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REVIEW ARTICLE

EVALUATION OF SINGLE PHOTON AND WAVEFORM LIDAR

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ABSTRACT: In this short paper, the principles of single photon sensitive LiDAR are presented and compared against state-of-the-art full waveform, linear-mode LiDAR. The differences are explained in theory, and data of either technology are evaluated based on the City of Vienna dataset, captured in 2018 with the SPL100 (Leica) and VQ-1560i (Riegl), respectively. While SPL features a higher areal performance, waveform LiDAR turns out to be more precise, especially in complex target situations like natural or steep surfaces. Furthermore, the article summarizes current activities within EuroSDR concerning a potential Single Photon and linear-mode LiDAR benchmark.

1. INTRODUCTION

In addition to conventional airborne laser scanning (ALS), single photon sensitive LiDAR (Light Detection and Ranging) became commercially available in the recent years. The higher receiver sensitivity enables higher flying altitudes resulting in an increased areal measurement performance, which makes this new technology especially interesting for National Mapping and Cadastral Agencies (NMCA) in the context of acquisition and updating of countrywide topographic datasets as is, e.g., already the case in the U.S. within the 3D Elevation Program (Sugarbaker et al., 2014). The new technologies come in two flavours: (i) Geiger-mode LiDAR (Clifton *et al*., 2015; Stoker et al., 2016), and (ii) Single Photon LiDAR (SPL) (Degnan, 2016). Both technologies enable measurement rates of 5MHz or more, can be operated from flying altitudes beyond 4000 m, and therefore provide single-strip swath widths of more than 2 km. The latter is at least a factor of 2 compared to conventional LiDAR, also referred to as linear-mode LiDAR[1]. However, the gain in areal measurement performance comes at the prize of a higher outlier rate and a lower measurement precision (Ullrich and Pfennigbauer, 2018), especially in complex target situations (Mandlburger *et al*., 2019). In this short paper, the theory of single photon sensitive laser scanning is briefly introduced in Section 2. Section 3 presents setup and evaluation

[1] The term linear mode relates to the employed Avalanche Photo Diode (APD) operating in linear mode, i.e., the portion of the receivers' dynamic range, where the output (photons/voltage) is linearly related to the optical power.

results of a data acquisition in 2018 in Vienna, Austria. The aim of this pilot project was to test the feasibility of Single Photon LiDAR for high resolution 3D capturing of city areas and to compare the results against state-of-the-art Full Waveform LiDAR data. Section 4 introduces the basic ideas and current status of a planned EuroSDR SPL benchmark. The paper ends with concluding remarks in Section 5.

2. TECHNOLOGY OVERVIEW

This section introduces the main principles of conventional and single photon sensitve LiDAR. While focusing on the main aspects here, more elaborate introductions of the fundamental principles of the respective techniques can be found in the related literature (Clifton *et al*., 2015; Stoker et al., 2016; Degnan, 2016; Hartzell *et al*., 2018; Mandlburger *et al*., 2019). Both conventional LiDAR and single photon sensitive LiDAR use the time-of-flight measurement principle, i.e., a short laser pulse is emitted and the part of the signal backscattered in the direction of the sensor is detected at the receiver. Knowing the speed of light, the measurement range can be calculated from the round trip time of the laser signal, and together with the concurrently measured scan angle and platform position and attitude, 3D object point coordinates can be derived. In conventional LiDAR, the backscattered signal of a single laser pulse is captured by one receiver using Avalanche Photo Diodes (APD) operating in linear mode for converting the incoming radiation into analogue signals (voltage) and Analogue-to-Digital (AD) converters to further convert the analogue signal to the digital domain. Echo detection can be performed directly in the instrument based on detection threshold techniques (discrete echo systems) or by firmware-based analysis of the sampled waveform (online waveform processing) (Pfennigbauer *et al*., 2014)), or by storing the full waveform for echo detection and modeling in postprocessing (Mallet and Bretar, 2009). In all cases, this multi-photon technology requires approx. 250-500 photons for reliable echo detection. The lower bound corresponds to bathymetric LiDAR sensors using laser radiation in the visible green domain of the spectrum (λ=532 nm) for detecting typically weak signals from below the water table (Mandlburger and Jutzi, 2018).

Single photon sensitive sensors, in contrast, enable echo detection on the arrival of one or a few photons using Avalanche Photo Diodes operated in Geiger-mode (GmAPD). Within single photon sensitive LiDAR, two flavors exist. In so-called Geiger-mode LiDAR, developed and operated by Harris cooperation (Harris, 2019), a broad laser pulse illuminates an array of 128x32 GmAPDs. The system can therefore be thought of as a 3D range camera (focal plane LiDAR). Each APD cell represents a binary, first echo detector, where the stop impulse coincides with the breakdown of the APD, i.e., the instant of the photo-electric avalanche effect. Once triggered, a cell will only be active after a reset of the entire APD array for the next laser pulse. The missing penetration capability of this technology is compensated by the high measurement rate and the highly overlapping laser footprints on the ground. In contrast to that, the so-called Single Photon LiDAR technology developed by SigmaSpace corporation and now marketed as the Leica SPL100 instrument (Leica, 2019) uses a diffractive optical element to split the laser beam into an array of 10x10 beamlets. For each beamlet, the receiver comprises an array of single photon sensitive cells (Silicon Photo Multiplier, SiPM, Degnan, 2018). The technology therefore provides inherent multi-target capabilities. Both technologies, however, are prone to noise, as the diodes may also trigger either spontaneously or based on weak reflections from aerosol particles. More information on subject matters and be found in the cited literature.

3. PRACTICAL EVALUATION

In 2018, the surveying department of the City of Vienna (MA41) commissioned a flight with the Leica SPL100 (Leica, 2019) sensor to test the Single Photon LiDAR technology for city modeling. A second dataset, acquired with a state-of-the-art full waveform laser scanner (Riegl, VQ-1560-i) as well as reference data from terrestrial survey and stereo photogrammetry served as basis for data evaluation. Both flights were conducted in summer 2018. Table 1 summarizes the flight mission parameters and selected data evaluation results.

Table 1. SPL/Full Waveform (FWF), mission parameters and selected results

Category	Unit	SPL	FWF LiDAR
measurement	[kHz]	5000	1333
flying height	[m]	4000	840
swath width	[m]	2000	750
nr. of strips		10	21
strip pt. density (mean)	[points/m^2]	21	25
strip pt. density (median)	[points/m^2]	16	25
strip height difference (σ_z)	[cm]	4.1	1.0
σ_z for sealed road	[cm]	1.1	1.0
σ_z for roof	[cm]	1.0	0.7
σ_z for steep roof	[cm]	9.5	3.1
σ_z for natural surface	[cm]	3.9	1.0

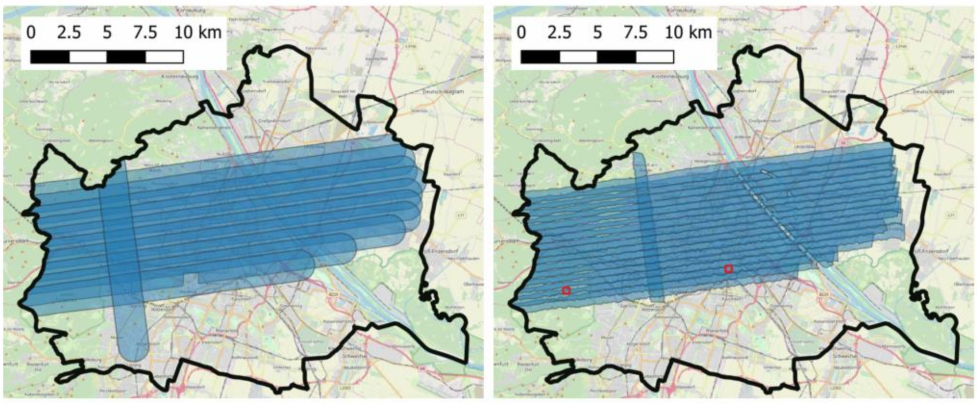

Figure 1. Strip overview of flight block Vienna; left: SPL, right waveform LiDAR

Figure 1 shows the study area and the flight block setup. For both acquisitions, the contracting authority requested a nominal single strip last-echo point density of 20 points/m^2 and a strip overlap of at least 50 %. A high overlap was chosen to test the façade capturing capabilities. To meet these specifications, the Single Photon LiDAR data acquisition was conducted with a total of 10 flight lines flown from 4000 m above ground level (AGL) with a pulse repetition rate (PRR) of 5 MHz. For the employed conical scanning mechanism (Palmer scanner) with an off-nadir angle of 15°, this resulted in a swath with of approx. 2000 m. For the linear-mode full waveform LiDAR system, 21 flight strips flown from 750 m AGL (swath width: 840 m) were necessary, to capture the same area. The employed sensor uses two independent laser sources deflected by the same rotating polygonal wheel, resulting in an x-shaped scan line pattern on the ground with a FOV of 56° featuring slight forwards/backwards, sidewards, and nadir looks for each strip. Figure 2 visualizes the actually achieved point density as color coded raster maps with different shades of green indicating the nominal last point density of at least 20 points/m^2. While the mean SPL point density of 21 points/m^2 meets the specification, this is mainly due to the very high density on the strip boundary as a consequence of the conical scan mechanism whereas the density in the strip center area is slightly below the requested 20 points/m^2. The rotating polygonal wheel used for the waveform LiDAR data acquisition, in turn, delivers a homogeneous density of 25 points/m^2, over-fulfilling the specification by 25 %. Figure 3 also reveals that, even with the 50% overlap, neither technology provides full façade coverage. Depending on flight direction, steepness of street canyon, building orientation, and roof overhang, facade points are present in the one dataset but not in the other, and vice versa.

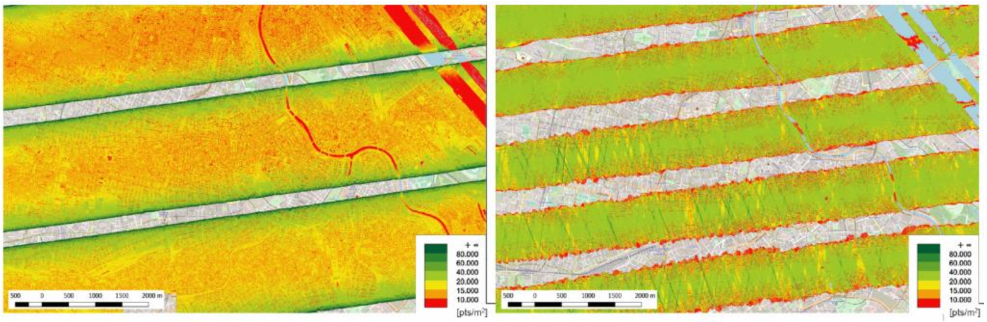

Figure 2. Color coded point density map for selected flight strips; left: SPL, right: waveform LiDAR

Figure 3 shows 3D point cloud of a building block for both the SPL and waveform LiDAR data capture. As can clearly be seen from Figure 3 (left), removal of the abundant clutter points is an important step within the SPL data processing pipeline. Still, with the noise points removed (middle), the waveform LiDAR point cloud (right) appears more crisp concerning, both, geometry and radiometry.

As a last data evaluation example, Figure 4 depicts the local measurement precision as a color coded map. SPL is competing with conventional waveform LiDAR on horizontal surfaces (sealed road, flat roof) with a height precision (σ_z) around 1 cm. At more complex target situations (steep roofs, meadow), a more pronounced drop of precision is observed for SPL compared to waveform LiDAR.

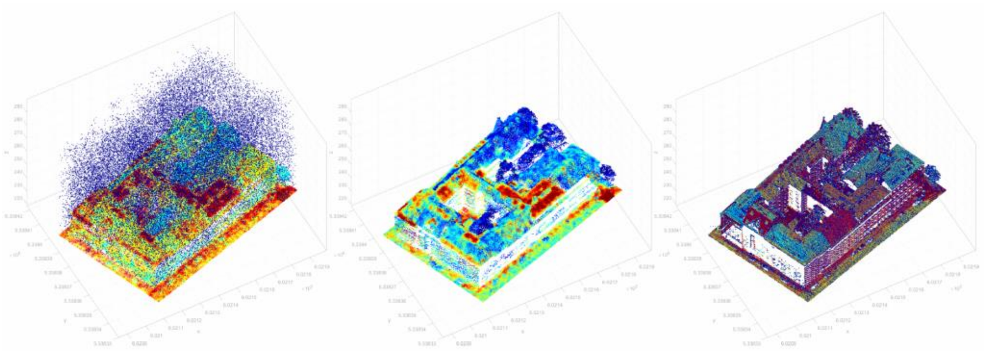

Figure 3. Perspective view of 3D point cloud; left: SPL-unfiltered, middle: SPL-post processed, right: waveform LiDAR

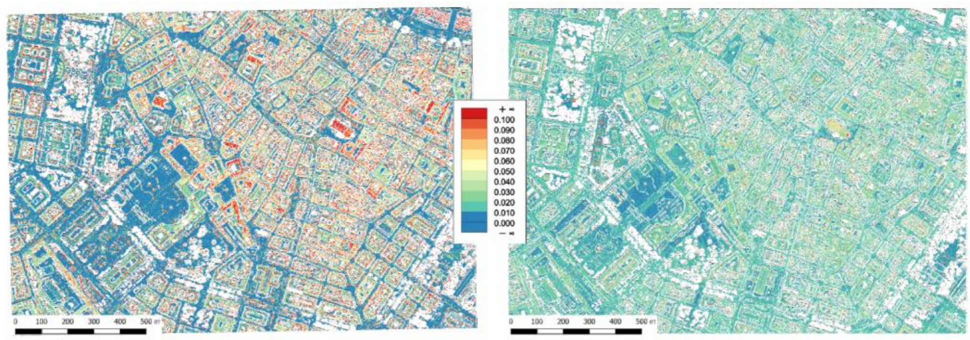

Figure 4. Color coded precision map for city center area; left: SPL, right: waveform LiDAR

4. PRELIMINARY IDEAS FOR A EUROSDR SPL BENCHMARK

As the potentially higher area capturing rate of single photon sensitive LiDAR is appealing for capturing and maintaining countrywide topographic datasets, EuroSDR Commission 1 promoted the idea of an SPL benchmark. Such a benchmark also appears necessary given the restricted availability of open SPL data. In a first step, the general interest of the community (NMCAs, research institutes, universities) was queried via an on-line questionnaire asking about the awareness of, experiences with, and the general knowledge about SPL (Bernard *et al.*, 2019). The good response lead to the organization of an SPL workshop in Barcelona in April, 2019, and the outcome was also reported to the EuroSDR board of delegates who approved the idea of organizing a benchmark. To date, there are ongoing negotiations with manufacturers for providing a preferably open dataset of approx. 100 km^2. The area should cover as many typical landscape features from flat, via undulating, to mountainous terrain, as well as different types of vegetation, and a city area with narrow street canyons, and tall buildings. Currently, a second on-line questionnaire is running asking for more specific feedback as basis for the final preparations of the potential benchmark (i.e. requirements concerning data density and quality, potential applications, etc.). Provided that a common denominator concerning product specifications, benchmark focus points, feasibility of data capturing is found among the involved institutions (manufacturers, NMCAs, academia), it is anticipated that the benchmark will proceed in 2020.

5. CONCLUSIONS

This short paper provided a review of the basic principles of single photon sensitive LiDAR as well as first results of a comparative study of SPL and linear-mode, waveform LiDAR. Single photon based technologies enable higher flying heights, resulting in larger swath widths and, thus, a potentially higher area coverage performance. This is especially useful for large-area topographic mapping. The higher receiver sensitivity entails a higher outlier point rate, which makes filtering of the raw SPL data a crucial and inevitable task. For a concrete data acquisition of the City of Vienna in 2018 with both sensor technologies, the post processed SPL point cloud still did not match the level of state-of-the-art waveform LiDAR data w.r.t. geometric and radiometric sharpness. However, to match the same point density, a lower flying altitude was necessary for conventional linear-mode LiDAR entailing a lower area performance. Concerning penetration capabilities waveform LiDAR outperformed SPL in the conducted evaluation under leaf-on conditions. SPL showed a good measurement precision in the cm range at smooth horizontal surfaces, and waveform LiDAR performed better in complex target situations (steep roofs, natural surfaces). To raise awareness and further test the capabilities of single photon sensitive systems, EuroSDR Commission 1 is currently planning a Single Photon and linear-mode LiDAR benchmark. The higher area performance is of special interest for National Mapping and Cadastral Agencies which are responsible for maintaining up-to date topographic information on a federal or countrywide level. One of the challenges for the proposed benchmark is keeping pace with the rapid development of both single photon sensitive and linear-mode LiDAR technology.

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OCENA SKANERÓW JEDNOFOTONOWYCH I LINIOWYCH

SŁOWA KLUCZOWE: skanowanie laserowe, LIDAR, czułość pojedycznego fotonu, skanowanie wielkoobszarowe, modelowanie miast 3D

Streszczenie

Zasady czułości sensora pojedynczego fotonu są w proponowanym referacie przedstawione i porównane z najnowocześniejszym zgodnym ze sztuką skanerem typu full waveform (pełny kształt fali) W referacie wyjaśniono różnice teoretyczne obydwu rozwiązań, a dane dotyczące obu technologii są oceniane na podstawie danych pozyskanych dla miasta Wiednia w 2018 r. odpowiednio za pomocą sensorów: SPL100 (Leica) i VQ-1560i (Riegl). Chociaż SPL ma wyższą wydajność powierzchniową, dane pełnego kształtu fali okazują się bardziej precyzyjne, szczególnie w złożonych sytuacjach docelowych, takich jak naturalne lub strome powierzchnie. Ponadto, artykuł podsumowuje aktualne działania w ramach EuroSDR dotyczące potencjalnego testu porównawczego LIDAR dla danych pojedynczego fotonu i trybu liniowego.

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