Sampling the World in 3D by Airborne LIDAR –
Assessing the Efficiency of LIDAR Systems
for Large-Scale Surveying

Geospatial World Forum 2014
May 09th, 2014
Geneve, Germany

Peter Rieger
RIEGL LMS GmbH

www.riezlms.com
With more than 30 years experience in the research, development and production of laser rangefinders, distancemeters and scanners, RIEGL delivers proven innovations in 3D.

Dedicated to designing, developing, and producing the best possible laser sensors for the desired application, in order to perfectly fulfil measurement tasks and therefore fully satisfy the customer’s expectations world-wide.

As a primarily technology-orientated company, RIEGL successfully cooperates with renowned system integrators, resulting in powerful turnkey solutions for multiple fields of application.

RIEGL has always been committed to delivering the highest performance, quality, reliability and longevity of all its products and services and strict adherence to applicable international standards is a priority.
The **RIEGL** staff in Austria comprises more than 140 highly skilled and motivated engineers, technicians, and other qualified employees.
Located in Horn, an attractive small town in Lower Austria, around 85 km northwest of the Austrian capital Vienna, the RIEGL headquarters is right in the heart of the European Union, with good transport connections in all directions.

Worldwide sales, training, support and services are delivered from RIEGL’s Austrian headquarters and its offices in Vienna and Salzburg, main offices in USA and in Japan, and by a worldwide network of representatives covering Europe, North and South America, Asia, Australia and Africa.
The **RIEGL** headquarters provides more than 40,000 square feet work space for research, development, production as well as for marketing, sales, training and administration.

Another 200,000 square feet of open air ground is used for product testing.
Explore Products

Terrestrial Scanning
Airborne Scanning
Mobile Scanning
Industrial Scanning

www.riegl.com
How long does the acquisition actually take?

- density and spacing
- LIDAR spec
- performance envelope
- scanner performance
- impact of terrain
- example on 3D sampling
- acquisition time

What will be the point cloud’s sampling quality?
- sequential data acquisition
- surface sampling at laser footprints
- “sampling” footprint $\leftrightarrow$ single point of point cloud (PC)
- organizing measurements in scan lines
  - intra-line spacing
  - inter-line spacing
- “2D” resolution limited by footprint size
- sampling density impacts information content of PC
- resolution in 3rd dimension
- echo-digitization with full waveform analysis $\rightarrow$ best multi-target resolution
LIDAR density and spacing specification
(ASPRS Version 1.0, Draft 2)

<table>
<thead>
<tr>
<th>LDSS point spacing</th>
<th>LDSS point density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-dimensional metric</td>
<td>2-dimensional metric</td>
</tr>
<tr>
<td>point-to-point distance</td>
<td>points in a given area</td>
</tr>
<tr>
<td>unit: meters (feet, yards, cm …)</td>
<td>unit: points per m² (ft², …)</td>
</tr>
</tbody>
</table>

LIDAR Guidelines and Base Specification
(U.S. Geological Survey, National Geospatial Program, Version 13)

<table>
<thead>
<tr>
<th>spatial sampling frequency</th>
<th>point density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-dimensional metric</td>
<td>2-dimensional metric</td>
</tr>
<tr>
<td>inverse of point spacing (1/NPS)</td>
<td>average points in a given area</td>
</tr>
<tr>
<td>unit: points per meters (feet, yards, …)</td>
<td>unit: points per m² (ft², …)</td>
</tr>
</tbody>
</table>
LIDAR density and spacing specification
(ASPRS Version 1.0, Draft 2)

Unbiased LiDAR Data Measurement (Draft)

Ty Naus, Fugro Horizons, Inc.

Figure 7b: Voronoi polygons shown in blue for actual LiDAR point distributions – the triangulation edges are shown in red.

\[ d_{p-p} = \frac{1}{N} \sum_{i=1}^{N} d_i \]

average or maximum?

point spacing
<table>
<thead>
<tr>
<th></th>
<th>Instrument A</th>
<th>Instrument B</th>
<th>Instrument C</th>
</tr>
</thead>
<tbody>
<tr>
<td>scan mechanism</td>
<td>rotating polygon</td>
<td>oscillating mirror</td>
<td>oscillating mirror</td>
</tr>
<tr>
<td>number of channels</td>
<td>single channel</td>
<td>dual laser output</td>
<td>dual laser output</td>
</tr>
<tr>
<td>flight altitude, AGL (^1))</td>
<td>50 m - 3500 m</td>
<td>150 m - 3500 m</td>
<td>150 m – 5000 m</td>
</tr>
<tr>
<td>laser pulse rate</td>
<td>100 kHz - 400 kHz</td>
<td>2 x 40 kHz – 2 x 250 kHz</td>
<td>2 x 50 kHz – 2 x 250 kHz</td>
</tr>
<tr>
<td>measurement rate</td>
<td>66 kHz - 266 kHz</td>
<td>80 kHz - 500 kHz</td>
<td>100 kHz - 500 kHz</td>
</tr>
<tr>
<td>pulses in the air</td>
<td>up to 12</td>
<td>2 x up to 2</td>
<td>not disclosed</td>
</tr>
<tr>
<td>field of view</td>
<td>0 deg - 60 deg</td>
<td>0 deg - 75 deg</td>
<td>0 deg - 75 deg</td>
</tr>
<tr>
<td>scan rate</td>
<td>10 LPS – 200 LPS</td>
<td>0 LPS- 2 x 200 LPS</td>
<td>0 LPS- 2 x 280 LPS</td>
</tr>
</tbody>
</table>

www.riegl.com

specification of LIDAR instruments
<table>
<thead>
<tr>
<th></th>
<th>Instrument A</th>
<th>Instrument B</th>
<th>Instrument C</th>
</tr>
</thead>
<tbody>
<tr>
<td>scan mechanism</td>
<td>rotating polygon</td>
<td>oscillating mirror</td>
<td>oscillating mirror</td>
</tr>
<tr>
<td>number of channels</td>
<td>single channel</td>
<td>dual laser output</td>
<td>dual laser output</td>
</tr>
<tr>
<td>flight altitude, AGL 1)</td>
<td>50 m - 3500 m</td>
<td>150 m - 3500 m</td>
<td>150 m – 5000 m</td>
</tr>
<tr>
<td>laser pulse rate</td>
<td>100 kHz - 400 kHz</td>
<td>2 x 40 kHz – 2 x 250 kHz</td>
<td>2 x 50 kHz – 2 x 250 kHz</td>
</tr>
<tr>
<td>measurement rate</td>
<td>66 kHz - 266 kHz</td>
<td>80 kHz - 500 kHz</td>
<td>100 kHz - 500 kHz</td>
</tr>
<tr>
<td>pulses in the air</td>
<td>up to 12</td>
<td>2 x up to 2</td>
<td>not disclosed</td>
</tr>
<tr>
<td>field of view</td>
<td>0 deg - 60 deg</td>
<td>0 deg - 75 deg</td>
<td>0 deg - 75 deg</td>
</tr>
<tr>
<td>scan rate</td>
<td>10 LPS – 200 LPS</td>
<td>0 LPS- 2 x 200 LPS</td>
<td>0 LPS- 2 x 280 LPS</td>
</tr>
</tbody>
</table>

specification of LIDAR instruments

www.riegl.com
<table>
<thead>
<tr>
<th></th>
<th>Instrument A</th>
<th>Instrument A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>scan mechanism</td>
<td>rotating polygon</td>
<td>rotating polygon</td>
</tr>
<tr>
<td>number of channels</td>
<td>single channel</td>
<td>dual channel</td>
</tr>
<tr>
<td>flight altitude, AGL 1)</td>
<td>50 m - 3500 m</td>
<td>50 m – 3500 m</td>
</tr>
<tr>
<td>laser pulse rate</td>
<td>100 kHz - 400 kHz</td>
<td>2 x 100 kHz – 2 x 400 kHz</td>
</tr>
<tr>
<td>measurement rate</td>
<td>66 kHz - 266 kHz</td>
<td>123 kHz – 532 kHz</td>
</tr>
<tr>
<td>pulses in the air</td>
<td>up to 12</td>
<td>2 x up to 12</td>
</tr>
<tr>
<td>field of view</td>
<td>0 deg - 60 deg</td>
<td>0 deg – 60 deg</td>
</tr>
<tr>
<td>scan rate</td>
<td>10 LPS – 200 LPS</td>
<td>2 x 10 LPS- 2 x 200 LPS</td>
</tr>
</tbody>
</table>

specification of LIDAR instruments
instrument A
rotating polygon, single channel
matrix scan pattern

instrument B
oscillating mirror, single channel

instrument C
oscillating mirror, dual laser output

RIEGL LMS-Q780

www.riegl.com
RIEGL LASER MEASUREMENT SYSTEMS

**instrument A**

- Rotating polygon, single channel

**instrument A2**

- Rotating polygon, dual channel

**instrument B**

- Oscillating mirror, dual laser output

**instrument C**

- Matrix scan pattern

*RIEGL LMS-Q780*  
*RIEGL LMS-Q1560*
<table>
<thead>
<tr>
<th></th>
<th>Instrument A</th>
<th>Instrument B</th>
<th>Instrument C</th>
</tr>
</thead>
<tbody>
<tr>
<td>scan mechanism</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of channels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flight altitude, AGL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>laser pulse rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>measurement rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pulses in the air</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>field of view</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>scan rate</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility

**performance envelope**

**scan speed vs FOV**

www.riegl.com

specification of LIDAR instruments
1) 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility

www.riegl.com
1) 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility
instrument A, RIEGL LMS-Q780
instrument B, 1 PiA, single channel
instrument B, 2 PiA, single channel

1) 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility
instrument A, *RIEGL* LMS-Q780
instrument B, 1 PiA, single channel
instrument B, 2 PiA, single channel
instrument C, single channel

1) 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility

[Diagram showing the performance envelope for different instruments.]

www.riegl.com

performance envelope
10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility
instrument A, RIEGL LMS-Q780
instrument B, 1 PiA
instrument B, 2 PiA
instrument C

1) 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility
1) 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility
1) 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility
\[ P_T(t) \]

\[ P_E(t) \]

\[ T_T[k-3] \quad T_T[k-2] \quad T_T[k-1] \quad T_T[k] \]

\[ T_E[k-3] \quad T_E[k-2] \quad T_E[k-1] \quad T_E[k] \]

MTA Zone 1, 2, 3 or 4?

r_{k,MTA1} 
r_{k,MTA2} 
r_{k,MTA3} 
r_{k,MTA4}
laser pulse repetition rate
PRR = 65 kHz

variation in AMSL within strip: 1000 m

150 m ≡ 1 µs
1500 m ≡ 10 µs ≡ 1/100 kHz
2300 m ≡ 15 µs ≡ 1/65 kHz

www.riegl.com
MTA Zones versus laser pulse repetition rate

laser pulse repetition rate
PRR = 130 kHz

2000 m
laser pulse repetition rate
PRR = 130 kHz

MTA Zones versus laser pulse repetition rate
laser pulse repetition rate
PRR = 250 kHz

MTA Zones versus laser pulse repetition rate

www.riegl.com
laser pulse repetition rate
$\text{PRR} = 400 \text{ kHz}$

MTA Zones versus laser pulse repetition rate
dead time?
data gaps?
Point density = 2pts/m²
Ground speed = 110kn
PRR=100kHz  \( R_0 = 1500 \text{m} \)
ground speed 110kn
point density = 2 pts/m²
PRR = 100kHz
altitude AGL = 550m
1 pulse in the air
29 scan lines
flight time = 1 hour
point density = 2pts/m²
ground speed = 110kn
PRR=400kHz \quad R_0 = 375m

Multiple pulses in the air…
ground speed 110kn
point density = 2 pts/m²
PRR = 400kHz
altitude AGL = 2200m
7 pulses in the air
7 scan lines
**flight time = 17 min**
Single pulse in the air…
..difficult flights
PRR = 400kHz

\[ R_u = 375 \text{m} \]

multiple pulses in the air
scan speed (lines per second) vs FOV

- Instrument A, RIEGL LMS-Q780
- Instrument B (single channel)
- Instrument C (single channel)
scan speed (lines per second) vs FOV

- instrument A, RIEGL LMS-Q780
- instrument B (single channel)
- instrument C (single channel)

FOV: field of view, LPS: lines per second, v: speed over ground, b: line spacing
Scan speed (degrees per millisecond) vs FOV

- Instrument A, RIEGL LMS-Q780 min/max
- Instrument B (single channel)
- Instrument C (single channel)
\[ PRR = 250 \text{ kHz} \]

\[ \theta = 0.35 \text{ mrad (1/e²)} \]

\[ a = \frac{R}{t} / \text{PRR} \]

For instrument A, RIEGL LMS-Q780 min/max.
For instrument B (single channel).
For instrument C (single channel).

www.riegl.com
CONSTRAINTS in LPS

\[ LPS_{\text{actual}} \leq LPS_{\text{maximum}} \]

for high PRR and oscillating mirror

\[ LPS_{\text{actual}} \ll LPS_{\text{optimum}} \]

optimizing scanner parameters
out-of-phase interference pattern (desired)

phase depends on
• speed
• AGL
• LPS

in any case:
2x “point density”

but:
“point spacing”?

dual channel interference pattern
1 LPS, 60 deg FOV, PRR 20 Hz ... just a sketch

27 LPS, 60 deg FOV, PRR 50 kHz

www.riegl.com
<table>
<thead>
<tr>
<th></th>
<th>scenario 1</th>
<th>scenario 2</th>
<th>scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>application</td>
<td>corridor mapping</td>
<td>high density survey</td>
<td>wide area mapping</td>
</tr>
<tr>
<td>terrain</td>
<td>flat</td>
<td>flat</td>
<td>mountainous</td>
</tr>
<tr>
<td>AGL</td>
<td>500 m</td>
<td>1000 m</td>
<td>2000 m – 1000 m</td>
</tr>
<tr>
<td>speed</td>
<td>60 kn</td>
<td>120 kn</td>
<td>140 kn</td>
</tr>
<tr>
<td>FOV</td>
<td>60 deg</td>
<td>60 deg</td>
<td>60 deg</td>
</tr>
</tbody>
</table>

**www.riegl.com**

simulation of point distribution on terrain
mountainous terrain
- variation in AMSL 1000 m
- scenario 3

simulation of point distribution on terrain

www.riegl.com
defining test area (scenarios 1 – 3)
choosing optimum flight parameters
performance envelope → PRR_{max}
calculating LPS_{\text{optimum}} → LPS_{\text{actual}}
generating trajectory
“mounting” LIDAR & generating “pulses”
intersecting beams with terrain
analyzing / visualizing point clouds

scan speed
ground speed
covered area per time unit
field of view
height above ground
pulse repetition rate

optimum nominal point spacing (best ground sampling)
Performance on flat terrain

- AGL at 1000 m
- Speed over ground 120 kn
- FOV of 60 degrees
- Optimum operating parameters for all instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>AGL (m)</th>
<th>FOV</th>
<th>MR</th>
<th>LPS</th>
<th>Across Spacing (m)</th>
<th>Along Spacing (m)</th>
<th>Point Density (p/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument A</td>
<td>1000</td>
<td>60 deg</td>
<td>1x 266 kHz</td>
<td>1x 108 LPS</td>
<td>0.57</td>
<td>0.57</td>
<td>4.1</td>
</tr>
<tr>
<td>Instrument B</td>
<td>1000</td>
<td>60 deg</td>
<td>2x 250 kHz</td>
<td>2x 93 LPS</td>
<td>0.61</td>
<td>0.66</td>
<td>7.7</td>
</tr>
<tr>
<td>Instrument C</td>
<td>1000</td>
<td>60 deg</td>
<td>2x 250 kHz</td>
<td><strong>53 LPS</strong></td>
<td>0.30</td>
<td><strong>1.16 m</strong></td>
<td>7.7</td>
</tr>
</tbody>
</table>
instrument A
RIEGL LMS-Q780

instrument B

instrument C

center of swath

flight direction

2.5 m

edge of swath

scenario 2, area scan

www.riegl.com
mountainous terrain
• variation in AMSL 1000 m
• scenario 3
Performance on mountainous terrain

- AGL from 1000 m to 2000 m
- speed over ground 140 kn
- FOV of 60 degrees
- optimum operating parameters for all instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>maximum AGL</th>
<th>FOV</th>
<th>meas. rate</th>
<th>LPS</th>
<th>across spacing</th>
<th>along spacing</th>
<th>avg. point density</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2000 m</td>
<td>60 deg</td>
<td>1x 266 kHz</td>
<td>1x 83 LPS</td>
<td>0.87 m</td>
<td>0.87 m</td>
<td>1.3 - 3.5 p/m²</td>
</tr>
<tr>
<td>B</td>
<td>2000 m</td>
<td>60 deg</td>
<td>2x 63 kHz</td>
<td>2x 37 LPS</td>
<td>1.94 m</td>
<td>4.32 m</td>
<td>0.53 - 1.9 p/m²</td>
</tr>
<tr>
<td>C</td>
<td>2000 m</td>
<td>60 deg</td>
<td>2x 66 kHz</td>
<td>2x 41 LPS</td>
<td>1.74 m</td>
<td>3.50 m</td>
<td>0.9 - 2.6 p/m²</td>
</tr>
</tbody>
</table>
- variation in terrain height permits only acquisition in MTA zone 1 (1 pulse in the air)
- dead time between zones reduces measurement rate even further
scenario 3, mountainous terrain

instrument A
RIEGL LMS-Q780

2.5 m

center of swath

2.5 m

edge of swath

2.5 m

best

worst

best

worst

best

worst
sampling objects – point spacing & spatial sampling frequency
2000 m AGL
140 kn GSP
60 deg FOV
mountainous terrain near edge of swath

www.riegl.com
2000 m AGL
140 kn GSP
60 deg FOV

mountainous terrain
near edge of swath

sampling objects – point spacing & spatial sampling frequency
2000 m AGL
140 kn GSP
60 deg FOV

mountainous terrain
near edge of swath

www.riegl.com

sampling objects – point spacing & spatial sampling frequency
sampling objects – point spacing & spatial sampling frequency
instrument A, **RIEGL LMS-Q780**
266 k meas./sec

instrument B
500 k meas./sec

**measurements per meter** [1/m]

covered area per time [km²/h]

33 km²/h

4 points/m
NPS 0.25 m

sampling frequency (1/NPS) vs acquisition speed

flat terrain

covered area per time [km²/h]

0.1

1

10

100

1000

www.riegl.com
instrument A, **RIEGL LMS-Q780**
266 k meas./sec

instrument B
up to 500 k meas./sec

sampling frequency (1/NPS) vs acquisition speed
instrument A, *RIEGL LMS-Q780* 266 k meas./sec

instrument B  
up to 500 k meas./sec

nominal covered area per time [km²/h]

measurements per meter [1/m]

www.riegl.com  
sampling frequency (1/NPS) vs acquisition speed
high ground sampling frequency  
low nominal point spacing   

AND  

high acquisition speed

- fast scan at high FOV (polygon mirror)
- no interference problems (single channel or sophisticated dual channel scanner design)
- wide performance envelope
- high pulse repetition rate at high AGL (high-MTA-zone processing capability)

“it is the point spacing, not the number of measurements on the ground”