Linearized SPAD response for high photon flux and histogram-less d-ToF systems

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Introduction

SPAD-based d-ToF image sensors measure the arrival times of photons emitted by a pulsed laser source to extract the distance of objects in the scene. Among the **performance-limiting** factors of such systems, the most impacting are:

- **High photon flux** scenarios **(background light)** → **pile-up** distortion
- **Amount of data** to be handled

SPADs are non-linear detectors, and together with system-related memory limitations, usually the first or the first N photons are timestamped.

We focus on the **linearization** of the **SPAD response** over time to achieve:

- **High photon flux** operation regime
- **Histogram-less** approach to d-ToF extraction

Linearization

A linearized SPAD response offers several advantages:

- **pile-up free** histogram with improved **SNR**
- **high photon flux** operation regime
- **Histogram-less** ToF computation

We propose two acquisition schemes to emulate a linear response over time from a SPAD

- "**Acquire or discard**" approach
- "**Asynchronous time-gated**" approach

Histogram-less approach

Split the measurement in two phases:

- phase (1) → only background
- phase (2) → background + laser

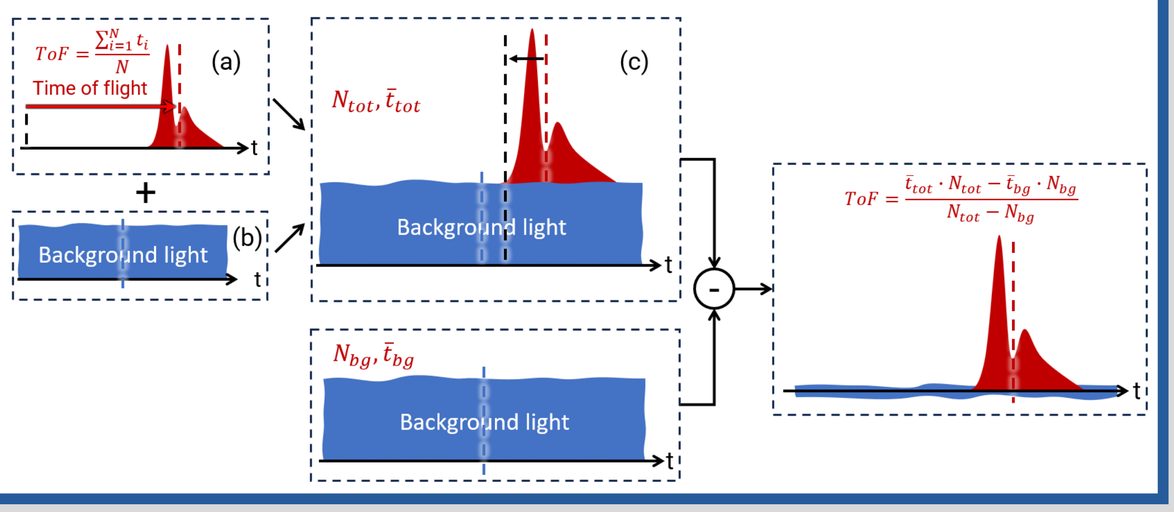
$$\text{ToF} \propto (2) - (1)$$

In particular:

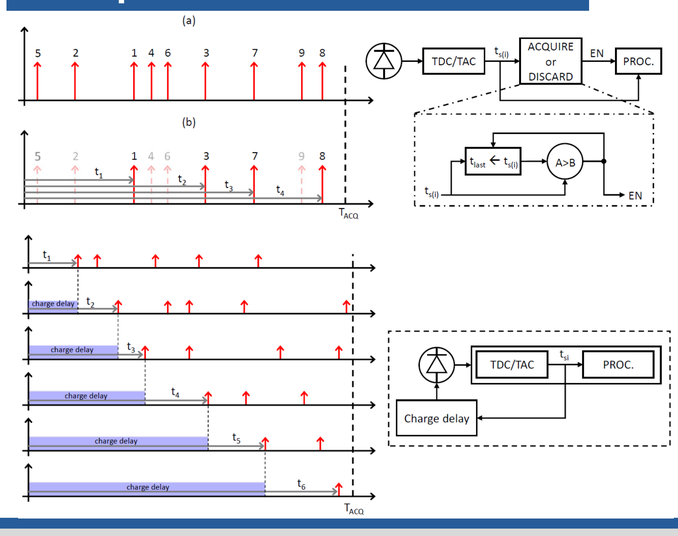
- (1) → $\bar{t}_{bg}, N_{bg}$
- (2) → $\bar{t}_{tot}, N_{tot}$

$$\boldsymbol{ToF = \frac{\bar{t}_{tot} \cdot N_{tot} - \bar{t}_{bg} \cdot N_{bg}}{N_{tot} - N_{bg}}}$$

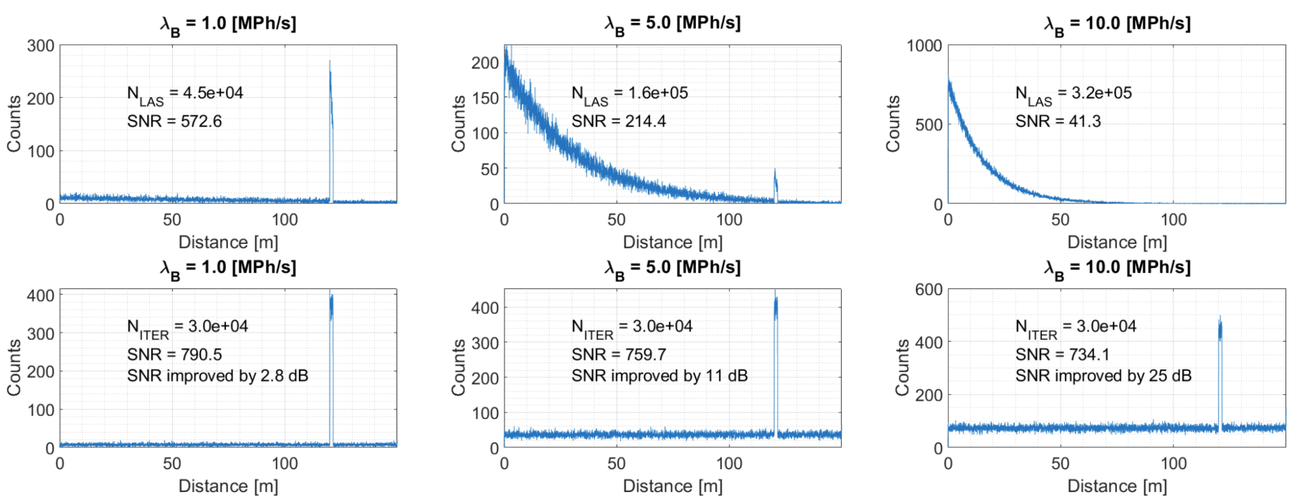
Histogram-less operation with low resource usage!



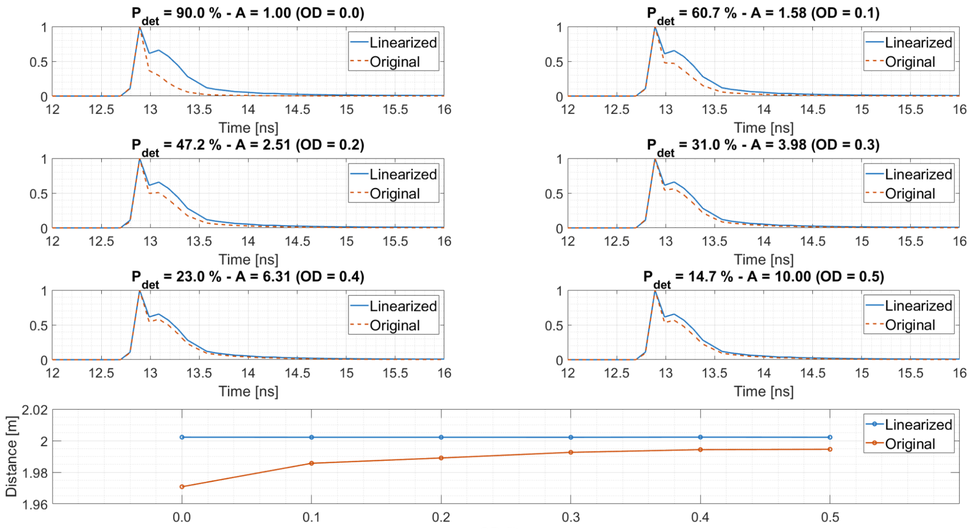
Acquisition schemes



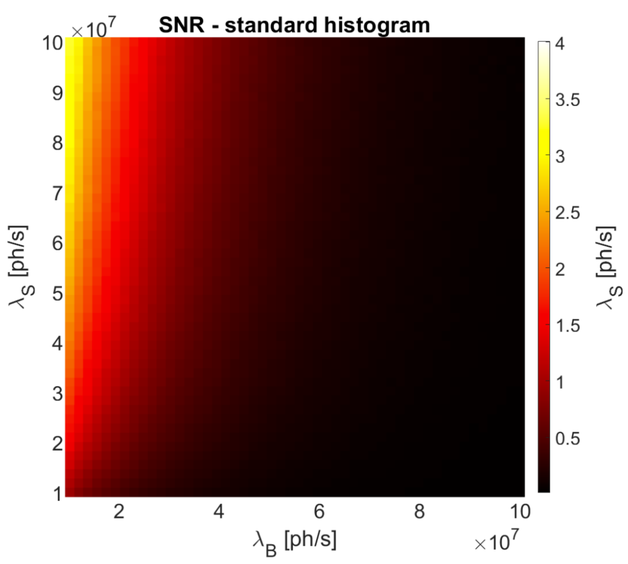
Results



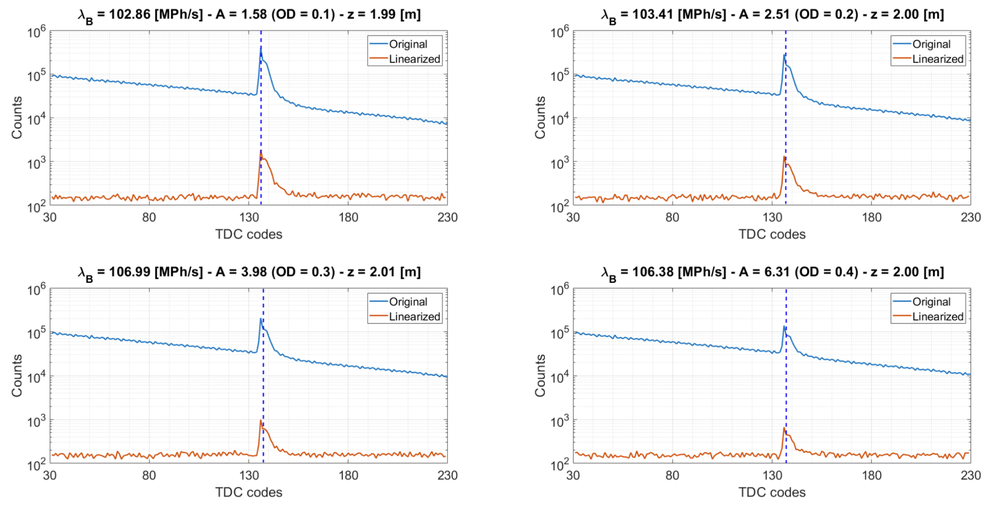
Simulation results: comparison of histograms from the standard detection approach (first hit – upper row) and linearized SPAD response (asynchronous time-gating – lower row). Thanks to the linearization over time, both range and SNR can be improved. The same number of laser shots has been considered for a fair comparison.



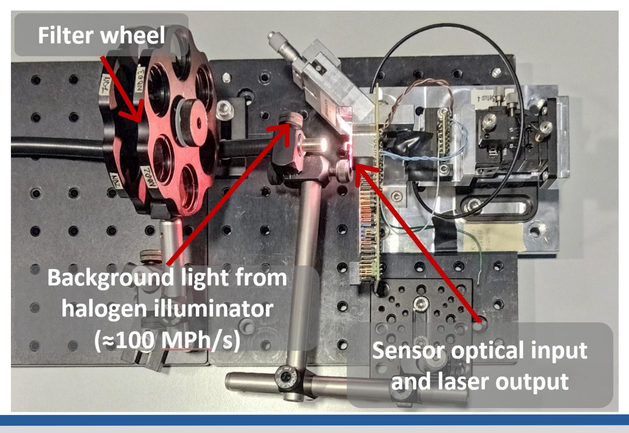
Measurement results: behavior in terms of pile-up error of the proposed linearized SPAD response. The accuracy error can be reduced from 2.4 cm (original histograms) down to 0.12 mm, equivalent to 99.5% reduction in the considered setup.



Comparison of histograms from the standard detection approach (first hit) and linearized SPAD response (asynchronous time-gating). Thanks to the linearization over time, both range and SNR can be improved. The same number of laser shots has been considered for a fair comparison. The average SNR increase is 7.8 dB.



Ranging measurements at 2 meters distance with the ToF extracted thanks to the proposed histogram-less approach. The original and linearized histograms of timestamps are shown for reference. The background rate has been set beyond $100 \cdot 10^6$ events/s and the measurements have been obtained with four different optical attenuation values for the returning laser intensity, to also demonstrate the effectiveness against pile-up distortion well beyond the standard 5% limit.



Measurement setup used for the characterization. The controllable fiber-coupled halogen illuminator is pointed directly toward the input facet. The equivalent rate of events at the output of the SPAD detector is over $100 \cdot 10^6$ events/s. The intensity of the received laser light can be attenuated with a set of ND filters (OD 0.1 to 0.5)

References

1. **M. Perenzoni et al.** A Fast 50 x 40-Pixels Single-Point DTOF SPAD Sensor With Photon Counting and Programmable ROI TDCs, With σ<4 mm at 3 m up to 18 klux of Background Light. *IEEE Solid-State Circuits Letters, 2020.*
2. **O. Kumagai et al.** A 189 x 600 Back-Illuminated Stacked SPAD Direct Time-of-Flight Depth Sensor for Automotive LiDAR Systems. *ISSCC 2021.*
3. **E. Manuzzato et al.** A 64 × 64-pixel flash LiDAR SPAD imager with distributed pixel-to-pixel correlation for background rejection, tunable automatic pixel sensitivity and first-last event detection strategies for space applications. *ISSCC 2022.*
4. **A. Tontini et al.** Histogram-less LiDAR through SPAD response linearization. IEEE Sensors, 2023.