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Time-walk and jitter correction in SNSPDs at high count rates

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ABSTRACT
Superconducting nanowire single-photon detectors (SNSPDs) are a leading detector type for time correlated single photon counting, especially in the near-infrared. When operated at high count rates, SNSPDs exhibit increased timing jitter caused by internal device properties and features of the RF amplification chain. Variations in RF pulse height and shape lead to variations in the latency of timing measurements. To compensate for this, we demonstrate a calibration method that correlates delays in detection events with the time elapsed between pulses. The increase in jitter at high rates can be largely canceled in software by applying corrections derived from the calibration process. We demonstrate our method with a single-pixel tungsten silicide SNSPD and show it decreases high count rate jitter. The technique is especially effective at removing a long tail that appears in the instrument response function at high count rates. At a count rate of 11.4 MCounts/s, we reduce the full width at 1% maximum level (FW1%M) by 45%. The method, therefore, enables certain quantum communication protocols that are rate-limited by the FW1%M metric to operate almost twice as fast.

Over the last decade, superconducting nanowire single-photon detectors (SNSPDs) have advanced rapidly to become essential components in many optical systems and technologies, owing to their high efficiency (>90%), fast reset times (<1 ns), and scalability to kilopixel arrays. The timing jitter of SNSPDs is also best-in-class—values as low as 3 ps have been demonstrated in short nanowires, and new high-efficiency designs exhibit sub-10 ps jitter.

SNSPD jitter increases with count rate due to properties of the nanowire reset process and features of the readout circuit. The effect bears resemblance to time-walk observed in silicon avalanche diodes and other detectors where the pulses have varying heights and slew rates, thereby causing a timing measurement using a fixed threshold to "walk" along the rising edge of the pulse [the labeled delay in Fig. 1(a)]. At low count rates, SNSPDs exhibit very uniform pulse heights. However, at high counts rates where the inter-arrival time is on the order of the reset time of the detector, current-reset and amplifier effects lead to smaller and distorted pulses. If photon inter-arrival times are not known a priori in the intended application, the uncorrected time-walk manifests as a perceived increase in jitter [Fig. 1(b)].

The time-walk effect in SNSPDs is typically not reported as jitter is usually measured at low count rates where the detector has ample time to reset following each detection. However, as communication and quantum information applications push into higher count rates, the high count rate-induced jitter becomes more relevant. LIDAR, quantum and classical optical communication, and imaging applications may all benefit from the development of new detection systems and methods that keep jitter as low as possible in this regime.

We first consider the features of SNSPD operation and readout that cause an increase in jitter with count rate. Then, we present multiple ways of mitigating or avoiding these effects, before reviewing our preferred method that relies on a calibration and correction process. The jitter increase observed at a high rate originates from two groups of system characteristics: (i) the intrinsic reset properties of the nanowire and (ii) properties of the amplification chain. These influence the system’s jitter differently; thus, it is helpful to consider them...
The nanowire reset process determines how the detector gate current, the calibration technique depending on the design of the readout circuit. If they last longer than the decay time constant of the RF pulse. The time walk manifests as an increase in the rising edge of each SNSPD pulse. If uncorrected for, this time-walk may correct for the potentially complex interactions between pulse waveforms that overlap in time.

There are various methods for correcting increased jitter at high count rates. These include (i) the use of extra hardware that cancels out some distortions or (ii) simple software-based data filtering that ignores distorted time tags. We review these techniques before covering the calibration and correction approach.

Variations in pulse height are a primary component of the distortions that appear at high rates. Such variations in other systems are commonly corrected with a constant fraction discriminator (CFD) that allows for triggering at a fixed percentage of pulse height rather than at a fixed voltage. Adding a CFD to an existing setup is straightforward for a single channel; however, it does require additional hardware, such as multiple high-speed discriminators and a D-type flip-flop, which significantly increases the circuit complexity and power budget of a multi-channel system. In addition, CFDs are not expected to optimally correct for distortions of the pulse rising edge, which may arise from the overlap of one pulse with a signal reflection or undershoot features on the falling edge of a previous pulse. Multi-channel time-to-digital converters (TDCs) used to reading out large SNSPD arrays typically only include fixed-threshold comparators. In a simple software-based jitter mitigation method, each time-tagged event may be accepted or rejected based on how soon it arrives after the previous pulse. Those that arrive within some pre-determined dead time are assumed to be corrupted by pulse distortions. These are rejected, and the rest are accepted. This method can lower system jitter and maintain high data rates, especially in the cases where only a few percent of pulses are filtered out. However, it can severely limit count rate near the 3 dB point where the majority of counts are rejected (see the supplementary material).

Our correction method preserves the original count rate and works with timing measurements from a fixed-threshold free-running TDC—the type that is often used for SNSPD readout. Pulse pileup correction techniques have been demonstrated with systems that fully digitize detector pulse waveforms. However, capturing the fast rising edges of SNSPD pulses in this way would require very high sample rates and, subsequently, impractically large data streams. In contrast, our method assumes one timing measurement is acquired from triggering on the rising edge of each SNSPD pulse.

We calculate the time between a given current SNSPD detection event and a preceding event. This inter-arrival time is used to determine a timing correction for the current event using a lookup table. A calibration routine described next is needed to build this lookup table. Applying these corrections during real-time processing removes deterministic delays correlated with the time between time tags, leaving only stochastic jitter.

We study the pulse distortions observed in a fiber coupled single-pixel tungsten silicide (WSi) SNSPD with 380 µm² active area and 160 nm nanowire width. The detector is biased at 9.3 µA, roughly 90% of the switching current. The readout is handled by a cryogenic DC-coupled amplifier, mounted on the 40 K-stage of the cryostat, which has 43 dB of gain and a 3 dB bandwidth of 700 MHz, followed by a 1 GHz amplifier with 20 dB of gain (MiniCircuits ZFL-1000LN+). The system reaches a 3 dB maximum count rate (MCR) of 15.6 MHz. The time constant of supercurrent recovery \( \tau_{\text{sh}} \approx 40 \) ns is significantly longer than the decay time constant of the RF pulse \( \tau_{\text{RF}} \approx 5 \) ns, owing to our use of a low-frequency cut-on of \( \approx 80 \) MHz (3 dB point

FIG. 1. (a) Diagram illustrating two major sources of correlated high count rate jitter. First, detections may occur during the reset time of a previous detection. At this time, the bias current in the nanowire is below its saturated value so that a photodetection triggers an RF pulse with correspondingly lower amplitude. Second, an RF pulse may arrive in the undershoot region of a previous pulse, where the undershoot is a period of negative voltage induced by the low-frequency cutoff properties of the readout amplifier chain. (b) Measured histograms of detections from short 3 ps mode-locked laser pulses. With lower attenuation and higher count rate, the instrument response functions (inside dashed black box) even at count rates significantly below the 3 dB point where detector efficiency has not started to drop significantly (e.g., the 1.7 Mcps data).
from the peak gain) in the DC-coupled amplifiers. For this detector, the calibration process primarily corrects for the lower bias current effects, rather than for any overlapping between RF pulse waveforms (see the supplementary material). Other detector types and readout systems may operate in a different regime.

The jitter increase with count rate is highly dependent on trigger level. High rate distortions affect the timing measurements less if the threshold voltage is set just above the noise floor. However, triggering on the pulse higher, where it achieves maximum slope, minimizes jitter at low-to-medium count rates. This level varies from 20% to 50% of pulse height depending on the detector. We found the minimum low-rate jitter at a trigger level of 50 mV, about 40% of the pulse height. All further calibration and analysis are performed by triggering at this level in order to optimize jitter across all count rates.

To perform our calibration, we illuminated the SNSPD with an attenuated 537.5 MHz mode-locked laser with a mean photon number per pulse between $5 \times 10^{-4}$ and 0.016. The 1.86 ns period of the pulse sequence is large enough that almost all SNSPD detections can be unambiguously matched with a preceding laser pulse—the period of the pulse train used must be greater than the worst detector jitter for this to succeed. The uncorrected jitter for the WSi detector varies from 50 ps FWHM at low count rates to about 350 ps at high rates.

We collect sorted time tags and first consider adjacent pairs of SNSPD events as illustrated in Fig. 2(a). The time between the two photons that produced these event pairs is defined as $t'$, which is an integer number of laser periods ($t' = nt_l$). Second, we derive the delay between the second event and its corresponding laser pulse, defined as $d$. For each laser period spacing $t'$, we make a histogram of the second event delays and find the median ($d$) and the FWHM ($\Delta d$) of this distribution. For shorter separations $t'$, the distribution is expected to have larger delays and FWHM [Fig. 2(b)] due to the smaller pulse height of the second event. Finally, we use the median delay as a function of laser spacing [Fig. 2(c)] to form a curve $d$–vs–$t'$ for the added time-walk vs inter-arrival time.

Figure 3(a) shows the $d$–vs–$t'$ and $\Delta d$–vs–$t'$ curves collected from our measurements of the WSi detector. The $d$–vs–$t'$ curve is the main result of the calibration process and is used as a lookup table in the correction method. $\Delta d$ is a measure of the more intrinsic jitter that the correction method cannot cancel out. While it is larger for small $t'$ due to triggers on lower amplitude pulses, it notably stays at a nearly minimized value down to around $t' = 50$ ns. $d$ grows more

![Figure 2](image-url)

**FIG. 2.** (a) Qualitative diagram illustrating how inter-pulse timing measurements $t'$ and $d$ are extracted. A small fraction of laser pulses contain a photon due to the low mean photon number per pulse of the attenuated laser. Pairs of subsequent photon arrivals are separated by a time denoted by $t' = nt_l$. (b) Possible distributions of delay $d$ measurements for two different $t'$. The median of these defines the extracted delay parameters $d$, which form the y-axis in the calibration curve illustrated in (c). The $d$ vs $t'$ curve in (c) approaches zero for $t'$ approaching infinity. Blue and green arrows with matching color and style denote the same measure in (a)–(c).
dramatically with decreasing $t'$, especially in the range from 50 to 100 ns. For count rates that do not exhibit many inter-pulse arrival events smaller than 50 ns, a method for removing the time-walk effect’s contribution to jitter should bring the entire system jitter back down to near the intrinsic limit implied by the $\Delta t$ curve.

The correction method we implement involves subtracting off the distortion-induced delays a time tag is expected to have based on the inter-pulse time that precedes it. For each time tag $t_n$ in a set, the inter-pulse time is $t_n - t_{n-1} = \Delta t_n$, where $t_{n-1}$ is the previous tag on the same channel. Using $\Delta t$ as an index, a corresponding delay correction $\Delta d$ is found by interpolating the $d$–$vs$–$t'$ curve from the calibration.

Given the density of points in the $d$–$vs$–$t'$ acquired here, a linear interpolation is sufficient. The correction may benefit from higher order interpolation if the $d$–$vs$–$t'$ curve is more sparse. This would be the case for calibrations built from a slower repetition rate pulsed light source. An assumption underlying the correction is that the interpolated value $d$ is a good estimator of the true delay added to the current time tag due to high count rate pulse distortions.

With the interpolation operation expressed as a function $D$, the correction is written as $t_n = t_n - D(\Delta t_n)$, where $t_n$ is the corrected version of tag $t_n$. Whether $t_{n-1}$ is itself corrected or uncorrected has negligible influence on the $t_n$ correction, as we assume $d \ll \Delta t$. The data correction shown here was applied in post-processing. However, since $D$ depends only on the current time tag and information available from earlier, the correction can be applied in real time in an FPGA or computer used for time tagging.

The correction we perform using the $d$–$vs$–$t'$ curve in Fig. 3(a) is applicable to a wide range of count rates and arbitrary modulation patterns; there is no requirement that applications match the repetition rate of the calibration laser. Figure 3(b) shows that the correction method, derived from the 537.5 MHz calibration data, significantly reduces jitter when applied to detections from a 2.15 GHz pulse train. A similar jitter reduction can be demonstrated for repetition rates below 537.5 MHz.

To study the effectiveness of our correction method at different count rates, we apply it to data collected at different mean photon numbers per pulse, with the same 537.5 MHz pulse train. As shown in Fig. 3(c), the correction improves the FWHM at rates approaching the 3 dB point and improves FW10% and FW1% (full width at ten percent/one percent maximum) dramatically, even at count rates significantly below the 3 dB point where detector efficiency is nearly maximized. This reduction is evident in 3d, where the correction works to remove a time-walk-induced tail in the instrument response function. The ratio of corrected FW1% over uncorrected FW1% reaches a minimum of 0.55 at a count rate of 11.5 MCounts/s. Therefore, if an application sets its repetition rate or bin size based on the FW1%M metric, the repetition rate can be increased and the bin size decreased by up to 45% without any increase in event misattribution errors. These improvements are notable for applications including biomedical imaging, quantum communication, and laser ranging that have stringent timing requirements over a large dynamic range.

For some SNSPD systems, the intrinsic reset time of the nanowire is considerably shorter than the reset dynamics of the amplifier chain. Then, the delay effect induced on each pulse may depend on the arrival time of multiple previous pulses, as amplifier reset dynamics combine additively. To optimally correct for this, higher order correction techniques are needed based on higher dimensional lookup tables. There is an avenue for exploring such methods for unique-use cases.

The technique described in this work could be adapted for pulses measured at multiple voltage levels, or even fully digitized pulses captured with high-speed ADCs and FPGAs. These more rigorous readout techniques may be needed to deconvolve photon timing and photon number resolution effects from the same nanowire at high count rates.

There is a broad range of extensions and modifications to the presented method that may prove to be useful. However, the single-$\Delta t$ measurement approach detailed here is broadly applicable and straightforward to implement.

As applications such as LIDAR and quantum communication demand ever higher data rates, multiple techniques for increasing photon and data throughput of SNSPD systems are being explored. Arrays or multi-channel SNSPD systems will play a role in satisfying that demand. However, compared to multiple lower count rate SNSPDs operating in parallel, a single detector operating at high rate has certain advantages. First, it makes more efficient use of the extensive bandwidth of the RF readout channel. Second, the single detector with single readout line puts less thermal load on the cooling system than multiple detectors with multiple readout lines. Therefore, paths toward operating individual SNSPDs at the limits of their count rate performance should be explored before extending to multi-pixel systems. This work is a step toward unlocking all available performance and timing precision of SNSPDs operated at high count rates.

See the supplementary material for details on the experiment setup and hardware (S1), the reset dynamics for the studied SNSPD (S2), and the dead time filtering technique (S3).

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AUTHOR DECLARATIONS
Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Andrew Mueller: Formal analysis (lead); Investigation (lead); Methodology (lead); Software (lead); Visualization (lead); Writing – original draft (lead). Emma Wollman: Conceptualization
DATA AVAILABILITY

The data that support the findings of this study are openly available in SNSPD-time-walk-and-jitter-correction at https://doi.org/10.6084/m9.figshare.20372646.v1.

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