Time of Flight Light Detection and Ranging (ToF LiDAR)

Time-of-Flight Light Detection and Ranging (ToF LiDAR) with Superconducting Nanowire Single-Photon Detectors and the Swabian Instruments Time Tagger X

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Time-of-Flight Light Detection and Ranging (ToF LiDAR) is a powerful method for 3D imaging, where a pulsed laser is reflected from a target and the time delay of the returned photons provides distance information. Achieving sub-millimeter resolution in such systems requires ultra-low-jitter detectors and high-precision timing electronics. At the University of Münster, PhD researcher Adrian Abazi developed an SNSPD-based ToF LiDAR platform that integrates waveguide-based SNSPDs (wi-SNSPDs) with Swabian Instruments' Time Tagger X in HighRes mode (TTX-HR). The waveguide geometry enhances photon absorption efficiency while maintaining low timing jitter, thereby enabling precise photon time-stamping for ranging applications. The system exploits multiphoton-enhanced resolution with the Time Tagger X to further reduce jitter, supporting high-accuracy ranging and novel applications such as digital twin generation of real-world environments [1].

EXPERIMENTAL SETUP

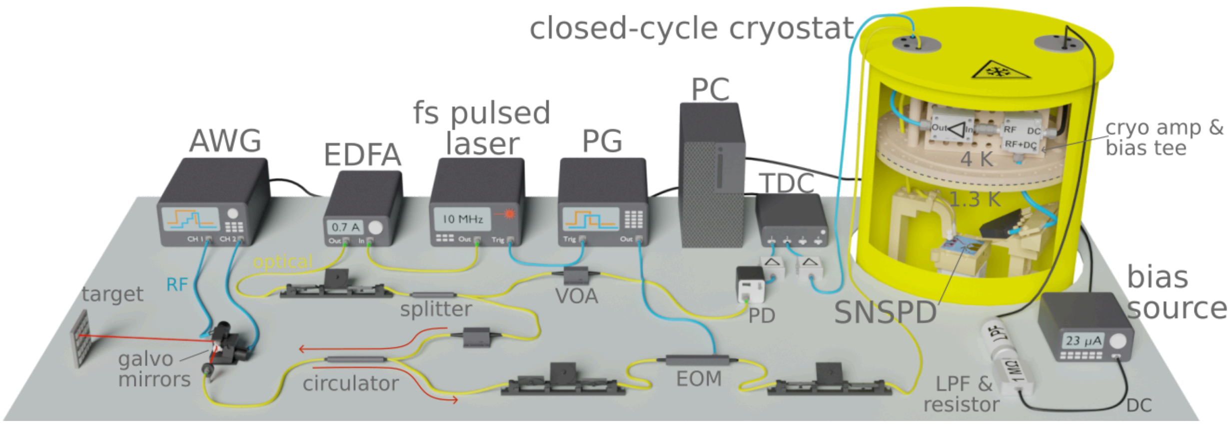

Figure 1 - SNSPD-based ToF LiDAR setup. Laser pulses are reflected off a target (left), collected, and detected with an SNSPD. The ToF is determined via the latency with respect to a reference signal on a photo-diode (PD) and a time-to-digital converter (TDC), Swabian Instruments' TTX. The galvo mirrors scan the beam over the target, creating an image by repeating the ToF measurement for varying angles. (Adapted from doi=10.1103/sv4y-qps6).

Figure 1 illustrates the experimental setup for ToF LiDAR measurements, consisting of a frequency-modulated pulsed laser source at 1550 nm. The system determines the ToF by measuring the delay between a reference signal captured by a photodiode ("start") and the reflected pulse detected by the wi-SNSPD ("stop"), both timestamped using the TTX-HR. By repeating this sequence while scanning the beam with galvo mirrors, ToF histograms are accumulated, and spatially resolved distance information is reconstructed.

MEASUREMENT AND RESULTS

The results demonstrate a range of precision of 750 µm when imaging an aluminum plate at a distance of 51 cm and a wavelength of 1550 nm. To achieve sub-millimeter ranging resolution, the detectors were driven into a multiphoton regime and the TDC jitter was minimized (TTX-HR = 1.5 ps RMS).

The contribution of all setup components (detector, synchronization, laser, etc) resulted in a low total system jitter of: $\Delta t\_TOF = \sqrt{\Delta t\_other^2 + \Delta t\_TTX^2} = \sqrt{4.2^2 + 1.5^2} \approx 4.5\ ps$ RMS

In addition to the enhanced resolution, the integration of the Time Tagger X enabled real-time histogramming and rapid optimization of detector bias voltages, which provided cleaner timing distributions and more stable calibration. Configurable trigger levels on the TTX were particularly valuable for resolving closely spaced photon arrival events. For more information on trigger level adjustments, histogramming capabilities, and overall data acquisition and analysis features, please visit Swabian Instruments' documentation on Measurements [2].

Together, these measurements confirm that combining waveguide-integrated SNSPDs with the picosecond-resolution timing capabilities of the Time Tagger X makes it possible to extend ToF LiDAR into a regime of unprecedented precision. The ability to achieve stable sub-millimeter ranging under experimental conditions illustrates the potential of this approach for next-generation LiDAR imaging and quantum sensing applications.

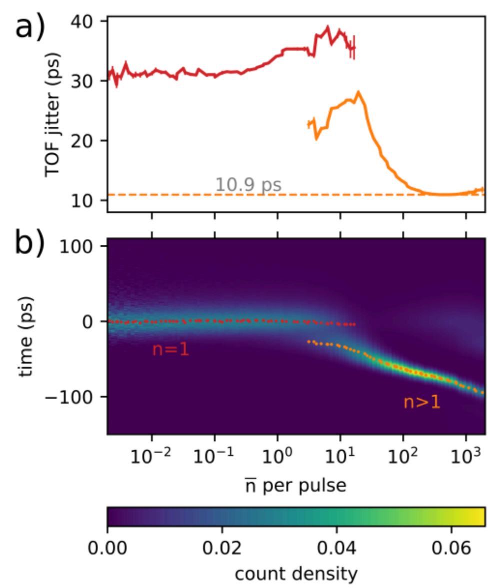

Figure 2 - SNSPD ToF measurements for different average photon numbers: a) FWHM ToF jitter values for n = 1 (red), n > 1 detections (orange). b) ToF histograms y-axis = latency time, x-axis = photon number, color = count density. Dots indicate the centers of Gaussian fits. (Adapted from doi=10.1103/sv4y-qps6)

CONCLUSION AND OUTLOOK

This application note demonstrates how a waveguide-integrated superconducting nanowire single-photon detector (SNSPD)-based Time-of-Flight (ToF) LiDAR system at the University of Münster, Germany, was enhanced using Swabian Instruments' Time Tagger. Thanks to the low intrinsic timing jitter of the Time Tagger X in High Res mode (~3.5 ps FWHM), its integration into the system resulted in total jitter of only ~11 ps, enabling sub-millimeter ranging precision of 750 µm at 1550 nm. This is only possible given the low timing jitter of all the components of the setup, including the single-digit picosecond precision of the Time Tagger X when operating in High Resolution mode.

Beyond the hardware capabilities of the Time Tagger X, the ability to capture rising and falling edges of the incoming pulses is critical for pulse width analysis and, therefore, Photon Number Resolving (PNR) applications. Future work by Adrian seeks to incorporate PNR measurements into their experiments to better characterize photon distinguishability and also advance quantum sensing applications.

REFERENCES

[1] A. S. Abazi, R. Jaha, C. A. Graham-Scott, W. H. P. Pernice, and C. Schuck, "Multiphoton enhanced resolution for superconducting nanowire single-photon detector-based time-of-flight lidar systems," Phys. Rev. Res., vol. 7, no. 3, p. 033114, Aug. 2025, doi: 10.1103/sv4y-qps6.

[2] https://www.swabianinstruments.com/static/documentation/TimeTagger/api/Measurements.html