High Accuracy Calibration of Photon-Counting Detectors “On Demand”

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ABSTRACT

We introduce a portable, inexpensive and reliable scheme for calibration of photon-counting detectors based on our recent comparison of two independent high accuracy primary standard calibration methods. We have verified the calibration method based on two-photon correlations and its uncertainty by comparing it to a substitution method using a conventionally calibrated transfer detector tied to a national primary standard detector scale. We have reported a relative standard uncertainty for the correlated-photon method of 0.18 % (*k*=1) and for the substitution method of 0.17 % (*k*=1). Further we established, by direct comparison in a series of measurements, that the two methods agree to within the uncertainty of the comparison, with the difference being 0.14(14) %. While this experiment can be repeated in the laboratory setting, the calibration methods are not appropriate for everyday use. However, using photon-counting detector properties brought to light by our comparison of the two methods we introduce a relatively low cost calibration technique that will allow for 0.5% (*k*=1) uncertainty.

Keywords: calibration, detector, metrology, photon, photon counting, down-conversion, correlated photons, statistical methods

1. INTRODUCTION

The need of an inexpensive, reliable and accurate calibration procedure for single-photon detectors (SPD) for industrial use is on the rise. Recently we completed a series of comparative high accuracy SPD calibrations [1], which were based on using two different a “primary standard methods.” [2] Besides obtaining the calibration and method verification with the lowest uncertainty achieved to date, this study revealed important features of SPDs, which need to be accounted for by any metrologist claiming better than ~1% uncertainty for detection efficiency (DE) calibration. We present a procedure for calibration of a SPD with 0.5% or better uncertainty with minimal equipment. In this submission, we review our verification results and identify the key features of SPDs that are relevant for a high-accuracy calibration setup suited for use outside of a metrology lab setting.

The two fundamentally absolute methods used in our study were a correlated-photon technique [3-16], and a detector substitution method traceable to the US radiometric scale. The absolute nature of the correlated method derives from the two-photon light source. Because the photons are produced in pairs, the detection of one photon heralds with certainty the existence of the other. This method relies on individual photons as a trigger, which allows operation in the photon-counting regime and is thus well suited to SPD studies. Such studies reveal features of SPD detection, some of which are well known (i.e. deadtime and afterpulsing), but, as it turns out, it is necessary to consider many additional effects to reach high accuracy. It was the independent calibration via detector substitution that allowed us to verify that those additional SPD features were identified and processed correctly.

2. CALIBRATION METHODS

2.1 Conventional Calibration (Substitution method)

Due to its relative simplicity, and proven potential for high accuracy, we propose using the substitution method SPD calibration outside of a metrology lab. The method relies on measuring the radiant power in the detector under test (DUT) channel with a calibrated transfer standard detector (traceable to NIST’s radiant power scale) and with the photon-counting detector under test (DUT) [17, 18]. To compare the radiant power measured by the standard detector to

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number of counts measured by the SPD, requires information about the spectrum of the source and specifics of the SPD itself. Moreover, one needs to measure and correct for all the properties of SPDs up to the desired level of accuracy.

2.2 Correlated-photon-pair calibration method

The correlated-photon method relies on a fundamental property of parametric down-conversion, namely, that photons from a pump beam are split into two photons (signal and idler), whose frequencies, and wavevectors are governed by energy conservation and momentum conservation, respectively. Therefore, detection of one photon of a correlated pair provides both spatial and temporal location information of the other photon of the pair. To make a detection efficiency measurement, a trigger SPD is set to intercept some of the downconverted light. The single-photon detector under test is positioned to collect all the photons correlated to those seen by the trigger detector. The DUT channel detection efficiency is the ratio of the number of coincidence events to the number of trigger detection events in a given time interval (assuming that the detectors only fire due to photons of a pair). A coincidence is defined as when both the trigger and the DUT detectors fire within a given time window due to detection of both photons of a downconverted pair. It can be shown [1] that for correlated calibration measurements, it is unnecessary to determine the efficiency of either the trigger SPD or the trigger channel collection efficiency . The drawback of this approach is that the losses in DUT channel must be considered separately. Also, some properties of both trigger and DUT SPDs must be characterized separately. While the drawbacks make this method less attractive for routine usage, it is very useful to identify and understand the properties of SPDs, as they will affect the accuracy of any single photon experiment (including the calibration scheme discussed here).

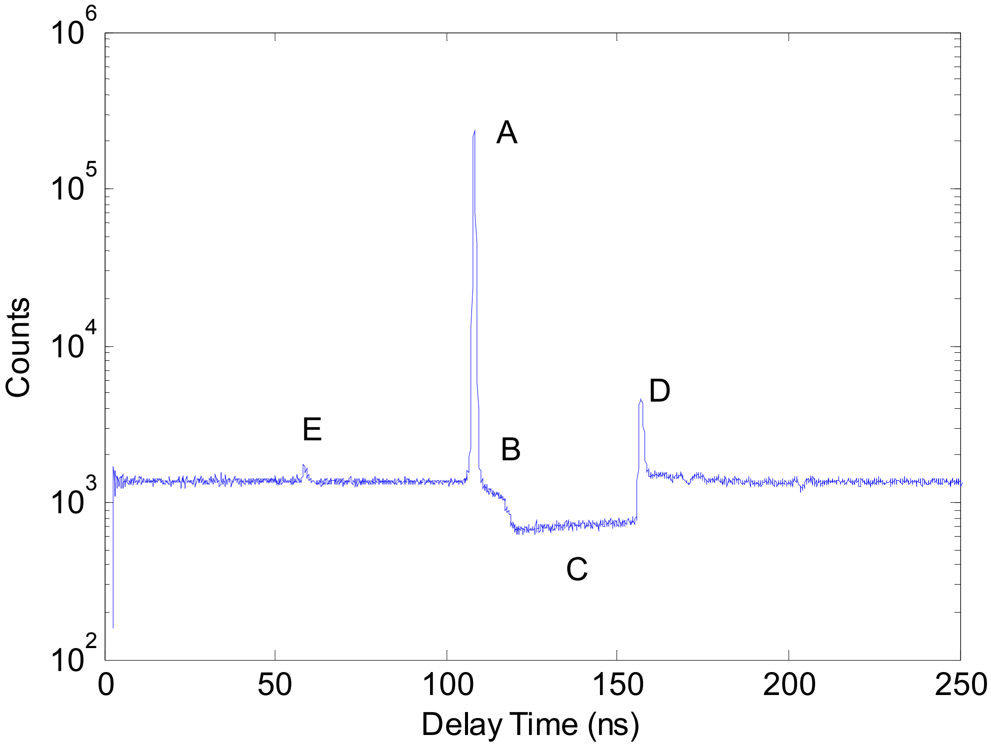

Fig. 1. Typical histogram of correlated photodetections and its main features. A – the main peak due to correlated photons, B – extended shoulder due to twilight events (see text), C – the region where the detector is dead after firing, D – peak due to afterpulsing, E – minor correlated photons peak due to double back reflection in the trigger fiber and afterpulsing of the trigger APD. The broad background is due to the uncorrelated firing of the DUT.

The setup uses avalanche photodiodes (APD) to detect single photons in the trigger and DUT channels. The electronic output of a trigger APD is connected to the start channel of a coincidence circuit and the DUT APD is connected to the stop channel after an additional length of cable to assure that the stop pulse arrives after the start. We obtain a histogram (see Fig. 1) of the delays between trigger and DUT detection events. This histogram contains the main correlation peak, along with other correlated features that result from various properties of the APDs used, along with peculiarities of the setup. After the main coincidence peak, the most obvious features are due to afterpulsing and deadtime. The correlated signal "sits" on top of a background of uncorrelated coincidences. To separate the signal and background with the precision needed for the ultimate detection efficiency determination, a detailed model of APD behavior [1, 19, 20] is required. After such separation, one needs to examine the properties of a SPD. Here, we will focus only on the features highly relevant to the calibration via detector substitution, as the treatment of other features is presented elsewhere [1, 19, 20].

3. IMPLEMENTATION OF A HIGH ACCURACY CALIBRATION METHOD "ON DEMAND"

3.1 Calibration Setup

To implement the calibration scheme based on substitution, one needs a calibrated high-gain low-noise photodiode/amplifier with a calibrated voltmeter, a narrow filter with known transmission spectrum, and an appropriate focusing lens, which should produce a focal spot with a waist at least 3 times smaller than the APD active area diameter. To match the active area size of the calibrated photodiode with that of the typically much smaller size of the photon counting SPD, one needs to use a non-reflective pinhole. The exposure time of the SPD should be measured to better than 0.1% uncertainty. There should be a separate detector to monitor the relative radiant power of the light source after the filter shown in Fig. 2 to ensure that only irradiance in the filter's transmittance band is measured. The beamsplitter shown in the figure is a high reflector so as to provide relatively high power to the monitor, while allowing a much lower power beam to impinge on the two detectors to be interchanged. The basic optical layout of a calibration setup is presented in Fig. 2.

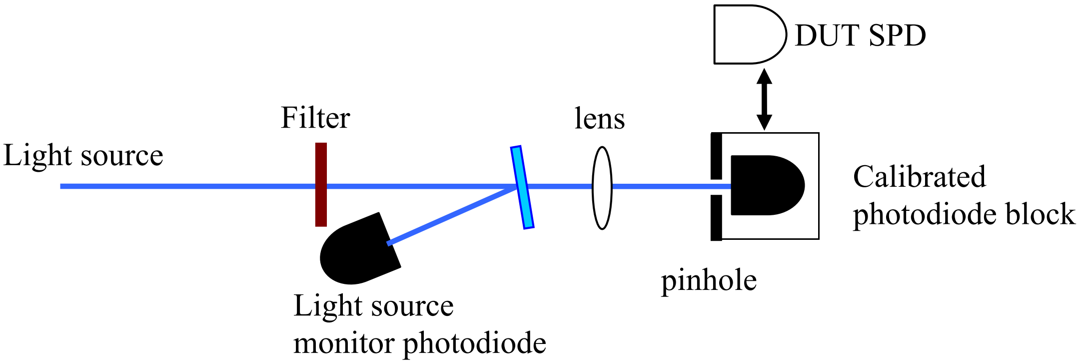

Fig. 2. Calibration setup.

The electronic signal from a calibrated photodiode can be converted to a measure of photon flux, after the filter transmittance is integrated with the detector radiant power responsivity spectral dependence to get an effective energy per photon. This signal is dominated by electronic noise and thus should be recorded for sufficient time to acquire the required statistics. Single photon detections of a DUT SPD can be recorded by any pulse counting hardware. Comparing the two values yields a rough estimate of the DUT SPD's DE. By no means, however, can this number be used as a calibrated value of DE, because corrections for the detailed properties of SPDs were not considered. In what follows we discuss these properties. Also, we consider various definitions of DE, because, as it was shown in [1] the final answer greatly depends on the definition. In what follows, the uncertainty figures are given for k=1, unless otherwise stated.

3.2 Complex Afterpulsing Properties of a SPD

An *afterpulse* is when the APD fires (produces a count) at the end of the deadtime associated with a previous count. If the APD is exposed to continuous wave (cw) light, in addition to the usual cause of an afterpulse due to lingering trapped carriers from a previous avalanche, an afterpulse can also result from a subsequent photon arriving during the last moments of the APD's deadtime [19, 20]. Thus the afterpulse peak consists of photon-related afterpulses (or twilight counts) and ordinary afterpulses, not related to a photon absorption. Depending on a definition of APD DE, twilight events may or may not be considered as valid, while ordinary afterpulses should not be counted. Note that the ordinary afterpulse fraction is a property of a specific APD, in that it varies from unit to unit and does not depend on count rate,. while the probability of getting a twilight event grows approximately linearly with increasing count rate. With count rates larger than ≈250 kHz, twilight counts noticeably affect the calibration result at desired accuracy. Considering the high DUT count rates typically used in substitution calibration measurements, this property must be taken into account to obtain an accurate DE result.

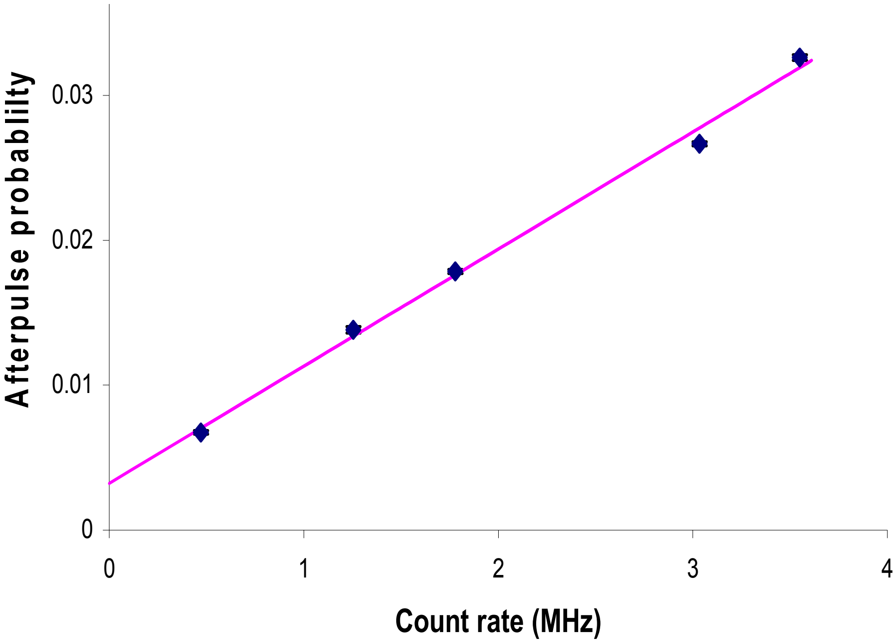

Fig. 3. Afterpulsing of the detector under test APD at various count rates. Uncertainty bars are shown.

We illustrate the effect of twilight counts in a separate set of measurements. By measuring the afterpulse fraction (defined as the likelihood of an afterpulse given an initial count of the detector producing a second pulse not due to a second photon) at a range of DUT count rates, we can quantify and fit the linearly growing component of the count rate. The slope of the resulting line is proportional to the duration of the twilight period and associated “twilight detection efficiency” (which might not be a constant throughout this interval). The zero rate intersection of this line is the ordinary afterpulse fraction. For the particular APD tested (Fig. 3), this method yielded an ordinary afterpulsing fraction of 0.00322(37). At the same time it is clear that the fraction of twilight events at the typical count rates of the calibration measurements is of the order of 1%. This is rather a big effect for the accuracies of interest. Notice that, effectively, the twilight effect shorten the deadtime, because the photon can produce an avalanche even if it is absorbed during the deadtime that will be detected by the APD electronics with a delay of up to 10ns [19, 20]. Therefore one can not simply use the measured deadtime as the region where the APD cannot fire, i.e. feature C in Fig. 1.

3.3 Definition of DE

To measure the DE of a SPD to high accuracy, we must first choose the appropriate definition of DE. Because of the multiple features of APDs which complicate their response, the most suitable definition will depend on the application. The most common definition of DE is the fraction of the number of events that would have been measured if the detector was ‘live’ (ready for a detection) each time a photon was incident on the system, denoted by η_{live}. This definition, however, does not fully describe the detector. Other factors play significant role in single photon detection, and must be accounted for. The main factors are: deadtime, twilight DE function $\eta_{\text{twilight}}(t)$, which describes the probability to detect a photon during the deadtime, and electronic afterpulsing probability. These characteristics vary between individual detectors, but are assumed not to vary with the count rate (an assumption supported by the linear dependence seen in Fig. 3 as well as other measurements [19]). In a cw measurement, η_{live} can not be measured directly. Thus, to complete the calibration, we need to extract the additional information to fully characterize the detector. For a cw source we could introduce an effective twilight time, which is the corrected time period so that the twilight DE can be set equal to the DE of the APD when it is 'alive'. The effective twilight time can be deduced, for example from the slope of the linear fit in Fig. 3. Then, the effective twilight time would be used to correct a deadtime. The most direct way of doing so, as well as computing the electronic afterpulsing fraction requires use of coincidence boards, which are rather expensive. We discuss a simpler solution, however, which will allow accurate calibrations using only pulse counting hardware.

As already stated, the appropriate definition of DE often depends on the particular application. As an example, an application that ignores delayed detections is a fast quantum key distribution channel. The DE definition for this application must reflect this and establish the DE with an appropriate cutoff of the 10 ns "twilight" tail.

3.4 Additional measurements

To fully characterize the detector to high accuracy, one needs to measure the deadtime (i.e. the time during which the detector can not produce a pulse), the twilight time (i.e. the fraction of deadtime when the detector produces an avalanche which can only be detected after the deadtime elapses), and the fraction of electronic afterpulses. We propose the following method to do so. One needs an electronic board to produce gate pulses of a fixed width (of 30-60ns for typical APDs), triggered by the APD output with a variable delay. The adjustment resolution of the delay line should be better than 0.5 ns. Pulses and the output of an APD are then combined on an AND gate, Fig. 4. The measurement consists of the following steps.

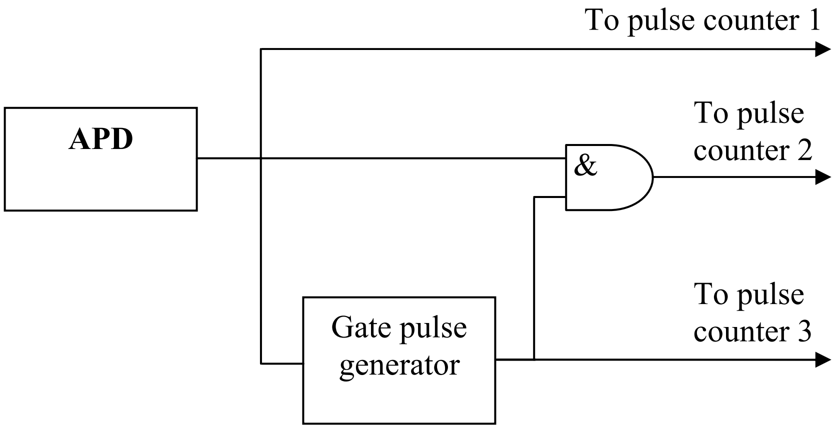

Fig. 4. Schematics of a setup to measure an electronic afterpulsing fraction and an effective twilight time.

Step 1: By varying the delay of a gate pulse at a high ($5 \cdot 10^6$) count rate on counter 1, the pulse count rate on counter 2 is maximized. This would correspond to recording the afterpulse feature D of Fig. 1.

Step 2: Measure the number of counts on counter 2 as a function of the rate of counts on counter 1. Normalize it by the number of pulses counted by counter 3.

Step 3: Delay the gate pulse by >200ns (i.e., much longer than the total deadtime) and measure the number of counts on counter 2 as a function of the rate of counts on counter 1. Normalize it by the number of pulses counted by counter 3. This is equivalent to measuring the "background".

Step 4: Subtract the curve obtained in step 3 from one obtained in step 2. This produces a function similar to one depicted in Fig. 3 that can be fitted to a straight line, whose properties are described in section 3.4. This yields an afterpulse probability, and twilight time values together with their uncertainties.

Step 5: The deadtime is measured separately on an oscilloscope. After this, the twilight time is subtracted from the deadtime.

The outlined procedure yields all necessary properties of an APD for a high accuracy calibration.

4. TYPICAL DETECTOR SUBSTITUTION METHOD UNCERTAINTY BUDGET

4.1 SPD-related features and uncertainties

DUT background events must be subtracted from the DUT signal events to obtain the DUT DE. Signal and background should be collected independently, in interleaved measurements. One needs to collect $\approx 2\cdot 10^6$ background counts . Then, after subtracting the background, the overall uncertainty due to *shot noise* will be below 0.1%. When needed, this uncertainty can be decreased further, by collecting more photoelectronic events. The *duration* of the measurement must be measured with an accuracy better than 0.1%.

Because of the *deadtime* property of the APD, in most cases the measurement time should be reduced by the total number of counts times the effective deadtime, which for most APDs is on the order of 50 ns. As the count rate increases so does the fraction of time when the APD is "dead," as does the uncertainty associated with the accuracy of deadtime measurement. For count rates of $2\cdot 10^6$/sec, the fraction of deadtime is 10% contributing significantly to the uncertainty. Note that the typical count rate for substitution measurements should be $\approx 10^6$/sec because the same photon flux (irradiance) has to be detectable by the photodetector. Hence, deadtime must be known with better than 2% uncertainty to result in 0.2% contribution to the overall uncertainty. This implies that the deadtime measurement of step 5 and twilight time should be known with nanosecond uncertainty.

Another potential source of uncertainty is *intensity fluctuations* of the light source. One can estimate the effect of such fluctuations by studying the nonlinearity of the APD as given by

$$C_{\tau=0} = \frac{C_{\text{measured}}}{1 - \tau\, C_{\text{measured}}}$$

where τ is the effective deadtime time, C_{measured} is the measured count rate, and $C_{\tau=0}$ is the hypothetical count rate at zero deadtime. For a typical power drift of 3 % root mean square (rms) this nonlinear response yields $\approx 0.02\%$ in overall uncertainty for the typical count rates.

Finally, one needs to know an *afterpulse probability* from step 4 to within 0.1% (approximately 20% of its value for most of APDs).

4.2 SPD-related features and uncertainties

Calibration of a conventional photodetector is an essential step in building a calibration facility. NIST provides calibration services that are traceable to NIST's cryogenic radiometer-based radiant power scale with a final detector calibration uncertainty of 0.1 % [21]. Because the detector has to operate at a gain of 10^{10} V/A for comparison with the APD, while the photodetector is calibration at a gain of 10^7 V/A, a separate step of gain calibration is required, which adds $\approx 0.05\%$ to the uncertainty budget. Typical spatial uniformity of the conventional photodetectors are measured as part of the NIST calibration procedure (see [21]). The standard deviation of the spatial variation of responsivity near the center of the detector is typically $\approx 0.01\%$ and hence can be neglected. For the purposes of our goal accuracy it seems reasonable to sacrifice some of the accuracy in favor of cost reduction. A conventional photodetector calibrated to an accuracy of 0.3% would be sufficient for this purpose.

Because the photodiode is calibrated for radiant power, a conversion is needed to obtain a DE value. For smooth spectral variations of radiant power responsivity of conventional photodiodes, an interpolation used over the filter's bandpass region weighted with the transmittance function of the filter would be sufficient. For a narrow filter (≈ 1 nm) one can assume an ideal white light source illuminating the calibration channel. *Filter transmittance* can be measured at NIST's Spectral Irradiance and Radiance Calibrations with Uniform Sources (SIRCUS) facility with an uncertainty of 0.1 % [22]. The absolute transmittance of the filter does not contribute to the final DE uncertainty, because only the bandpass shape, not its absolute transmittance is used in the calibration. The possible fringing effects, transmission tails of the filter , and the wavelength uncertainty of SIRCUS (0.01 nm) contribute negligibly (at the level of $\approx 10^{-3}$ %). [1]

Because the reflectance of the conventional photodetector is quite high (~30 %), *light trapping* can significantly affect these measurement results. The blackened apertures were checked and found to minimize any scattered/reflected light off of the photodiode from coupling back into the photodiode. Our experiment [1] showed that the magnitude of any residual backscatter from blackened apertures is low: less than the 0.1% measurement uncertainty.

Each substitution photodetector calibration consists of interleaved signal and background measurements to correct for any long-term drift. Electronic noise of the conventional detector dominates in this measurement. Therefore, data must be collected until the relative uncertainty for the averaged *signal* (less background) of ≈ 0.1 % is achieved.

4.3 Uncertainty estimate

For convenience, the estimation of realistically achievable uncertainties is combined in the Table 1. We note that some of the uncertainties, such as shot noise of the APD and conventional detector's shot noise can be reduced by increasing the overall time of measurement. Other values, such as deadtime and twilight time measurements, and light trapping can be measured with better uncertainty if the calibration facility has access to state of the art laboratory equipment.

Table 1. Detector substitution (conventional) calibration uncertainty budget

	units	Uncertainty	Relative Uncertainty of DE, %
APD Shot noise	%	0.1	0.1
APD Deadtime	ns	1	0.2
APD Twilight time	ns	1	0.2
Source Intensity fluctuations (APD)	%	3	0.03
APD Afterpulse probability	%	0.1	0.1
Time (APD)	%	0.1	0.1
Conventional detector's signal to noise	%	0.1	0.1
Calibration of a conventional detector	%	0.3	0.3
Light trapping	%	0.1	0.1
Filter transmittance	%	0.1	0.1
Total			**0.5**

5. CONCLUSION

In conclusion, we have introduced a portable and reliable procedure for high accuracy calibration of photon-counting detectors, realistically implementable on a moderate budget. Together with the DE, the calibration setup will fully characterize the APD, which is very important to correctly estimate its performance in different applications. We estimate that the total relative uncertainty of the DE can realistically be ≈0.5% (k=1) or better. This estimated uncertainty is only 3 times the current world record for such calibration. With all feasible optimizations and the best available conventional photodiode calibration a final uncertainty of 0.3% is possible. To reach the world record calibration, one requires coincidence boards to better characterize the APD's properties.

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