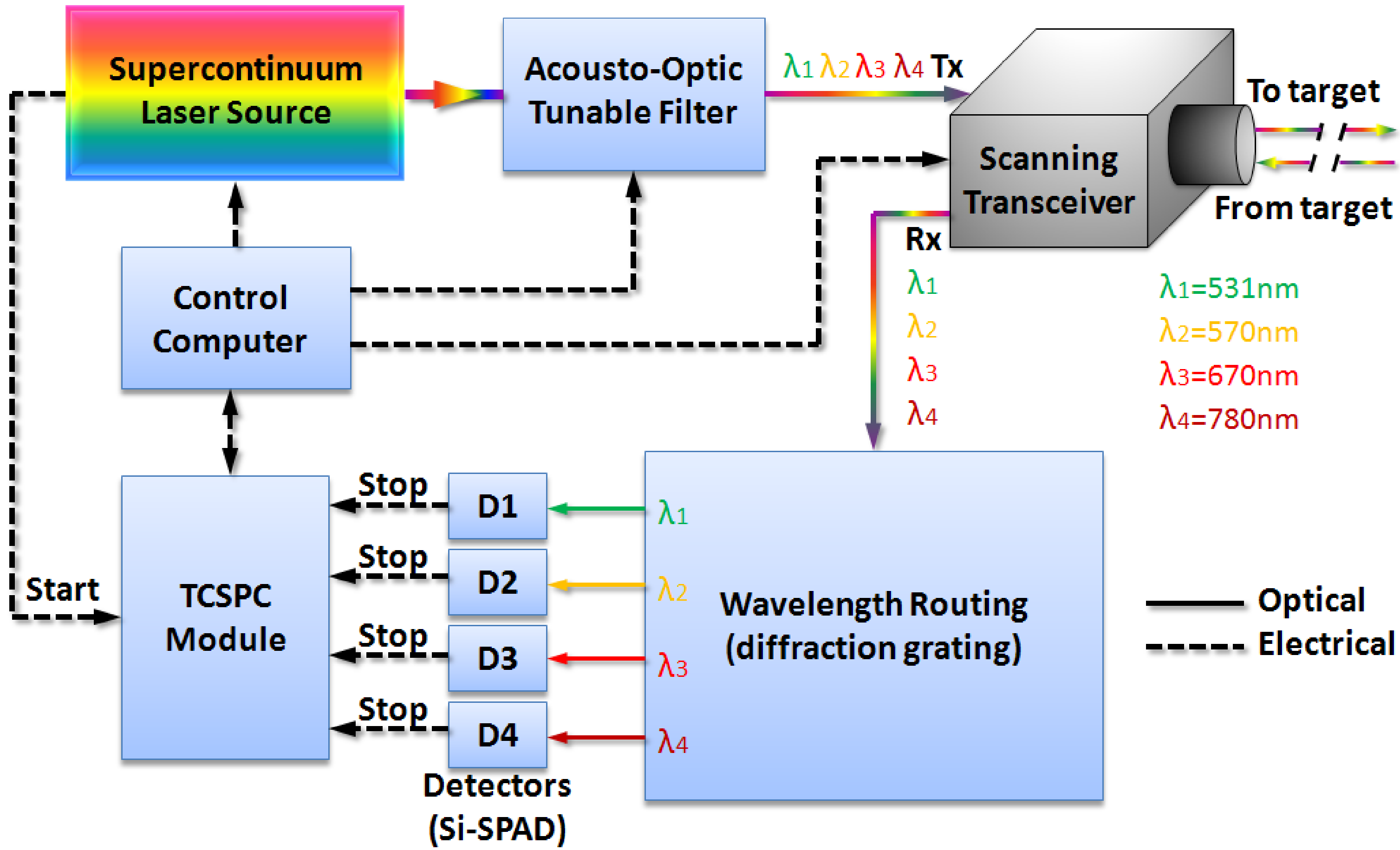
Photon-counting depth imaging at λ ~ 1550nm

- Compact Peltier-cooled InGaAs/InP SPAD module used for kilometer range, sub-centimetre resolution depth imaging of non-cooperative targets

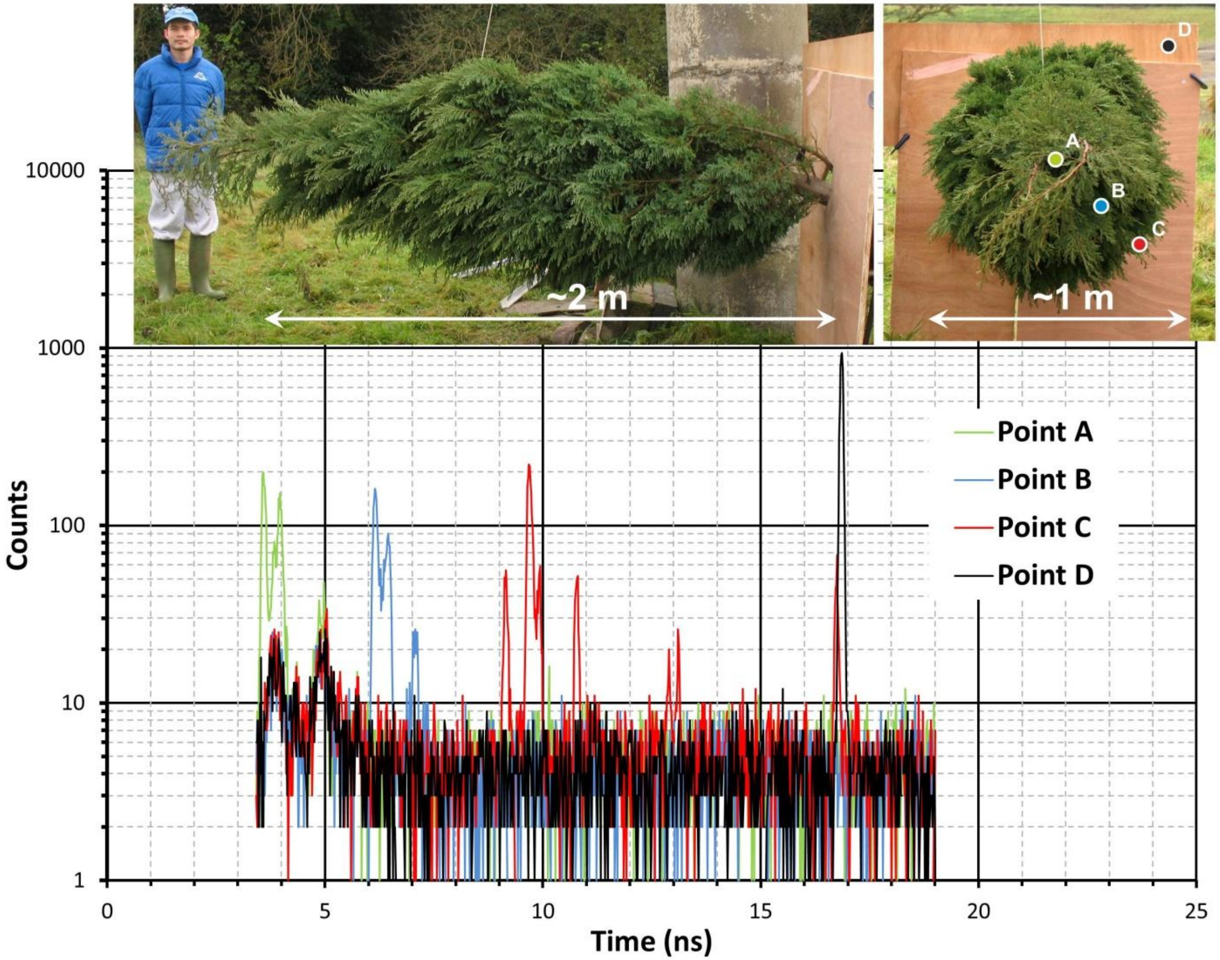
- Results comparable with SNSPD under similar operating conditions

Aongus McCarthy, Ximing Ren, Adriano Della Frera, Nathan R. Gemmell, Nils J. Krichel, Carmelo Scarcella, Alessandro Ruggeri, Alberto Tosi, and Gerald S. Buller
"Kilometer-range depth imaging at 1550 nm wavelength using an InGaAs/InP single-photon avalanche diode detector"
Optics Express, **21**, 19, pp. 22098-22113 (2013)

Multiple wavelength depth imaging system



Multi-spectral depth analysis on fir tree



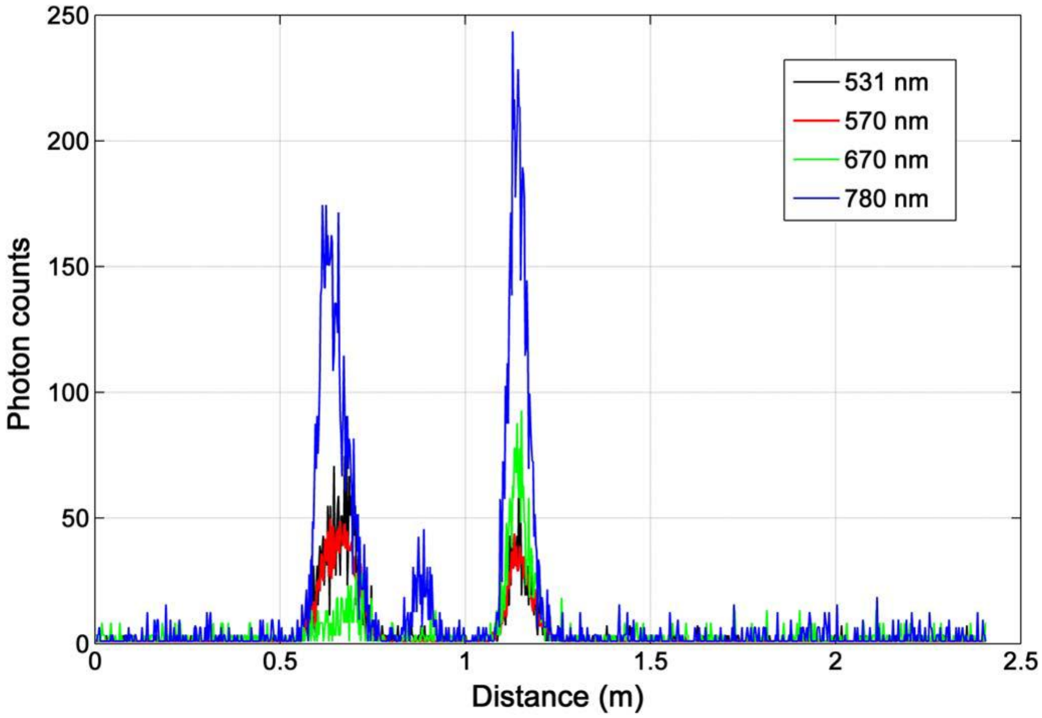
Biochemical parameter analysis

NDVI – Normalized Difference Vegetation Index, measure of photosynthetic efficiency

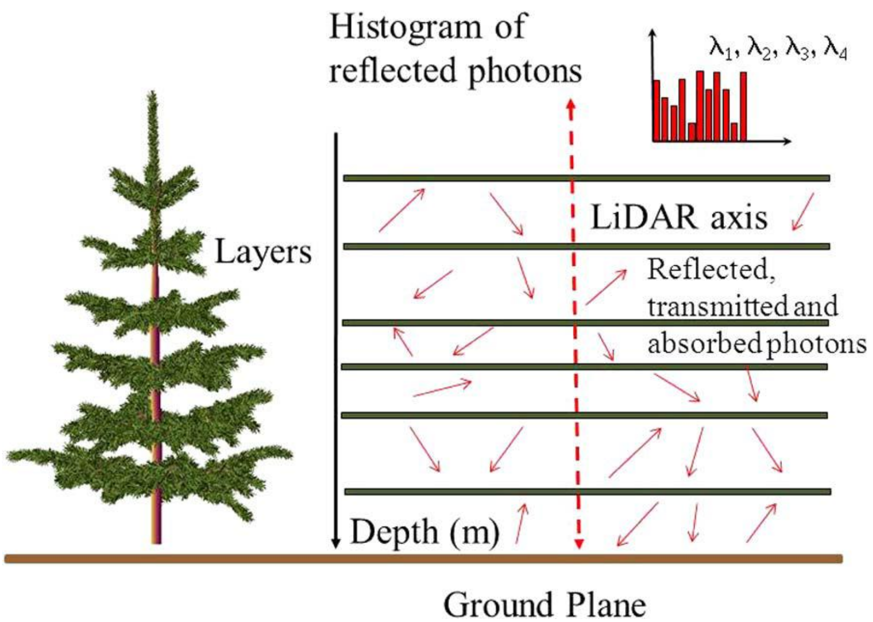
$$\textbf{NDVI} = \frac{R_{\lambda = 570nm} - R_{\lambda = 531nm}}{R_{\lambda = 570nm} + R_{\lambda = 531nm}}$$

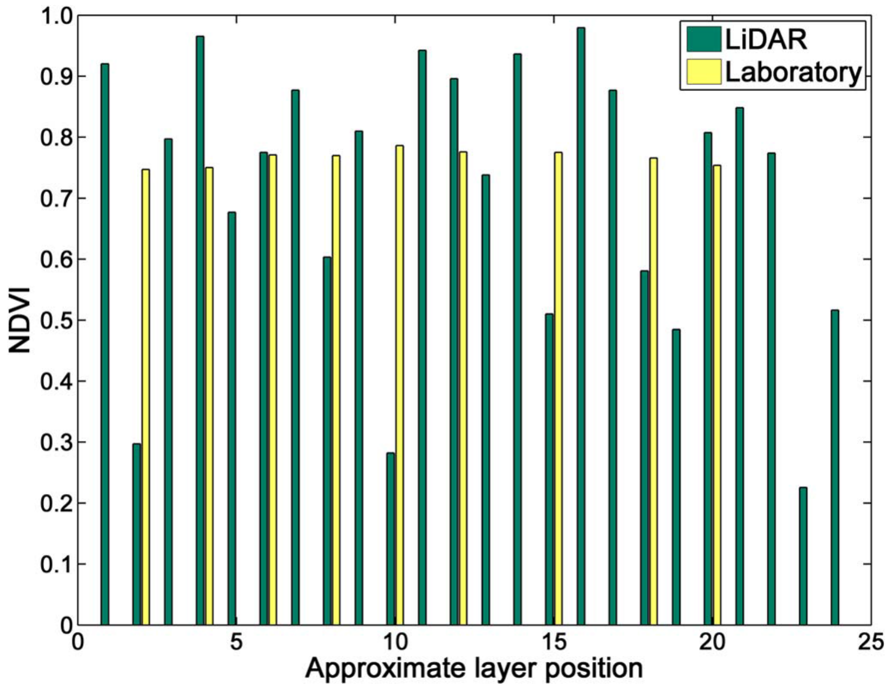
PRI – Photochemical Reflectance Index, measure of biomass

$$\textbf{PRI} = \frac{R_{\lambda = 780nm} - R_{\lambda = 670nm}}{R_{\lambda = 780nm} + R_{\lambda = 670nm}}$$



Biochemical parameter analysis





The LIDAR data is analysed using the Reversible Jump Markov Chain Monte Carlo to give a layer-by-layer analysis of tree at each wavelength – NDVI is shown in green on right. Laboratory analysis of same tree is shown for nine selected layers (yellow)

A.M. Wallace, A. McCarthy, C.J. Nichol, X. Ren, S. Morak, D. Martinez-Ramirez, I.H. Woodhouse, and G.S. Buller, *"Design and Evaluation of Multispectral LiDAR for the Recovery of Arboreal Parameters",* IEEE Transactions on Geosciences and Remote Sensing (in press).

Conclusions

- Compact Peltier-cooled InGaAs/InP SPAD module used for kilometre range, sub-centimetre resolution depth imaging of non-cooperative targets at $\lambda \sim 1550$nm. Results comparable with SNSPD under similar operating conditions.
- Remote measurements on tree samples indicate biochemical parameters can be ascertained as a function of tree height. Current experiments are being tested at 300-900 metres range
- Arrayed SPADs used in conjunction with scanner to obtain high-resolution images. Challenge is non-cooperative targets at kilometre range.