Less Photons for More LiDAR?
A Review from Multi-Photon Detection to Single Photon Detection

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Introduction

Aerial photogrammetry and Airborne Laser Scanning (ALS) are the most widely used methods for generating Digital Elevation Models (DEMs), including Digital Terrain Models (DTMs) that depict ground topography and Digital Surface Models (DSMs) that depict the height of the ground, structures and vegetation cover. In contrast to photogrammetry, active LiDAR systems allow a direct and illumination-independent measurement of the distance to a surface also known as range.

The interrelationship between aerial photogrammetry and ALS has been intensely discussed within the aerial surveying community in the last decade. Different comparison factors concerning data acquisition (e.g. area coverage, weather conditions, costs) and surface reconstruction (e.g. accuracy, redundancy, processing time) have to be taken into account to choose the optimal method for a certain mapping campaign.

Conventional pulsed LiDAR systems for topographic mapping are based on Time-of-Flight (ToF) ranging techniques to determine the range to the illuminated object. The Time-of-Flight is measured by the elapsed time between the emitted and backscattered laser pulses.

Recently the laser pulse detection with the enhanced photon receiver technology seems to be offering new improvements for applying LiDAR, especially for ALS. Currently two companies designed LiDAR sensors with an enhanced photon receiver technology, the Harris IntelliEarth™ Technology based on a Geiger Mode LiDAR (GML) and the Sigma Space Single Photon Technology based on Single Photon LiDAR (SPL) [Stoker et al., 2016]. If new technology is introduced, concerns about them are often common. The same happened to conventional LiDAR, referred to as Multi-Photon LiDAR (MPL), but nowadays it is established for many applications. The goal of this short review is to focus on the main aspects and highlight some potential of this enhanced photon receiver technology with GML and SPL.

Photon detection for LiDAR

Depending on the application, LiDAR systems can be designed and characterized in different ways. They may differ in techniques concerning e.g. the modulation or detection. Concerning the modulation techniques, LiDAR systems can be separated into continuous wave (cw) laser or pulsed laser systems. For applications in remote sensing, the pulsed laser with the higher power density compared to cw laser is of advantage, because it allows operating at long ranges.

Detection techniques can be divided in coherent detection and direct detection. Coherent detection, namely heterodyne or homodyne detection, is based on signal amplification due to constructive interference of the optical wave front of the received signal with that of the reference signal from a laser. In direct detection laser systems, the received optical energy is focused onto a photosensitive element that generates an output signal that depends on the received optical power of a laser pulse. Two direct detection techniques, namely *Multi-Photon Detection* and *Single Photon Detection*, are appropriate for recording the temporal characteristics of a laser pulse, and also known in literature as full-waveform or waveform.

Multi-Photon Detection

The classical or conventional direct detection operates with a single photodiode. For optical detectors, a PIN (Positive Intrinsic Negative diode) or the more sensitive APD (Avalanche PhotoDiode) are utilized. The photodiode generates an electrical signal (voltage or current) that is directly linear proportional to the optical power of incident light composed by multiple photons, as well-known as photon flux. Therefore this kind of detection is also referred to as linear LiDAR [Ullrich & Pfennigbauer, 2016]

Figure 1 sketches a pulse remaining from a varying number of photons n over time t. For detailed analysis of the analogue signal, a digitising receiver unit is essential. Analysing the signal of the emitted short duration laser pulse with only a few nanoseconds pulse width (typically with 2-5 ns) requires a high bandwidth receiver that resolves the signal at MHz to GHz rates and a correspondingly high digitiser sampling rate. Increasing bandwidth results in decreasing sensitivity of the photodiode which can be compensated by increasing the power of the emitting laser source. An example of a Nd:YAG laser pulse sampled with 5 GSample/s is given in Figure 3A.

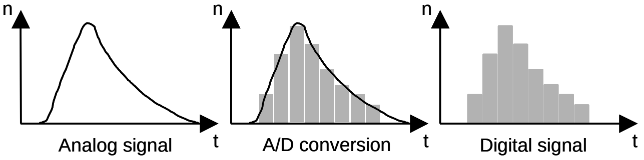


Fig. 1. Digital recording of the pulse waveform with Multi-Photon Detection [Jutzi et al., 2016].

Single Photon Detection

The principle of Single Photon Detection is depicted in Figure 2. A short duration pulse (typically shorter than 1 ns) is emitted by the laser source. A single photon of the backscattered pulse is detected by the receiver after the time interval τ_1. This event blocks the receiver for a certain period of time during which no further photons are able to trigger the receiver. This time is known as dead time or recovery time. The Time-of-Flight of this single event is collected into a corresponding time bin of a histogram. After the period of blocking, the receiver is open to detect a new single photon event. Multiple measurements are repeated and the Time-of-Flight of each single event (τ_2,τ_3, …) is registered into the corresponding time bin of the histogram. Let us assume a static scene and a stationary sensor platform. In this case the statistical properties of the laser radiation do not change with the time and time-average quantities are equal to the ensemble quantities. Under these assumptions, the radiation ensembles are stationary and ergodic. The counting of single photon events with assignment of their Time-of-Flight into time bins of a histogram is closely related to integration of multi photons over time. That means the temporal waveform of the pulse can be reconstructed from a histogram of single photon arrivals over time.

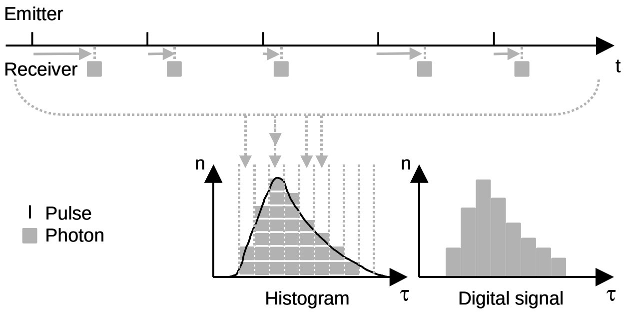
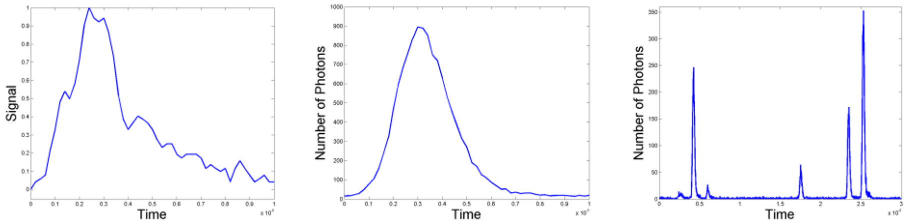


Fig. 2. Digital recording of the pulse waveform with Single Photon Detection [Jutzi et al., 2016].

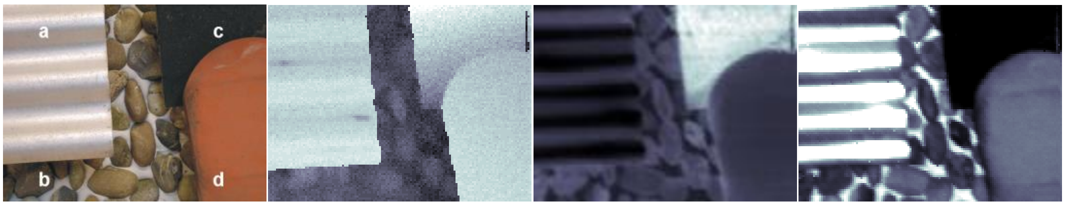
Many transmitted pulses are necessary to obtain the waveform with Single Photon Detection. The quality of the sampled waveform depends on the number of photon counts. Various optical detectors can be used for this purpose, namely PMT (photomultiplier tubes), MCP-PMT (micro channel plate PMT) or APD (avalanche photodiode) detectors. Figure 3B shows a pulse plotted from a histogram containing the Time-of-Flight measurements from 16252 photons distributed in 50 bins, where the bin width is 40 ps. Note that the full-width-half-maximum (FWHM) of the waveform in Figure 3A is about five times of the pulse in Figure 3B. Both widths of the waveform obviously rely on the FWHM of the emitted laser pulse. Furthermore a qualitative example for a waveform with multiple pulses (sum of pulses is 6) is depicted in Figure 3C. The number of photons per pulse peak in this example is in the range of about 20 to 350 photons. All measurements are acquired in a lab environment, but already show the potential of Single Photon Detection capabilities in terms of surface discrimination and sensitivity.



A B C

Fig. 3. Examples of waveforms from laser pulses backscattered from a diffuse surface. A) Multi-Photon Detection (FWHM 2.3 ns), B) Single Photon Detection (FWHM 0.3 ns), C) Waveform with multiple pulses (sum of pulses is 6) [Jutzi & Stilla, 2003].

Beside the measurement with Single Photon Detection already pulse feature extraction, namely range, pulse width, and pulse power, can be applied on the captured full-waveforms to exploit different surface characteristics like range, surface roughness, and surface reflectance as depicted in Figure 4.



A B C D

Fig. 4. Pulse features extracted from Single Photon Detection measurements. A) Test board with different urban materials: corrugated iron (a), pebbles (b), slanted slate plate (c), plane roof tile (d), B) Range image, C) Pulse width image, D) Pulse power image [Jutzi & Stilla, 2003].

Enhanced photon receiver technology with GML and SPL

Until a new technology is established, often the terminology is vague and confusing due to the different wording of the developers, researchers, surveyors, and customers. Beside the terminology, an accurate comparison with an essential evaluation between the different technologies is challenging because the techniques themselves are specific and sometimes not straight comparable at all. However, in the following, a comparison of the enhanced photon receiver technology with GML and SPL is tackled. The specifications are derived from company brochures (if specified), internet research or literature [Clifton et al., 2015; Degnan, 2016; Stoker et al., 2016; Ullrich & Pfennigbauer, 2016]. Furthermore, it has to be mentioned, that the interpretation of the specifications in Table 1 has to be done with respect to the applications of interest.

Type	**Multi-Photon LiDAR (MPL)**	**Geiger Mode LiDAR (GML)**	**Single Photon LiDAR (SPL)**
Technology	Various companies	Harris IntelliEarth™	Sigma Space
Instrument Name			HRQLS-1/HRQLS-2
Laser Wavelength	532/1064/1550 nm	1064 nm	532 nm
Laser Pulse Width @ FWHM	1-5 ns	0.55 ns	0.7/0.5 ns
Laser Beam Divergence @ 1/e^2	0.25-1 mrad	~5mrad	N/A (~0.2 mrad/beamlet)
Field-of-View (FoV)	≤ 72°	30°	0-40/20, 30, 40 or 60°
Detector Elements	1-2 PIN/APD	128x32=4096 GmAPD	10x10=100 MCP-PMT
Min. Pulse Detection	250-1000 Photons	8-10 Photons	1 Photon
Instantaneous FoV (iFoV)	0.25-1 mrad	0.035 mrad	0.2 mrad
Jitter Timing (Precision)	50-500 ps	250-500 ps	50-100 ps
BlankingLoss/Dead/Recovery Time	N/A	N/A (50-1600 ns typical)	1.6 ns
Pulse Repetition Rate (PRR)	≤ 1000 kHz	50-60 kHz	25/60 kHz
Max. Flying Height (AGL)	≤ 5800 m/15500 ft	≤ 11000 m/36400 ft	≤ 5500 m/18200 ft
Areal Coverage @ 8 pts/m^2	≤ 450 km^2/h	≤ 2100 km^2/h	≤ 808/2350 km^2/h

Table 1. Specifications of current Multi-Photon LiDAR in general as a standard combination of specifications from various companies, Geiger Mode LiDAR (GML) with Harris IntelliEarth™ and Single Photon LiDAR (SPL) with Sigma Space HRQLS-1/HRQLS-2.

Geiger Mode LiDAR (GML)

The Geiger Mode LiDAR with Harris IntelliEarth™ Technology operates in the near-infrared wavelength with 1064 nm. This near-infrared wavelength is favourable for LiDAR due to lower solar background, generally high reflectances from natural surfaces (soil/dry vegetation 25% and green vegetation 65%) and slightly better atmospheric transmission [Degnan, 2016].

The core of the GML technology is the optical receiver, it is not a single detector as presented in the section before, it is a relatively expensive array of APDs with 128x32 elements in total for the GmAPD array. The Instantaneous FoV (iFoV) is about 0.035 mrad per element and optical cross-talk can be an issue. The GmAPD array allows 4096 observations for each emitted short duration laser pulse of about 0.55 ns. The moderate pulse repetition rate is obtained with a 50-60 kHz laser. Multiple observations for the same surface spot, composed by four looks from four different directions, are provided by scanning stripes with 50% overlap. This scanning method leads to reliable 3D surface estimations if a highly accurate navigation solution is utilized during the measurement. For example, a GmAPD with a common Photon Detection Probability (PDE) of 0.3 for detecting a single photon theoretically [Ullrich & Pfennigbauer, 2016] already leads to a 90% surface detection probability with about 8 measured photon events.

Currently, the main limitation of GmAPDs is referred to as blanking loss. Blanking loss appears after a photon event is triggered, then an avalanche is released and the detector cannot detect incoming photons anymore. Typically values for blanking loss are 50 to 1600 ns (respectively 7.5 to 240 m in range), therefore in the most cases per each emitted laser pulse only a single measurement is derived per period. Thus GmAPDs range measurements show a systematic density shift towards the sensor, or with other words the penetration capabilities are very limited. As consequences while mapping vegetation, mainly the forest canopy hull is captured, below the hull the LiDAR measurements are underrepresented [Ullrich & Pfennigbauer, 2016]. With this kind of data, DSMs can be well determined, but generating DTMs might be challenging. But fortunately blanking loss is not an inherent limitation of GmAPDs. Future asynchronous Readout Integrated Circuits (ROICs) will probably enable multiple events per measurement cycle to overcome this restriction [Clifton et al., 2015].

The areal coverage with up to 2100 km^2/h (@ 8 pts/m^2) is enormous in comparison to MPL. But it has to be mentioned, that this could be only derived by the corresponding Maximum Flying Height of 11000 m/36400 ft Above Ground Level (AGL). Flying high altitudes for large mapping coverage are definitely more sensitive to atmospheric influences and effects caused by weather conditions like clouds.

Single Photon LiDAR (SPL)

The Single Photon LiDAR instruments HRQLS-1 and HRQLS-2 from Sigma Space operate in the visible domain with a wavelength of 532 nm. This wavelength is in the visible domain, with generally low reflectances from natural surfaces (soil/dry vegetation 15% and green vegetation 10%) is advantageous for LiDAR because the optical components are inexpensive, the detector arrays show a high efficiency, detector dark count contributions to background noise are typically much lower and the good transmission characteristic in water supports topographic mapping as well as bathymetry with a single instrument [Degnan, 2016].

Again, the optical receiver is the key for the SPL technology, a relatively inexpensive Micro Channel Plate photomultiplier tubes (MCP-PMT) with a 10x10 regular array of tiny tubes also known as microchannels. The jitter time of these tubes with 50-100 ps (respectively 0.75 to 1.5 cm in range), which has a significant impact on the range accuracy, is very low. Furthermore, the recovery time with 1.6 ns (respectively 24 cm in range) is important for daytime measurement capability. The low jitter time allows measuring multiple events per measurement cycle with great penetration capabilities for vegetation mapping or bathymetry. However, only a single event is generated per surface illumination, regardless of the amount of photons received, due to the short laser pulse width of 0.7/0.5 ns compared to the recovery time of 1.6 ns.

To ensure an efficient illumination of the microchannel and reduce optical crosstalk, each microchannel is illuminated by a so-called beamlet, therefore 10x10 beamlets are regularly arranged by a passive Diffractive Optical Element (DOE) in front of a 25/60 kHz laser. Thus the laser beam divergence of the beamlets is supposed to merge approximately the given 0.2 mrad Instantaneous FoV (iFoV) of the microchannels.

The instrument design is optimized to gain a maximum point density. Therefore per microchannel at least a single observation is expected. The SPL is tuned for Photon Detection Probability (PDE) of 0.95 for a 10% surface reflectance (e.g. green vegetation) and a PDE of 0.99 for a surface reflectance for a 15% surface reflectance (e.g. soil/dry vegetation). Then the sum of photons collected by the full 10x10 array is comparable to the sum of photons collected with a conventional Multi-Photon LiDAR (MPL). However, for each single microchannel measurement of the array, the 3D position can be reconstructed for all observations, while for a single detector element from a MPL the spatial information is reduced to a single observation due to the integration over the complete footprint [Degnan, 2016]. Depending on the iFOV of MPL (0.25.-1 mrad) and SPL (0.2 mrad), the influence is more or less significant.

The areal coverage of SPL is approximately in the same scale as for GML, but can be already achieved by half of the Maximum Flying Height of 5500 m/18200 ft of AGL.

Outlook

Currently, the greatest benefit of this enhanced photon receiver technology is the increased point density measurement capability or with other words the large area coverage with the corresponding advantageous economics. But at this point, some technical aspects must be tackled and clarified. A crucial aspect for the customer might be the surface reflectance capabilities of this technology, which is in principle possible (cf. Figure 4) but results in some design adaptation for the currently available GML and SPL systems. Due to the technical constraint that there are only a few photons used for the range measurements, the related intensity values might have less confidence for a reasonable radiometric measurement, but this has to be proven and depends strongly on the required measurement technique. Even more of interest for the surveying community is the range accuracy of the GML and SPL systems. There are some first independent investigations about the range accuracy already available [Stoker et al., 2016] but having said this, more investigations must follow to ensure a reliable answer for the applications of interest, like topographic or bathymetric mapping.

Some general remarks about the enhanced photon receiver technology with focus on principle constraints and potentials for prospective LiDAR sensing:

- SPL in the visible domain (532 nm) is excellent for bathymetry.
- Multi-spectral LiDAR with detector arrays is challenging.
- Optical crosstalk should be avoided by anti-reflecting coating.
- High altitude for large area coverage is more sensitive to atmospheric influences and effects caused by weather conditions.
- Small Field-of-View (which is a scanning issue) is suboptimal for real 3D data (façades).
- For GML the penetration capabilities are limited, DTM generation might be difficult.
- Image-based detector array analysis has potential for noise reduction, feature extraction or improved range accuracy.
- Surface reflectance capabilities should be provided by a reasonable radiometric measurement.
- The ranging accuracy of GML and SPL must be further investigated.

Finally, it can be stated that *Less Photons for More LiDAR* is possible but still challenges are remaining to handle this enhanced photon receiver technology with GML and SPL.

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