Traceable characterisation of free-space and fibre-coupled single-photon avalanche diodes in the vis/NIR

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ISSW 2024 | UKRI Innovate UK | AQuRAND | AIRQKD

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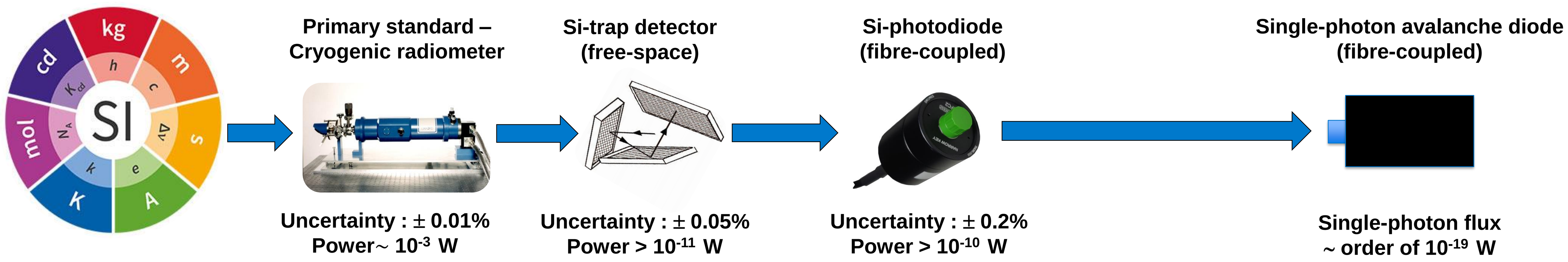
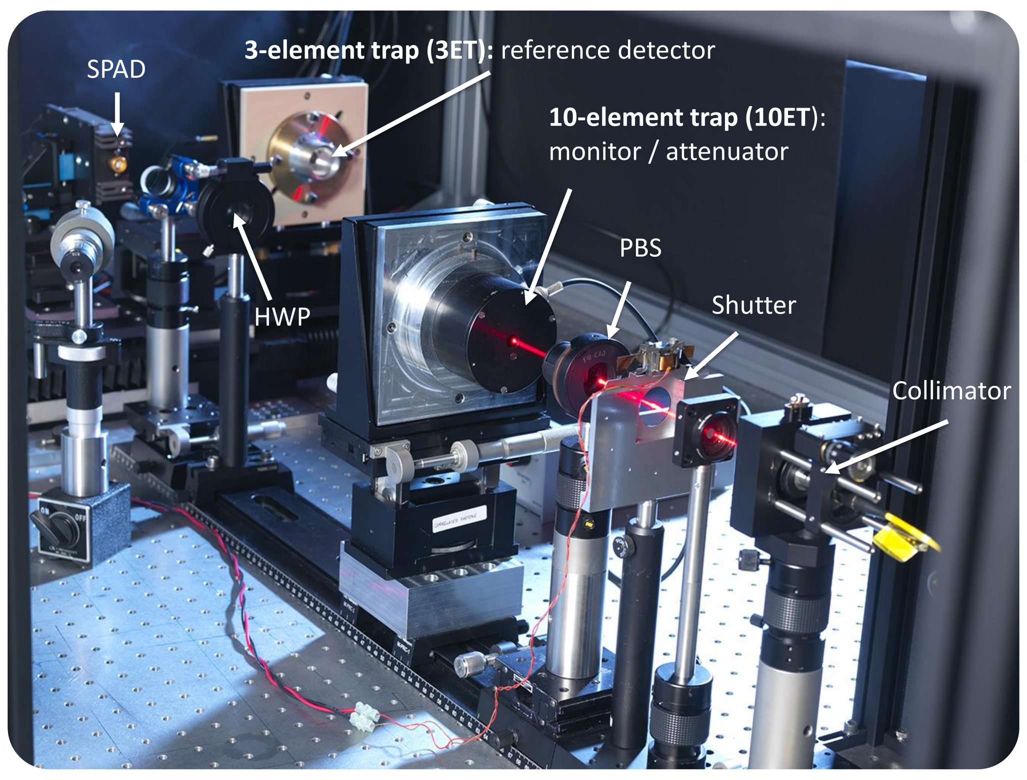
Motivation

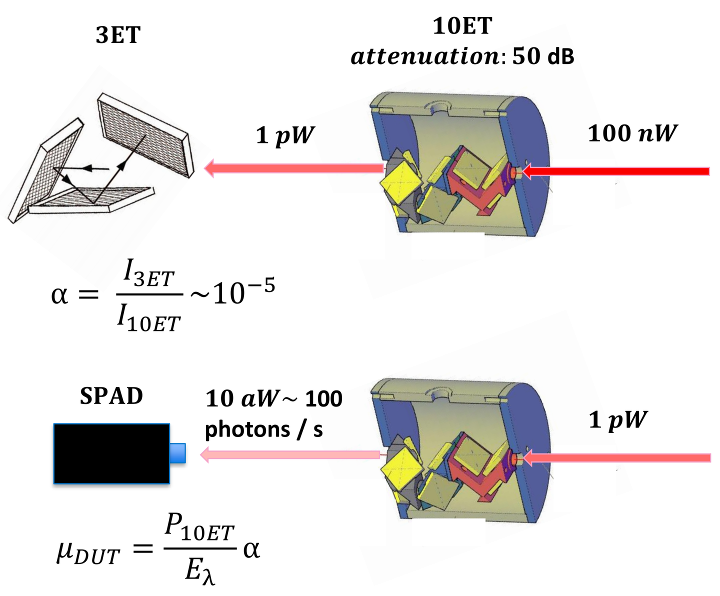
Single-photon avalanche diodes (SPADs) are utilised in a growing number of applications [1]. Consequently, many national measurement institutes have dedicated substantial efforts to the development of SI-traceable optical power measurements at the few-photon level [2,3]. At the National Physical Laboratory (NPL) we have an established free-space facility [4] and have recently developed a simple fibre-based setup, both of which enable device characterisation in the vis/NIR region of the spectrum. In this presentation, we outline these two setups and present two related works: interference effects in the spatial response of free-space devices, and a new model for calculating afterpulse probability.

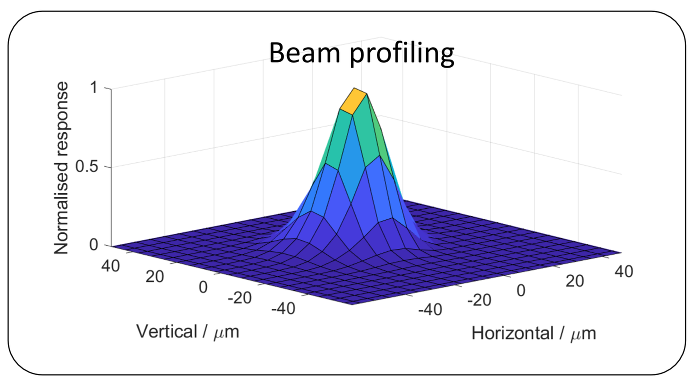


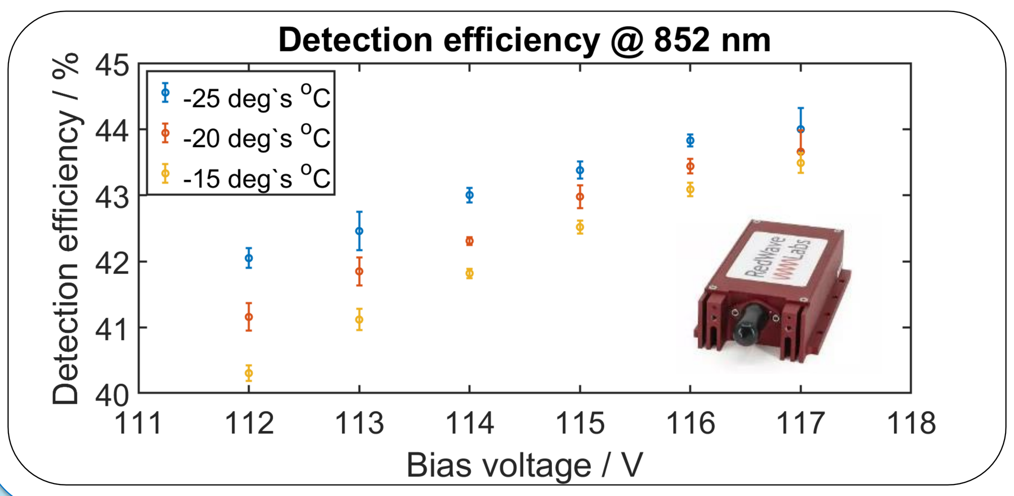
1. Free-space-coupled

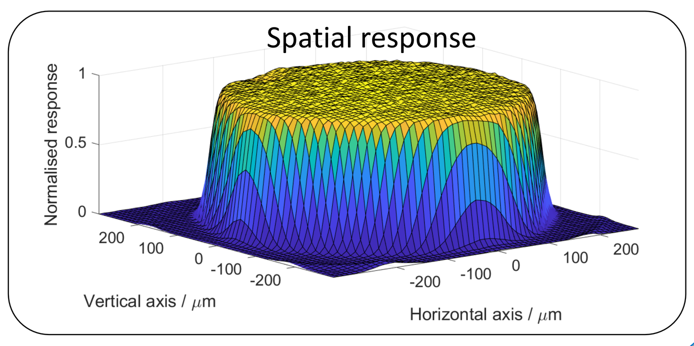
Our free-space facility uses an attenuation and substitution technique. This allows a known mean photon number incident upon a detector to be set, enabling the characterisation of a detector's efficiency. Absolute expanded uncertainties < ± 0.4% *(k = 2)* are achievable [4].





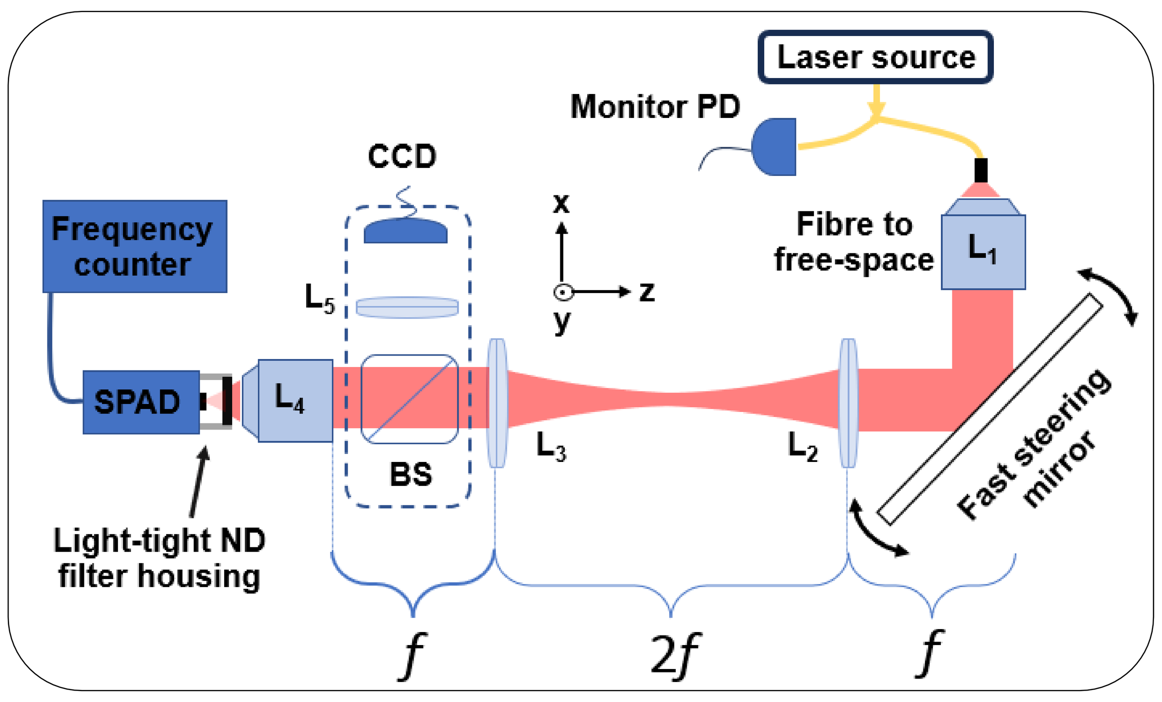




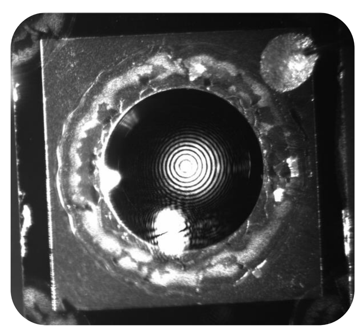


2. Interference effects

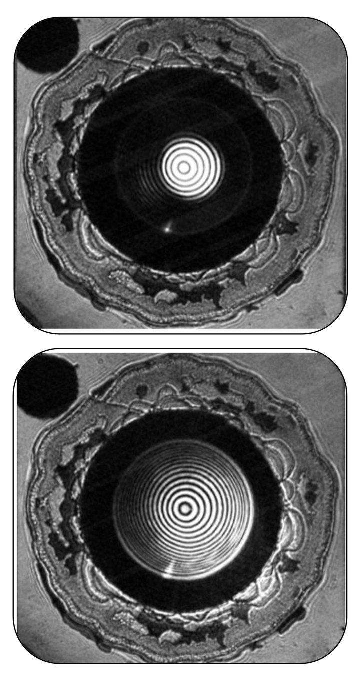
We investigated interference effects in the spatial response of free-space SPAD detectors which are detrimental to their performance. Four detectors from two manufacturers were tested. A Gaussian beam with a 4-micron waist was used to map their response with both incoherent and coherent light @ ~ 852 nm.

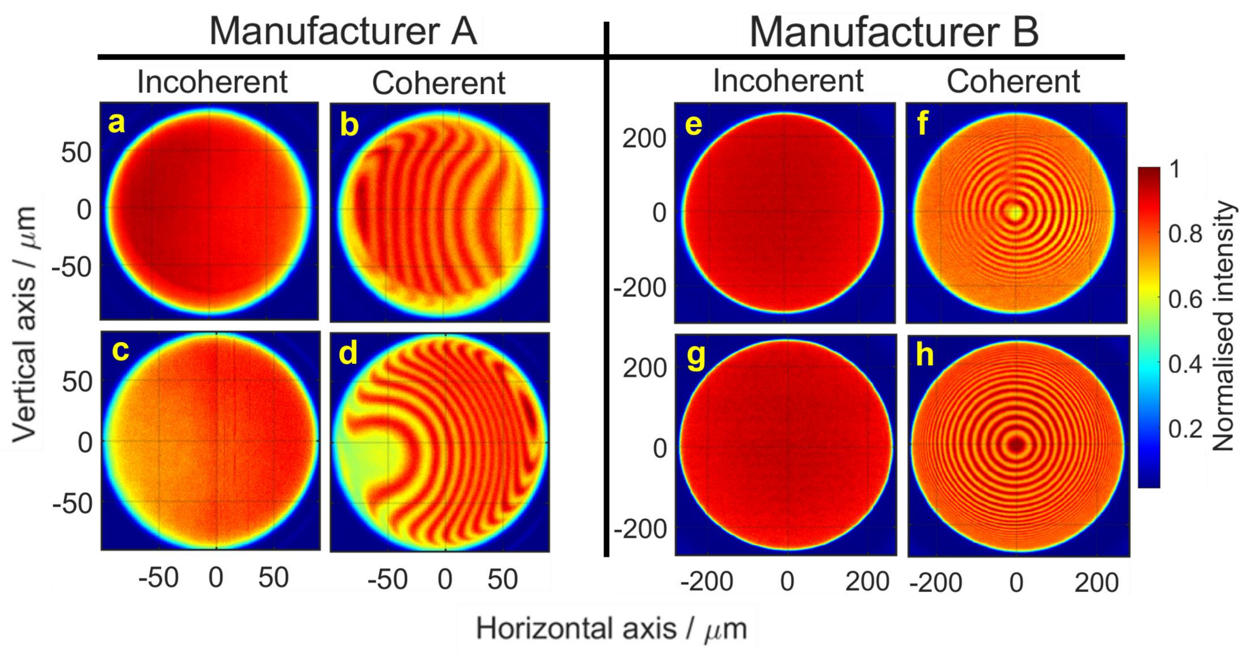


Coherent light incident upon functional device with window included



Coherent light incident upon a different, non-functioning device **with window removed**





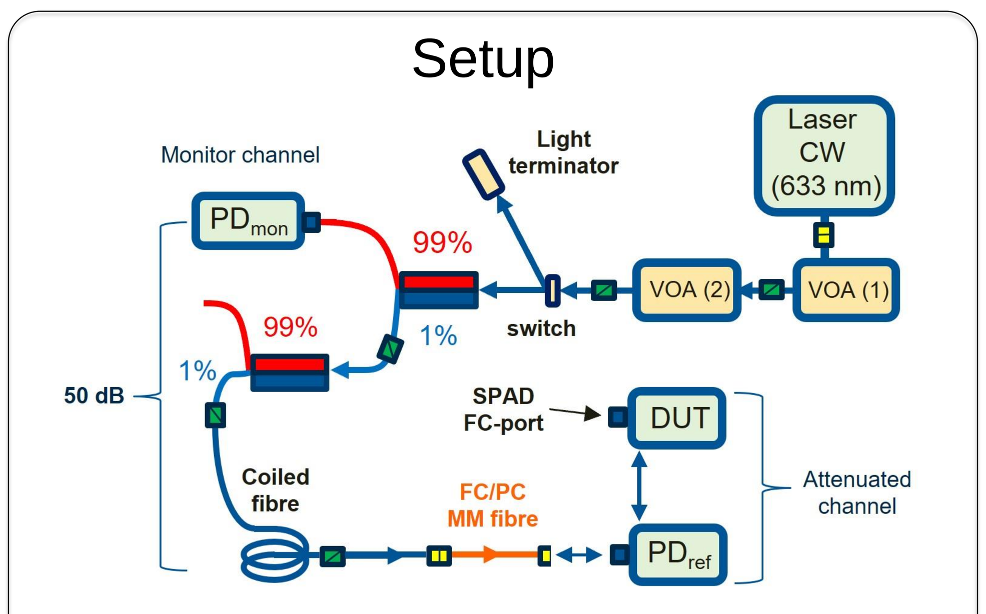
Outlook

- We will further develop our measurement capabilities to better align with the needs of industry.
- Complete an ongoing measurement comparison with another national measurement institution to verify the fibre-based setup; free-space measurements will also be performed.
- Confirm the origin of free-space coupled detector interference.
- Explore methods to characterise afterpulse probability with an incident photon flux, rather than with dark counts alone.

3. Fibre-coupled

We developed a simple setup for calibrating fibre-coupled single-photon detectors which was used to traceably measure the detection efficiency (DE) of four Hamamatsu C13001-01 fibre-coupled SPADs [5]. We investigated the repeatability of fibre-based measurements and performed a preliminary comparison between our established free-space facility and the new fibre-coupled setup.

Setup



- CW – continuous wave
- VOA – variable optical attenuator
- PD_{mon} / I_{mon} – monitor photodiode / photocurrent
- PD_{ref} / I_{ref} – reference photodiode / photocurrent
- DUT – device under test
- MM – multimode
- β – attenuation factor = 50 dB
- μ_{DUT} – mean photon number incident upon the DUT

$$\beta = \frac{I_{ref}}{I_{mon}} \sim 10^{-5}$$

$$\mu_{DUT} = \frac{P_{mon}}{E_\lambda}\beta$$

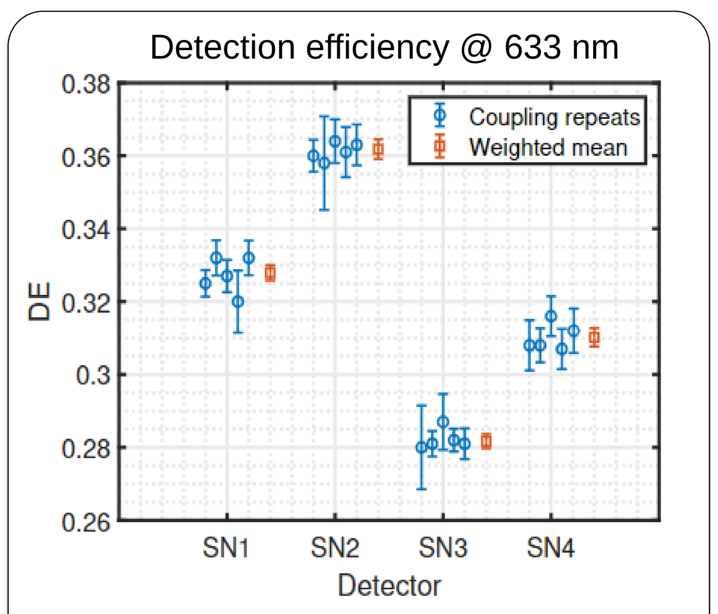
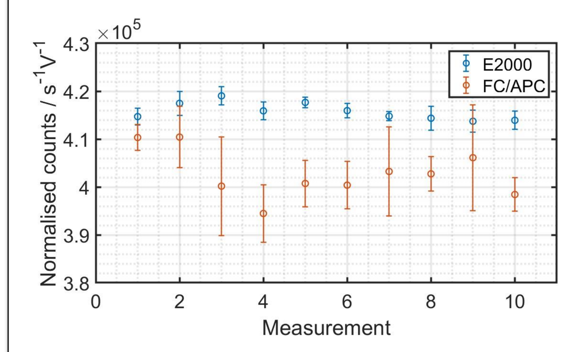


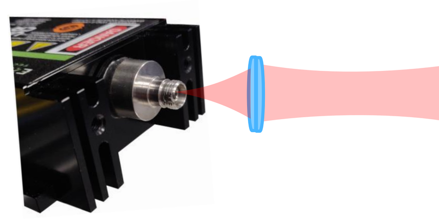
Table 1. Detection efficiency results summary

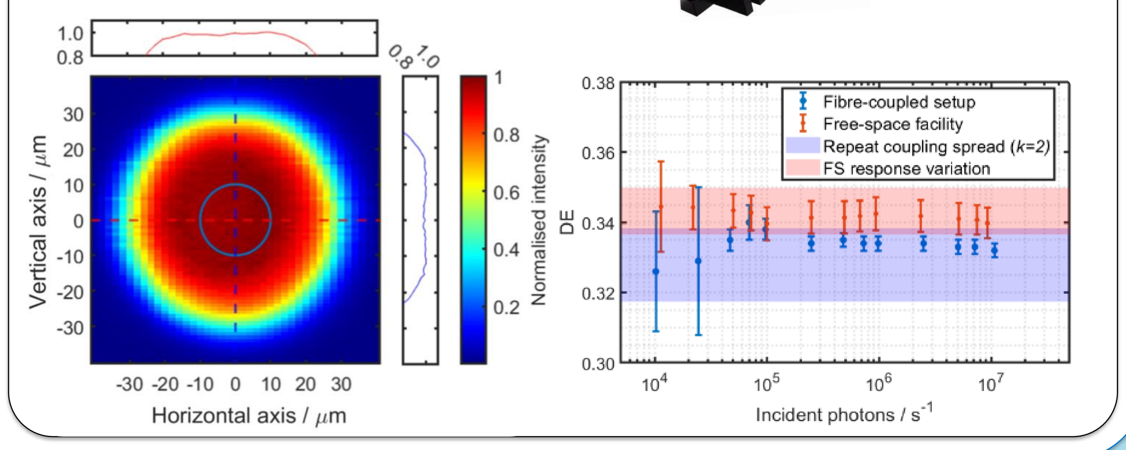
Detector	Detection efficiency $\overline{\eta}_d$	Std. Dev. (k=2)	Std. Unc. $U(\overline{\eta}_d)$ (k=2)
SN1	0.3279	0.0105	0.0022
SN2	0.3618	0.0050	0.0027
SN3	0.2817	0.0052	0.0020
SN4	0.3102	0.0072	0.0025

The dominant uncertainty in fibre-based measurements is often a result of re-coupling a device. Here we compare standard FC/APC connectors with E2000 connectors.



The DE of SN1 was measured in the free-space facility with a focused beam aligned centrally (see blue circle in the figure below). The measurement was then repeated in the fibre-coupled setup.



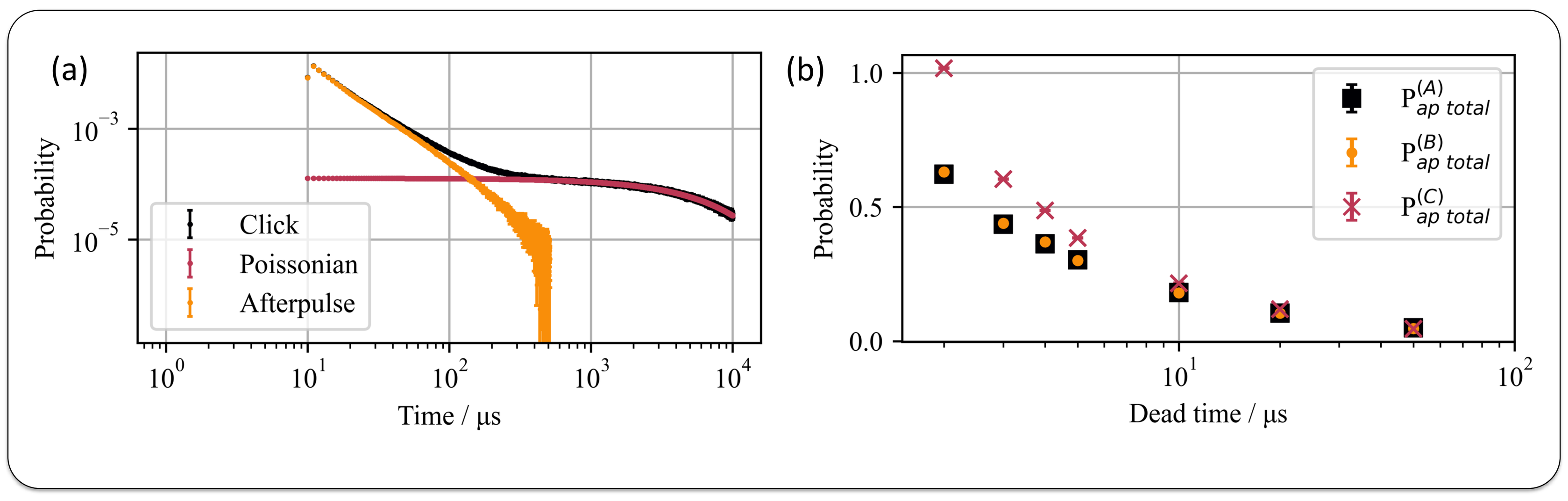


4. Afterpulse probability – new model

We have developed a novel method for accurately calculating the afterpulse probability of SPAD detectors, including its temporal distribution.

Below are the results showing (a) the temporal probability distribution of afterpulses, and (b) the total afterpulse probability as a function of detector deadtime for two different types of experiments – one using pulsed illumination in a synchronised experiment (black squares) [6, 7], and one with CW illumination in a non-synchronised experiment (orange circles) [8], analysed using our method as well as a previously published method (red crosses).

The results in (b) show very good agreement between the two experiments using our analysis method and demonstrate the divergence of the previous method as the dead time of the detector decreases.



References

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[4] Chunnilall, Christopher J., et al. (Forthcoming)
[5] Arabskyj, Luke, et al. (Forthcoming)
[6] A. W. Ziarkash et al, Scientific reports 8, **5076** (2018).
[7] G. Kawata, IEEE Transactions on Nuclear Science **64**, 2386–2394 (2017)
[8] European Telecommunications Standards Institute (ETSI) GS QKD 011 V1.1.1