CCPR WG-SP TG 11

Pilot study on the detection efficiency of single-photon detectors – Si-SPAD

CCPR.PR-Pxxx

Technical Protocol

1. Introduction

1.1 To provide a snapshot of measurement capabilities of National Measurement Institutes in the area of photon counting detection, this pilot study will implement a combined round-robin and star-type calibration of test detectors. The results of this effort will provide a number of benefits to the measurement community. While ultimately it will enable NMIs to improve methodologies and measurement uncertainties, at this initial point it will allow the participants and the community as a whole to better understand the technical and logistical challenges and resources required to move from measurement efforts that are largely research projects to measurements that are practical and robust enough to be considered as a more routine measurement service. In addition, this initial test should provide guidance on what measurement and operational parameters are better suited for those calibrating photon counting detectors and those who wish to make use of high accuracy calibrated detectors.

1.2 In the first phase of this pilot study detection efficiency measurements will be made on several Si-SPAD single-photon detectors at a wavelength of 850 nm in free-space beam following a technical protocol agreed upon by all participants of this pilot study, see section 2.2.

1.3 The procedures outlined in this document cover the technical procedure to be followed during measurement of the transfer standards.

1.4 A similar pilot study on the detection efficiency of single-photon detectors at a wavelength of 1550 nm with a fibre-coupled detector will follow. It is envisioned that a InGaAs-SPAD module would be used for this, although a superconducting nanowire detection system maybe included upon agreement of the participants.

2. Organization

2.1. Participants

2.1.1. The PTB is acting as a pilot laboratory in this pilot study.

2.1.2. All the participants should document traceability to an independent realization of the measurement quantity, or should make clear the route of traceability to the quantity via another named laboratory.

2.1.3. By their declared intention to participate in this pilot study, the laboratories accept the general instructions written down in this technical protocol and commit themselves to follow the procedures.

2.1.4. Once the protocol represented by this document has been agreed, no change to the protocol may be made without prior agreement of all the participants.

2.1.5. The participant's details are given in Appendix A.

2.2. Form of pilot study

2.2.1. The pilot study will principally be carried out through transfer detectors, specifically in the first phase, silicon single-photon avalanche detectors (Si-SPAD).

2.2.2. A description of the transfer detectors used in this pilot study is given in section 3 of this protocol.

2.2.3. The transfer detectors used in this pilot study are supplied by PTB.

2.2.4. The pilot study will be performed in a combined star-type- and round-robin-manner.

2.2.5. Each participant will send the transfer detectors to the next participant, as listed in the timetable, as soon as possible after finishing its measurements.

2.2.6. The timetable in Appendix B gives an overview on how the pilot study is planned.

2.2.7. Each laboratory has two months for measurement and transportation. With its confirmation to participate, each laboratory has confirmed that it is capable of performing the measurements in the time allocated to it.

2.2.8. Each laboratory shall aim to achieve the best possible measurand uncertainty possible given within the given timeframe.

2.2.9. If for some reasons, a participant foresees that it will not be able to perform the measurements in the time slot allocated to it, or if the measurement facility is not ready or customs clearance takes too much time so that it could not meet the timetable, the laboratory must contact the pilot laboratory immediately.

2.2.10. Any information obtained relating to the use or any results obtained by a participant during the course of the pilot study shall be sent only to the pilot laboratory which will be responsible for co-ordinating how the information should be disseminated to other participants. No communication whatsoever regarding any details of the pilot study other than the general conditions described in this protocol shall occur between any of the participants or any party external to the pilot study without the written consent of the pilot laboratory. If such communication is requested by a participant, the pilot laboratory will in turn seek permission of all the participants. This is to ensure that no bias from whatever accidental means can occur.

2.3. Handling of the transfer detector

2.3.1. The transfer detector should be examined immediately upon receipt. However, care should be taken to ensure that the transfer detectors have sufficient time to acclimatise to the room environment thus preventing any condensation etc. The condition of the transfer detectors and associated packaging should be noted and communicated to the pilot laboratory. If any damage is detected, the pilot should be contacted immediately.

2.3.2. The transfer detectors should only be handled by authorized persons and stored in such a way as to prevent damage. If the window of the transfer detector appears to be dusty, dirty or otherwise contaminated, contact the pilot laboratory immediately to discuss the options of cleaning the detectors input window.

2.3.3. During operation of the transfer detectors, if there is any unusual occurrence, e.g. change of sensitivity, etc., the pilot laboratory should be notified immediately before proceeding.

2.3.4. Please inform the pilot laboratory via e-mail when the measurements on the transfer detectors are completed to arrange a suitable date for dispatch, see Appendix F.

2.3.5. After the measurements, the transfer detectors should be repackaged in their original transit case(s). Ensure that the content of the package is complete before shipment. Always use the original packaging.

2.4. Transporting of the transfer detector

2.4.1. It is of utmost importance that the transfer detectors be transported in a manner in which they will not be lost, damaged or handled by un-authorized persons.

2.4.2. Packaging for the transfer detector should be suitably robust to protect the transfer detector from being deformed or damaged during transit.

2.4.3. The transfer detectors must be sufficiently robust to be sent by courier. If the possibility arises to hand-carry the package(s), this should be done.

2.4.4. The transfer detector will be accompanied by a suitable customs carnet (where appropriate) or documentation identifying the items uniquely.

2.4.5. The cost of transportation is the responsibility of each participating laboratory. Each participating laboratory covers the cost for its own measurements, transportation and any customs charges as well as for any damages that may have occurred within its country.

3. Description of the transfer detector for Phase 1

3.1.1. The measurement transfer detector is a free space Si-SPAD detector.

3.1.2. The Si-SPAD transfer detectors are Perkin-Elmer-SPCM-AQR-16 single photon counting modules. They are operated with the standard power supply delivered together with the detector. A picture and a technical drawing of the detector are attached (Appendix C), so that each lab already can prepare a proper mount corresponding to their measurement setup.

3.1.3. The spatial uniformity of response of the detector was measured by the pilot (PTB) and will be taken into account in the evaluation of the measurement results.

3.1.4. PTB will provide a standard threaded optical mount (1.035”-40) for straight forward implementation into an existing setup. The use of this mount is optional for each participant. In addition, PTB will send out a technical drawing of the detectors to aid the participants in fitting the detectors into their setup.

3.1.5. Details of detectors for subsequent phases of this pilot study will be developed at a later date.

4. Measurement instructions

4.1. Traceability

4.1.1. Temperature measurements should be made using the International Temperature Scale of 1990 (ITS-90).

4.1.2. Electrical measurements should be independently traceable to the latest realisation of the Second, Ampere and Volt.

4.2. Measurand

4.2.1. The measurand for the Si-SPAD detector is the detection efficiency of the transfer detector at low signal (close to 1 photon per second) at a wavelength of 850 nm under continuous wave irradiation in free space with a beam diameter ($1/e^2$-value) of smaller than 40 µm, (or at least 99.9 % beam capture), no matter what conditions are actually used in the measurements. If different beam sizes are used, inhomogeneity effects (see 3.1.3) and the effect of overfilling the detector have to be taken into account. The detection efficiency is defined as the ratio of the count rate of the transfer detector (minus the dark rate and the after-pulse rate) and the photon rate impinging on the detector. This definition is an extrapolation to low count-rate to provide a standard operating condition for the measurand to minimize effects of dead time.

4.2.2. The measurements should be performed in suitable laboratory conditions maintained at a temperature of 23.0 °C $\pm$ 1°C. The exact temperature of the laboratory during the time of the measurements must be reported.

4.2.3. Each measurement may consist of more than one set of measurements. The exact number of measurements used should be stated in the measurement report.

4.2.4. It is recommended that an evaluation of beam size and alignment be performed by moving the free space beam relative to the active area of the detector in two dimensions, with the flatness of the response plateau and steepness of the edges being good indicators of proper beam geometry.

4.3. Measurement instructions

4.3.1. The Si-SPAD detector is provided with a power supply and the operation manual. To avoid any issues with voltage-dependent detector performance, the supplied input voltages of the detectors should be 5.1 V ± 0.1 V. If this value is not achieved, the pilot laboratory should be contacted immediately and the option of using a bench-top power supply will be discussed.

4.3.2. Upon receipt of the detectors, they should be inspected for damage. Any damage should be documented by a drawing using the appropriate form in Appendix D and E.

4.3.3. The Si-SPAD modules must be operated in continuous wave mode using the power supply provided with the detector.

4.3.4. The beam profile should be described if possible.

4.3.5. The polarization of the impinging beam with respect to the longer edge of the front surface of the detector module should be reported.

4.3.6. To avoid damage to the test detectors, no other measurements are to be attempted by the participants or any modification performed to the detector during the course of this pilot study. The transfer detector used in this pilot study should neither be used for any purpose other than described in this document nor given to any party other than the participants in the pilot study.

4.3.7. The operation manual for the Si-SPAD detectors must be followed. Especially high irradiance of the detector when powered must be avoided.

5. Reporting of results and uncertainties, report preparation

5.1.1. The report on the calibrations for the Si-SPAD detector must include:

- a description of the participant's measurement facility and the procedure or a reference to a published work of the facility;
- a comprehensive uncertainty budget, comprising all the contributions to the total uncertainty. The uncertainty of measurements shall be estimated according to the *ISO Guide to the Expression of Uncertainty in Measurements*;
- make and type of primary standard;
- laboratory transfer standards used (if any);
- description of measuring technique (please include a diagram);
- traceability route of primary scale;
- wavelength and bandwidth, polarization with respect the detector module, source used, beam diameter at detector;
- curve of the scan of the detectors with respect to the beam, showing the response plateau as well as steepness of the edges being good indicators of proper beam geometry, see section 4.2;
- description of calibration laboratory conditions: e.g. temperature, humidity etc

5.1.2. The report should be completed and sent back electronically to the pilot laboratory.

5.1.3. Following receipt of all measurement reports from the participants, the pilot laboratory will analyze the results and prepare the first draft report on the pilot study. This will be sent to the participants for comments, additions and corrections.

5.1.4. Subsequently, the procedure outlined in the BIPM Guidelines will be followed.

Appendix A: Laboratory contact persons

Participant	Laboratory contact person	Institute	Address	Phone	e-mail
Germany (Div. 4 - Pilot)	Stefan Kück	Physikalisch-Technische Bundesanstalt FB 4.1 Photometrie und angewandte Radiometrie	Bundesallee 100 38116 Braunschweig Germany	+49 531 592 4100	stefan.kueck@ptb.de
China	Haiyong Gan	National Institute of Metrology Optics Division	Bei San Huan Donglu Road 18 Chaoyang District, Beijing 100029 China	+86 10 64524829	ganhaiyong@nim.ac.cn
Czech Republic	Marek Šmíd	Laboratory of Fundamental Metrology Czech Metrology Institute	V Botanice 4 150 72 Praha 5 Czech Republic	+420 257 288 328	msmid@cmi.cz
Germany (Div. 7)	Ingmar Müller	Physikalisch-Technische Bundesanstalt Arbeitsgruppe 7.33 Detektorradiometrie	Abbestr. 2-12 10587 Berlin Germany	+49 30 3481 7406	ingmar.mueller@ptb.de
Italy	Giorgio Brida	Istituto Nazionale di Ricerca Metrologica (INRiM) Photometry & Radiometry	Strada delle Cacce 91 10135 Torino Italy	+39 011 3919 222	g.brida@inrim.it
Japan	Daiji Fukuda Ken-ichi Watabe	National Metrology Institute of Japan, AIST Research Institute for Physical Measurement Laser Radiometry Research Group	AIST Tsukuba Central 3 Tsukuba 305-856 Japan	+81 29 861 6834 +81 29 861 4270	d.fukuda@aist.go.jp k.watabe@aist.go.jp
Korea	Dong-Hoon Lee Kee Suk Hong	Korea Research Institute of Standards and Science (KRISS) Center for Photometry and Radiometry	267 Gejeong-Ro, Yuseong-Gu 34113 Daejeon Rep. Korea	+82 42 868 5706	dh.lee@kriss.re.kr hongi2011@kriss.re.kr
Russia	Sergey Moskalyuk Aleksey Mikryukov	NMI - Federal State-Owned Unitary Enterprise “All-Russian Research Institute for Optical and_Physical Measurements” Department: Laser Metrology and Radiometry	119361, Moscow Ozernaia str. 46 Russia,	+7 495 437-34 47	mrsergik@mail.ru anzio64@gmail.com
Switzerland	Peter Blattner	Federal Institute of Metrology (METAS)	Lindenweg 50 3003 Bern-Wabern Switzerland	+41 58 387 01 11	peter.blattner@metas.ch
UK	Christopher Chunnilall	National Physical Laboratory Group: Quantum Detection	Hampton Road Teddington TW11 0LW UK	+44 20 8943 6872	christopher.chunnilall@npl.co.uk
USA	Thomas Gerrits	National Institute of Standards and Technology Applied Physics Division	325 Broadway Boulder, CO 80305 USA	+1 303 497 4661	thomas.gerrits@nist.gov

Appendix B: Time schedule

Activity	Date
Circulation of technical protocol and invitation of participation	Nov 2015
Confirmation of participation by member labs and revision of protocol	Dec 2015
Technical protocol agreed by all participants	Feb 2016
Start of pilot study	May 2016
Measurements at PTB	May - Jun 2016
Measurements at NIST	Aug - Sep 2016
Measurements at NPL	Nov - Dec 2016
Measurement at CMI	Jan - Feb 2017
Intermediate measurements at PTB	Mar - Apr 2017
Measurement at INRIM	May - Jun 2017
Measurement at KRISS	Jul - Aug 2017
Measurements at PTB, Div. 7	Sep - Oct 2017
Intermediate measurements at PTB	Nov - Dec 2017
Measurements at METAS	Jan - Feb 2018
Measurements at VNIIOFI	Mar - Apr 2018
Measurements at AIST	May - Jun 2018
Measurements at NIM	Jul - Aug 2018
Final measurements at PTB	Sep - Oct 2018
Pre-draft A report for pilot study finished	Dec 2018
Draft A completed	Apr 2019
Final report completed	Oct 2019

Appendix C: Technical details of the transfer detector

The transfer detector is a Silicon Single Photon Avalanche Diode, type Perkin-Elmer-SPCM-AQR-16 – SN: 19743 and SN: 18752*

A picture and a technical drawing of the detector are attached, so that each lab already can prepare a proper mount corresponding to their measurement setup.

“The SPCM-AQRH uses a unique silicon avalanche photodiode (SLiK) with a circular active area, achieving a photon detection efficiency greater than 70% at 700nm over a 180µm diameter with unmatched uniformity over the full active area. A TTL level pulse is generated for each photon detected and the signal is available at the BNC connector at the rear of the module. The signal should be terminated into 50Ω.

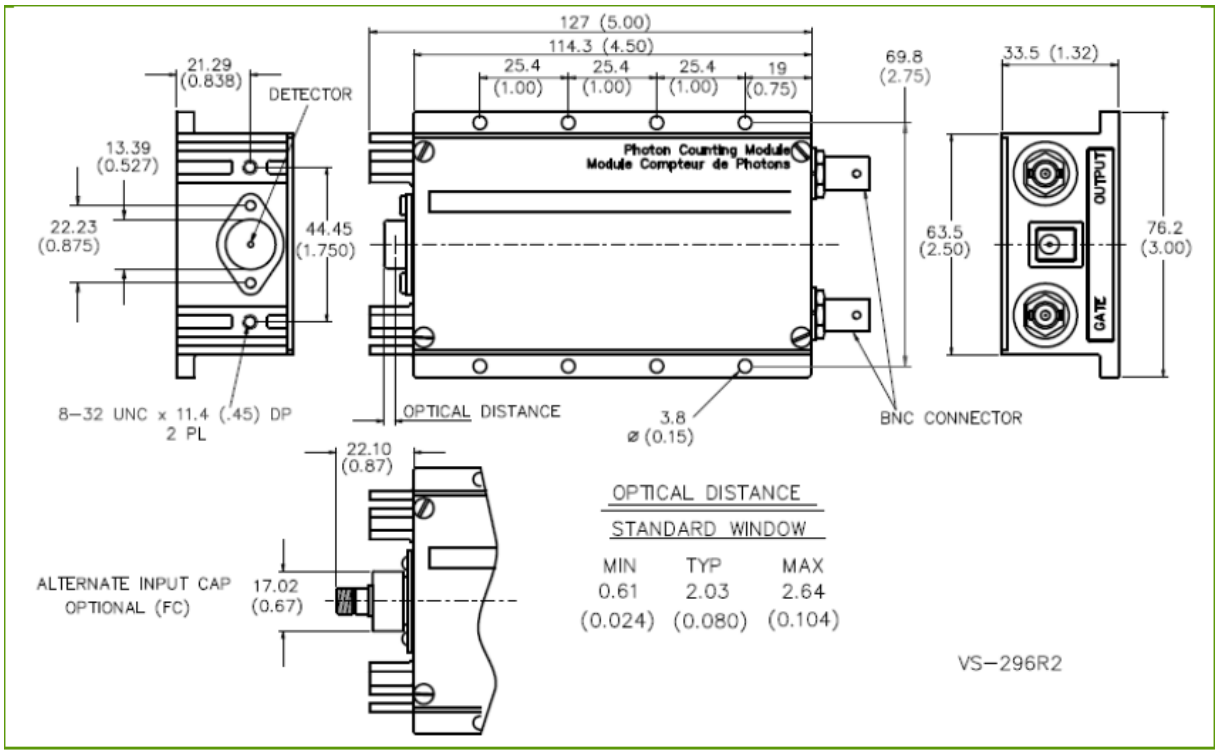
The photodiode is both thermoelectrically cooled and temperature controlled, ensuring stabilized performance despite ambient temperature changes. Operating temperature range has been increased and the module (case temperature) will function between 5˚C and 70˚C.

Recent electronic circuit improvements have reduced the minimum dead time to 20ns, thereby increasing linearity and improving the dynamic range of the module. Timing resolution of the module was also improved significantly. The SPCM-AQRH has internal protection circuitry that protects the avalanche photodiode and the module electronics from damage due to accidental overload from exposure to ambient lighting.”

(www.excelitas.com, SPCM-AQRH Rev 2014-09)

* Certain commercial equipment, instruments or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for the purpose.

(www.excelitas.com, SPCM-AQRH Rev 2014-09)



(www.excelitas.com, SPCM-AQRH Rev 2014-09)

Appendix D: Receipt confirmation

(Please send scanned signed copy to pilot laboratory)

To: **Dr Stefan Kück**

Physikalisch-Technische Bundesanstalt

Bundesallee 100

D-38116 Braunschweig

Germany

e-mail: stefan.kueck@ptb.de

From: (*Participating Laboratory*)

We confirm having received the transfer detectors of the CCPR WG-SP TG 11 “Pilot study on the detection efficiency of single-photon detectors – Si-SPAD” on

(*date*).

After visual inspection

☐ No damage has been noticed.

☐ The following damage must be reported:

Appendix E: Inspection of the transfer detector

Has the detector transportation package been opened during transit, e.g. customs? Y / N

If Yes please give details:

Is there any damage to the transportation package? Y / N

If Yes please give details:

Are there any visible signs of damage to the detector or housing? Y / N

If Yes please give details (e.g. scratches, dust etc.):

Do you believe the transfer detector is functioning correctly? Y/ N

If not please indicate your concerns:

Laboratory:

Date: Signature:

Appendix F: Completion confirmation

(Please send scanned signed copy to pilot laboratory)

To: **Dr. Stefan Kück**

Physikalisch-Technische Bundesanstalt

Bundesallee 100

D-38116 Braunschweig

Germany

e-mail: Stefan.kueck@ptb.de

From: (*Participating Laboratory*)

We confirm having completed the measurements of the detectors of the CCPR WG-SP TG 11 "Pilot study on the detection efficiency of single-photon detectors – Si-SPAD" on (*date*).

The detectors were sent to (*participant*) on (*date*).

Further remarks:

Laboratory:

Date: Signature: