Single Photon vs Full Waveform LiDAR - technological differences and point cloud properties

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EuroSDR
Overview

- **Basics/Theory**
  - (Conventional) Full Waverform Airborne Laser Scanning (ALS) – Linear mode LiDAR
  - Geiger-mode LiDAR (GmLiDAR)
  - Single Photon LiDAR (SPL)

- **Pilot study „City of Vienna“**
  - Single Photon LiDAR acquisition (Leica Geosystems SPL100), end July 2018
  - Full waveform (FWF) LiDAR acquisition (RIEGL VQ-1560i), mid Sept 2018
  - Additional dataset: Lake Constance 2018 (Data: LUBW)

- **Results of data evaluation**
  - Visual comparison of 3D point cloud
  - Multi-target and penetration capability, point density
  - Strip fitting precision
  - Measurement precision
Conventional vs Single Photon LiDAR

**Conventional LiDAR**

Linear-mode LiDAR

- Diameter of laser footprint

**Geiger-mode LiDAR**

- Laser footprint illuminates entire Receiver's FOV

**Single Photon LiDAR**

- 10x10 partial beams (beamlets) derived from single laser pulse via Diffractive Optical Element (DOE)

Receivers's Field Of View (FOV)

Geiger-mode Avalanche Photo Diode array (GmAPD array, 32x128)

E.G. Silicon Photo-Multiplier (AGISHEV et al, 2013)
Discrete echoes vs. Full Waveform
Full Waveform Analysis

- **Gaussian decomposition:**
  (Wagner et al, 2004)
  - *Echo detection* by fitting of Gaussian curves

\[
wf(t) = c + \sum_{i=1}^{m} A_i e^{(t-\mu_i)^2 / \sigma_i^2}
\]

→ Parameters per echo:
  - **Amplitude** \( A_i \)
  - **Range** \( R(\mu_i) \)
  - **Echo width** \( w(\sigma_i) \)

\[
P_E = \frac{P_S D^2}{4\pi\gamma^2 R^4} \times \frac{4\pi A \rho}{\Omega} \times \eta_{ATM} \eta_{SYS} + P_{BK}
\]

characterizes scattering object

EuroSDR Workshop Barcelona: "SPL and GmLiDAR"
SPL100 – scan pattern
Data acquisition Single Photon LiDAR (SPL 100)

Flight mission parameters

<table>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Flight date</td>
<td>29.07.2018</td>
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<tr>
<td>Scan rate</td>
<td>5 MHz</td>
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<tr>
<td>Flying altitude</td>
<td>4000m</td>
</tr>
<tr>
<td>Swath width</td>
<td>2000m</td>
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<tr>
<td>Scan pattern</td>
<td>circular</td>
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<tr>
<td>Field-of-View</td>
<td>30°</td>
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<tr>
<td>Overlap</td>
<td>&gt;50%</td>
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<tr>
<td>Nom. pt. density</td>
<td>20 Pkt/m²</td>
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<tr>
<td>Nr. of strips</td>
<td>10</td>
</tr>
</tbody>
</table>
Datenerfassung Full Waveform LiDAR (VQ-1560i)

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Flight data:
- **Flight date**: 20.09.2018
- **Scan rate**: 1,33 MHz
- **Flying altitude**: 750m
- **Swath width**: 840m
- **Scan pattern**: x-shaped scan lines
- **Field-of-View**: 58°
- **Overlap**: >50%
- **Nom. pt. density**: 20 Pkt/m²
- **Nr. of strips**: 18
Detailed study areas: Forest + City

(a) Forest LiDAR

(b) City LiDAR
Single Photon LiDAR: Unfiltered 3D point cloud

(a) Perspective view

(b) City test area Section view

Signal intensity [DN]
Visual comparison of 3D point clouds

SPL

Aerial image (RGB)

Waveform LiDAR

Signal intensity [DN]
Comparison: longitudinal section

Legend:
- SPL unfiltered
- SPL postprocessed
- Waveform LiDAR
Comparison: cross section

Legend:
- SPL unfiltered
- SPL postprocessed
- Waveform LiDAR

EuroSDR Workshop Barcelona: "SPL and GmLiDAR"

Mandiburger: SPL vs. Full Waveform LiDAR
SPL: pulse duration / beam divergence

Laser beamlet

1.2m

0.08 mrad
32 cm

400 ps
12 cm

Bright scatterer

EuroSDR Workshop Barcelona: "SPL and GmLiDAR"

Mandlburger: SPL vs. Full Waveform LiDAR
Penetration capability (leaf-on)

SPL

(a)

Perspective view: Forest test area

(b)

Waveform LiDAR

(c)

Section view

- SPL unfiltered
- SPL postprocessed
- Waveform LiDAR
Point density maps (all echoes)

SPL post processed

Waveform LiDAR

Waveform: 1.84 echoes/puls
SPL: 1.06 echoes/puls

Forest

City

SPL: lower point density in vegetation und at facades
→ Elimination of useful points by post processing
Comparison strip differences

SPL post processed

Waveform LiDAR

unmasked

masked

σ_{MAD}=4\,\text{cm}

σ_{MAD}=1\,\text{cm}
Neighborhood/measurement precision I

SPL

Waveform LiDAR

Histogram: Nachbarschaftsgenauigkeit

#Samples: 590386
Min: 0.002
Max: 0.052
Median: 0.008
StdDev: 0.012
StdDevMAD: 0.006

Histogram: Nachbarschaftsgenauigkeit

#Samples: 1411233
Min: 0.000
Max: 0.050
Mean: 0.009
Median: 0.005
StdDev: 0.009
StdDevMAD: 0.003
Neighborhood/measurement precision II

- **Asphalt**
  - SPL unfiltered: $\sigma = 1.5$ cm
  - SPL post proc.: $\sigma = 1.1$ cm
  - Waveform LiDAR: $\sigma = 1.0$ cm
- **Flat roof**
  - SPL unfiltered: $\sigma = 1.2$ cm
  - SPL post proc.: $\sigma = 1.0$ cm
  - Waveform LiDAR: $\sigma = 0.7$ cm
- **Steep saddle roof**
  - SPL unfiltered: $\sigma = 9.8$ cm
  - SPL post proc.: $\sigma = 9.5$ cm
  - Waveform LiDAR: $\sigma = 3.1$ cm
- **Meadow**
  - SPL unfiltered: $\sigma = 5.8$ cm
  - SPL post proc.: $\sigma = 3.9$ cm
  - Waveform LiDAR: $\sigma = 1.0$ cm
Summary and conclusions

- **Single Photon LiDAR**
  - Higher flying altitude → larger swath width → less flight strips
  - potentially higher area performance while maintaining the same point density

- **Full Waveform LiDAR**
  - Sharp capture of topography and buildings
  - Reliable measurement of signal strength and reflectance (via radiometric calibration)

- **Penetration of vegetation under leaf-on conditions**
  - **SPL**: penetration possible but moderate
  - **Full waveform LiDAR**: pronounced penetrations capabilities

- **Measurement precision**
  - **SPL**: high prec. @ smooth, horizontal surfaces (~1-2 cm), Decreasing precision @ tilted, poorly reflecting surfaces (~10 cm)
  - **Full waveform LiDAR**: Advantages @ complex target situations (tilted and rough surface, vegetation; ~1-3 cm)
Addendum

Screenshots from animations of City of Vienna dataset
Single Photon LiDAR (SPL): Unfiltered 3D point cloud

City of Vienna, 3rd district, Scanner: Leica SPL100
Single Photon LiDAR (SPL): Postproc. 3D point cloud

City of Vienna, 3rd district, Scanner: Leica SPL100
Full Waveform LiDAR: 3D point cloud

City of Vienna, 3rd district, Scanner: RIEGL VQ-1560i
Addendum

Dataset: Argen, Schussen, Lake Constance
Landesamt für Umwelt, Baden-Württemberg (LUBW)
Single Photon LiDAR 3D point cloud

Colored by classification

Laimnau, Lake Constance
Acquisition: 04.08.2018
Sensor: Leica, SPL100
Data: LUBW, Germany
Single Photon LiDAR 3D point cloud

Colored by intensity

Laimnäu, Lake Constance
Acquisition: 04.08.2018
Sensor: Leica, SPL100
Data: LUBW, Germany

EuroSDR Workshop Barcelona: "SPL and GmLiDAR"
Mandlburger: SPL vs. Full Waveform LiDAR
Single Photon LiDAR 3D point cloud

Colored by RGB (RCD30)

Laimnau, Lake Constance
Acquisition: 04.08.2018
Sensor: Leica, SPL100
Data: LUBW, Germany
Single Photon LiDAR 3D point cloud

Forest, Lake Constance
Acquisition: 04.08.2018
Sensor: Leica, SPL100
Data: LUBW, Germany
Single Photon LiDAR 3D point cloud

Forest, Lake Constance
Acquisition: 04.08.2018
Sensor: Leica, SPL100
Data: LUBW, Germany
Single Photon LiDAR 3D point cloud

Colored by classification
- unclassified
- ground
- low vegetation
- medium vegetation
- high vegetation
- buildings

Forest, Lake Constance
Acquisition: 04.08.2018
Sensor: Leica, SPL100
Data: LUBW, Germany
Colored by classification

Forest, Lake Constance
Acquisition: 04.08.2018
Sensor: Leica, SPL100
Data: LUBW, Germany

SPL: 1.12 echoes/puls