XXVII FIG CONGRESS
11–15 SEPTEMBER 2022
Warsaw, Poland

Survey-grade Lidar Systems utilizing Sensor Fusion for Static and Kinematic Lidar Data Acquisition

Dr. Andreas Ullrich
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Business Division Manager – Terrestrial Laser Scanning
RIEGL Laser Measurement Systems, Austria

Scientific Workshop on Uncertainty and Quality of Multi-Sensor Systems

Session 4: Quality of Terrestrial Laser Scanning, 11.9.2022

Contents

- About *RIEGL*
- Waveform Lidar Technology
- Multi-Sensor Systems for Static and Kinematic Lidar Acquisition
- Registration and Adjustment in Terrestrial Laser Scanning


RIEGL Canada Ltd.
Toronto, Canada
RIEGL Austria
Headquarters Worldwide
Horn and Vienna, Austria
RIEGL China Ltd.
Beijing, China
RIEGL USA Inc.
Headquarters North America
Winter Garden, Florida
RIEGL Japan Ltd.
Tokyo, Japan
RIEGL Asia Pacific Ltd.
Hong Kong, China
RIEGL UK Ltd.
York, United Kingdom
RIEGL Australia Ltd.
Southport, Australia
Asia
South America
Australia

RIEGL headquarters provides more than 6000 square meters work space for research, development, production, as well as for marketing, sales, training and administration.

Another 32,500 square meters of outdoor facilities are available for product calibration and testing.

Vienna Office, Millennium Tower

Research, Development & Production

Outdoor 3D-Test Range

CNC Production

Headquarters North America:
Winter Garden, FL, USA

Main offices:
Tokyo, Japan
Beijing, China
Southport, Australia
York, United Kingdom
Toronto, Canada
Hong Kong, China

Worldwide network of **distribution partners**

Terrestrial Laser Scanning

Airborne Laser Scanning

Unmanned Laser Scanning

Mobile Laser Scanning

Bathymetric Laser Scanning


2022
LASER SCANNERS for TLS
LiDAR ENGINES & SYSTEMS for ULS
LiDAR ENGINES for ALS, MLS, & BLS
LiDAR SYSTEMS for MLS
LASER SCANNERS for ILS
LiDAR SYSTEMS for ALS & BLS

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Waveform LiDAR Core Technologies

- PURE DIGITAL LiDAR SIGNAL PROCESSING
- OPTIMUM DISTRIBUTION OF MEASUREMENTS
- CALIBRATED AMPLITUDES & REFLECTANCE ESTIMATES
- UNIQUE APPROACH FOR RESOLVING AMBIGUITIES IN RANGING
- SEAMLESS INTEGRATION AND CALIBRATION

Ultimate LiDAR Core Technologies

PURE DIGITAL LiDAR SIGNAL PROCESSING

CALIBRATED AMPLITUDES & REFLECTANCE ESTIMATES

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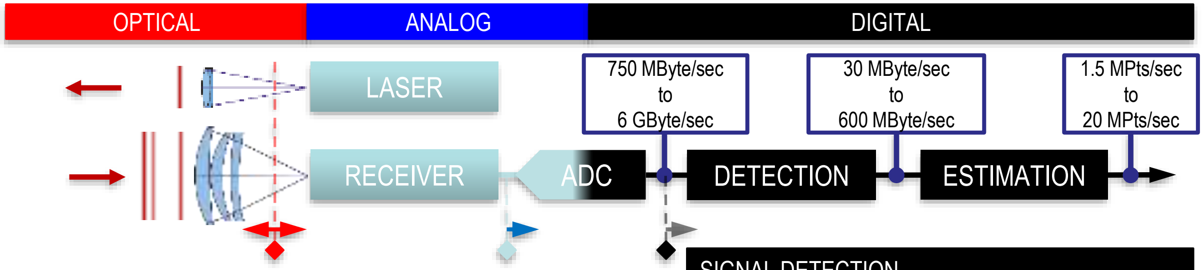
RIEGL Waveform LiDAR Technology



SIGNAL DETECTION

- sample block / sample datagram for **Full Waveform Analysis**
- internal sample datagrams for **Online Waveform Processing**

SIGNAL ESTIMATION

- temporal position / **range**
- signal strength / **amplitude** / **reflectance**
- pulse width / **pulse shape deviation**
- backscatter coefficient of turbid media

Ultimate LiDAR Core Technologies

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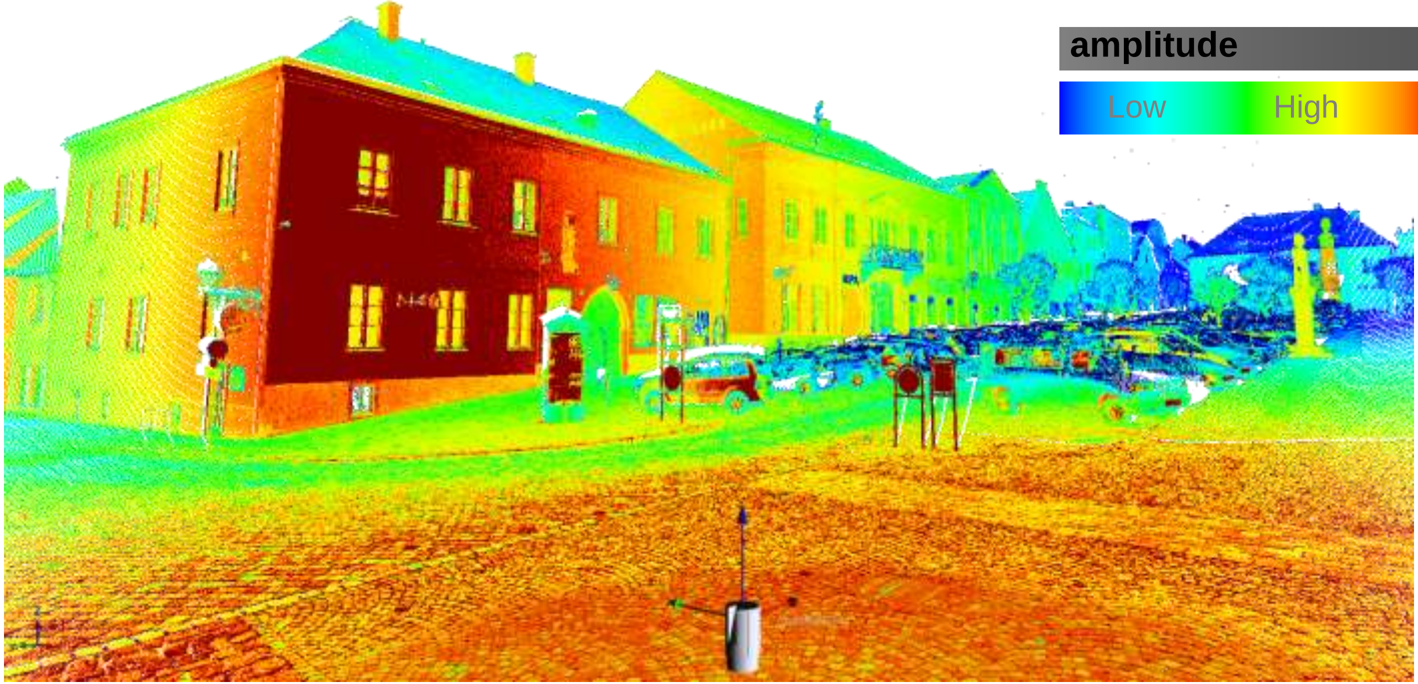
LiDAR – Point Attributes

	geometry	native attributes	external attributes
discrete return point cloud	X, Y, Z	timestamp, intensity return number 1 to 4	colour, classification …
waveform point cloud	X, Y, Z	timestamp, return number 1 to n **calibrated** amplitude **calibrated** reflectance pulse width / pulse shape estimate	colour, classification …

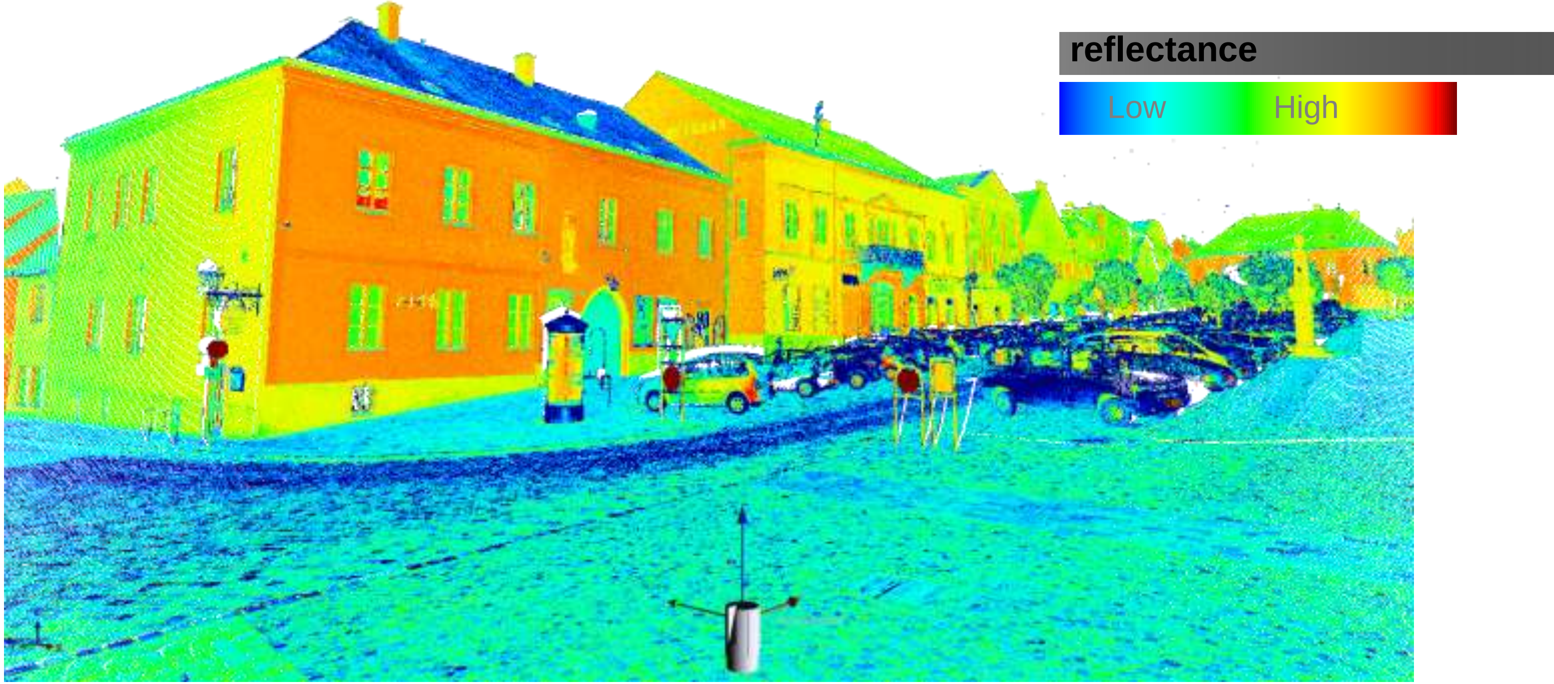
Amplitude vs. Reflectance



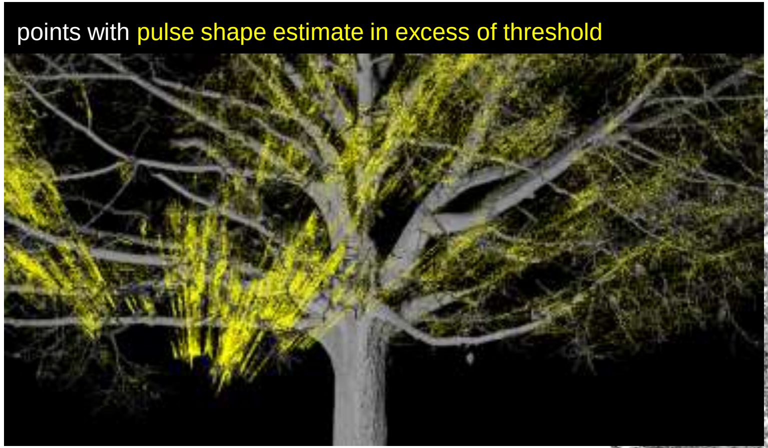
amplitude

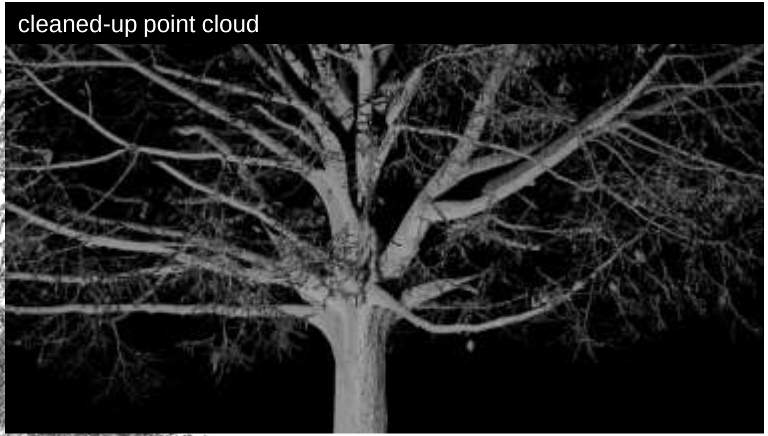
Low High

Amplitude vs. Reflectance



all points (regardless of pulse shape estimate)


points with pulse shape estimate in excess of threshold


cleaned-up point cloud

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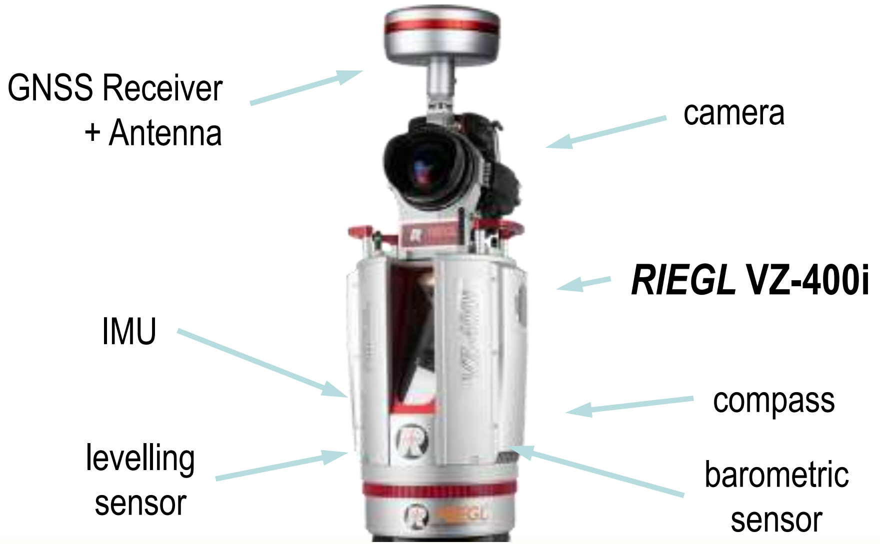
Multi-Sensor Systems for Static and Kinematic Lidar Acquisition

Lidar System for Terrestrial Laser Scanning
(Static Laser Scanning)



Lidar System for UAV-based Laser Scanning
(Kinematic Laser Scanning)

Multi-Sensor System Calibration

Example Mobile Laser Scanning
RIEGL VMX-2HA

for each **LiDAR**:
- inner orientation
  (raw measurements to point coords in SOCS)
- outer orientation (SOCS in e.g. body frame)

for each **camera**:
- inner orientation (pixel to beam in CMCS)
- outer orientation (CMCS in e.g. body frame)

for inertial measurement unit (**IMU**):
- inner orientation
  (raw meas. to accel. and rot. speeds in IMCS)
- outer orientation (IMCS in e.g. body frame, BOCS)

for **GNSS receiver**:
- antenna model (only for mm-accuracy req.)
- position (and orientation) of antenna in body frame

Example Airborne Laser Scanning
RIEGL VQ-1560II-S

SOCS … scanner's own coordinate system, CMCS … camera CS, IMCS .. inertial measurement unit CS, BOCS .. Body CS

Multi-Sensor System Calibration

Example Terrestrial Laser Scanning
RIEGL VZ-400i

for each **LiDAR**:
- inner orientation
  (raw measurements to point coords in SOCS)
- outer orientation (SOCS in e.g. body frame)

for each **camera**:
- inner orientation (pixel to beam in CMCS)
- outer orientation (CMCS in e.g. body frame)

for inertial measurement unit (**IMU**):
- inner orientation
  (raw meas. to accel. and rot. speeds in IMCS)
- outer orientation (IMCS in e.g. body frame, BOCS)

for **GNSS receiver**:
- antenna model (only for mm-accuracy req.)
- position (and orientation) of antenna in body frame

Example Unmanned Laser Scanning
RIEGL VUX-120

SOCS … scanner's own coordinate system, CMCS … camera CS, IMCS .. inertial measurement unit CS, BOCS .. Body CS

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- **Registration and Adjustment in Terrestrial Laser Scanning**
  - Stop-and-Go Data Acquisition
  - Kinematic Data Acquisition

Registration
finding initial estimate of poses (position and orientation) for each scan position

Adjustment
optimizing poses of each scan position in order to achieve best consistency of final data with all measurements/observations

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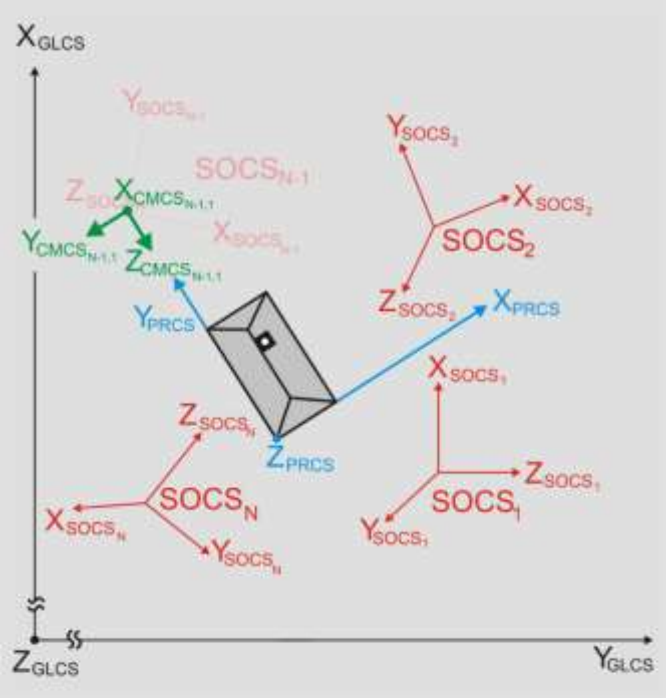
Sensors supporting Registration and Adjustment of Lidar Data

	output	update rate	accuracy / bias and scale stability	repeatability / noise	probability of outliers	price range
GNSS Receiver	position	1 – 100 Hz	1 cm – 10 m	low	high	50 – 5,000 €
Inertial Measurement Unit	acceleration & angular rate	0.1 – 10 kHz	low - high	low – high	very low	1 – 100,000 €
Magnetic Field Sensor	orientation	up to 1 kHz	medium	medium	very high	1 – 10 €
Barometric Sensor	height	up to 100 Hz	low	medium	medium	1 – 10 €
Camera	orientation change	1 – 100 Hz	medium – high	medium – high	medium	10 – 10,000 €
LiDAR	3D data	none – 50 Hz	mm – few cm	mm – few cm	very low	100 – 100,000 €



Registration

Approaches

- finding & matching tie objects (markers, cylinders, spheres)
- supplementing points by local feature vectors with subsequent feature matching
- minimizing errors in overlapping regions with ICP algorithms

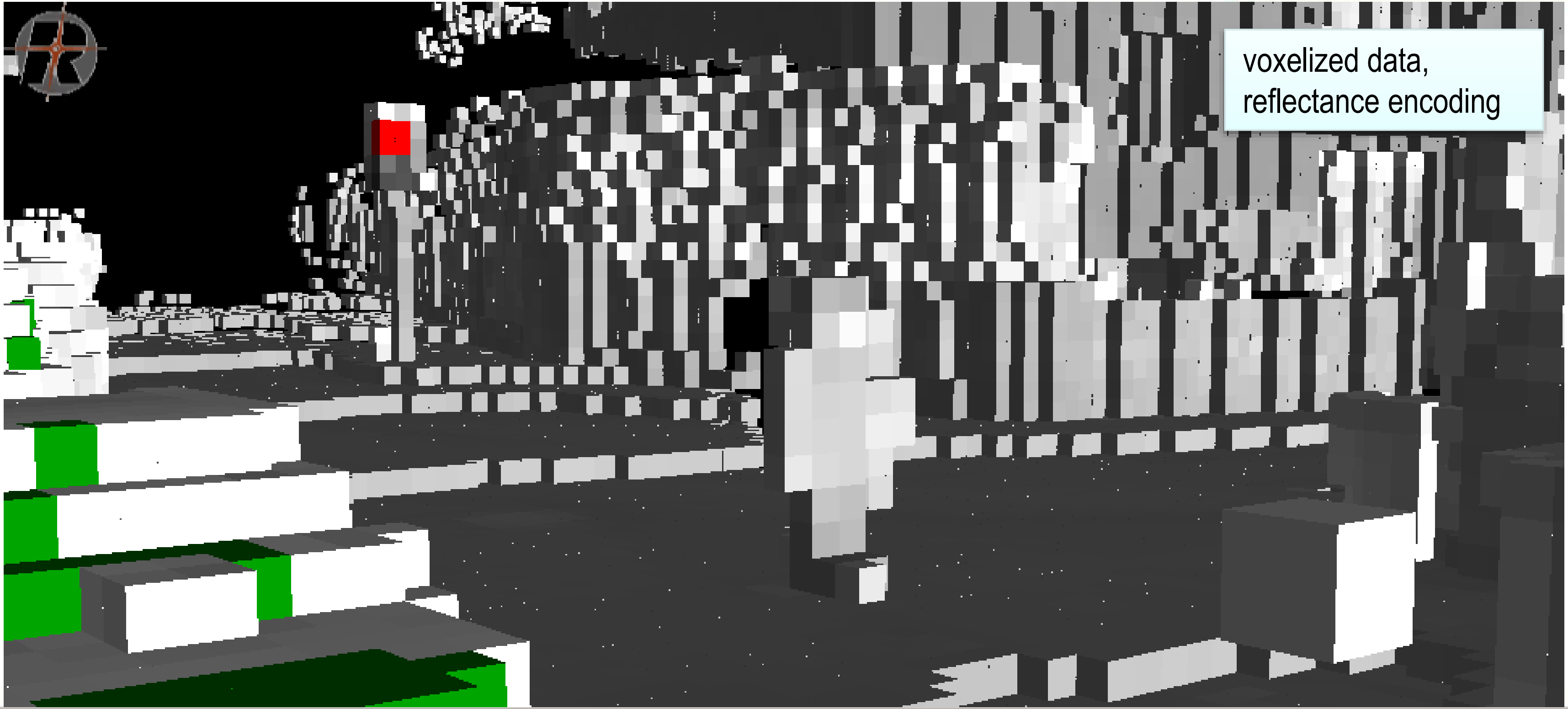
Registration in the Spectral Domain

- automatic and sequential registering of newly acquired point cloud wrt. to all previous ones
- especially robust

point cloud with reflectance encoding

spectral registration – phase-only matched filtering

- resampling of irregular point cloud yields 3D voxel dataset: $v_1(\boldsymbol{x})$

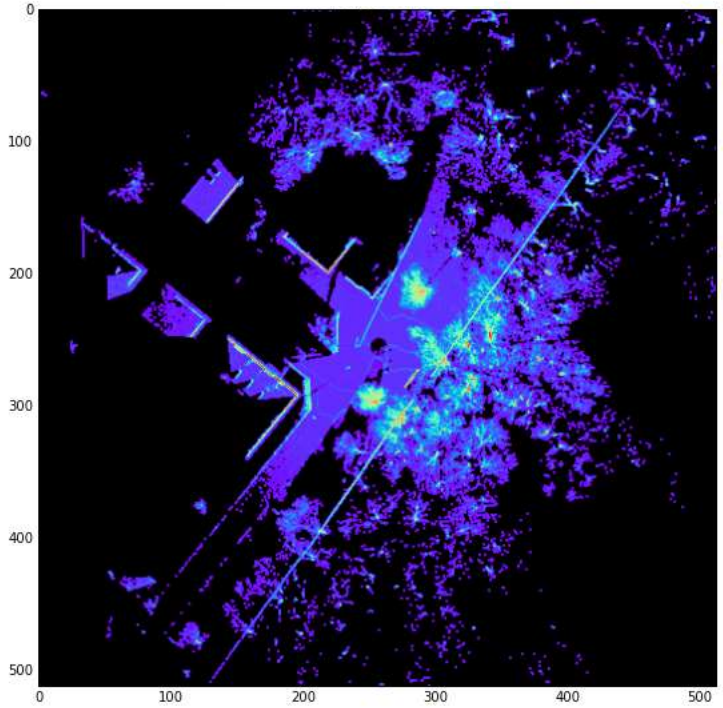


voxelized data,
reflectance encoding

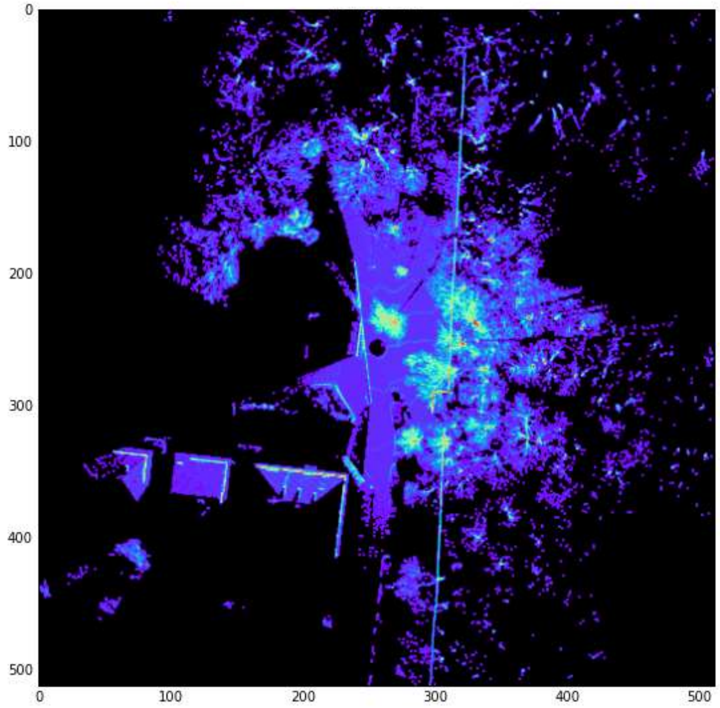
spectral registration – phase-only matched filtering

- resampling of irregular point cloud yields 3D voxel dataset: $v_1(\mathbf{x})$
- same „signal“ but rotated and shifted and denoted as $v_2(\mathbf{x})$: $v_2(\mathbf{x})=v_1(R\mathbf{x}+\mathbf{t})$

point set 1, v1(x)



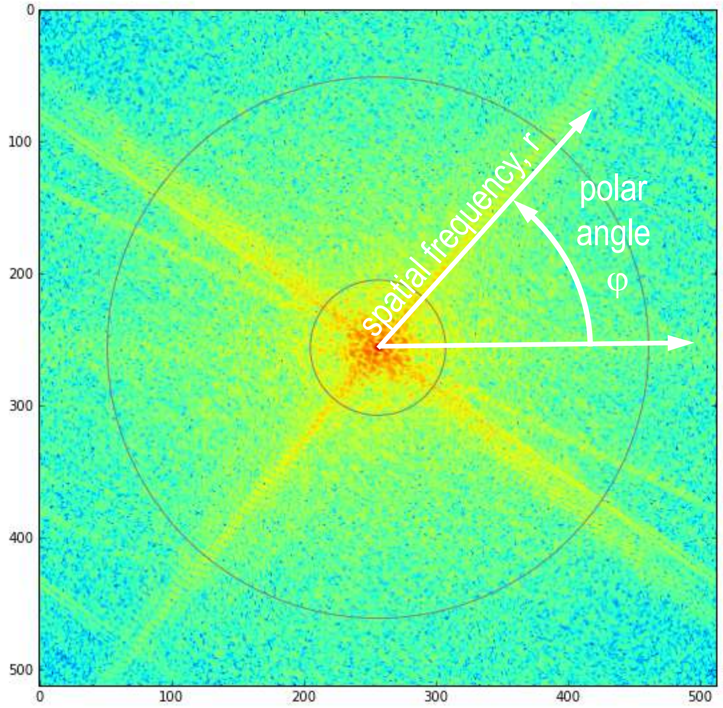
point set 2, v2(x)



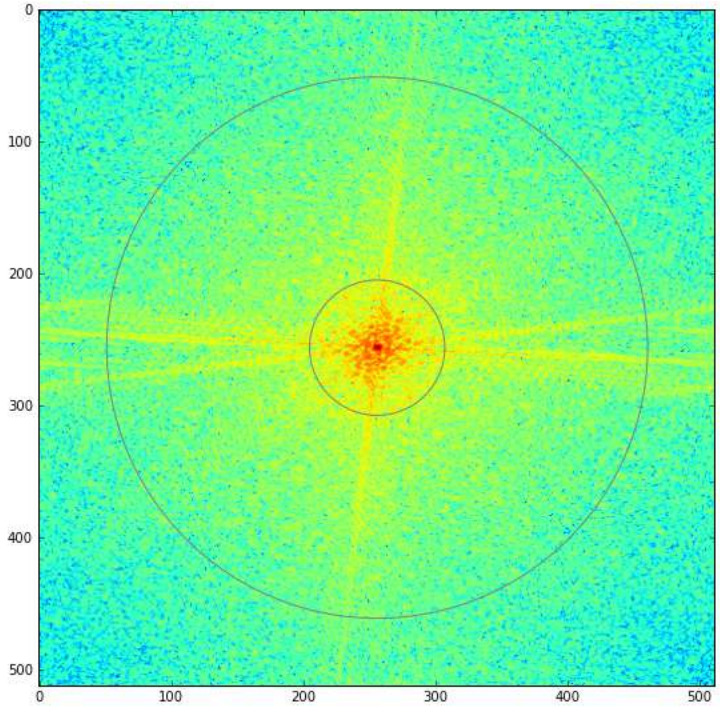
spectral registration – phase-only matched filtering

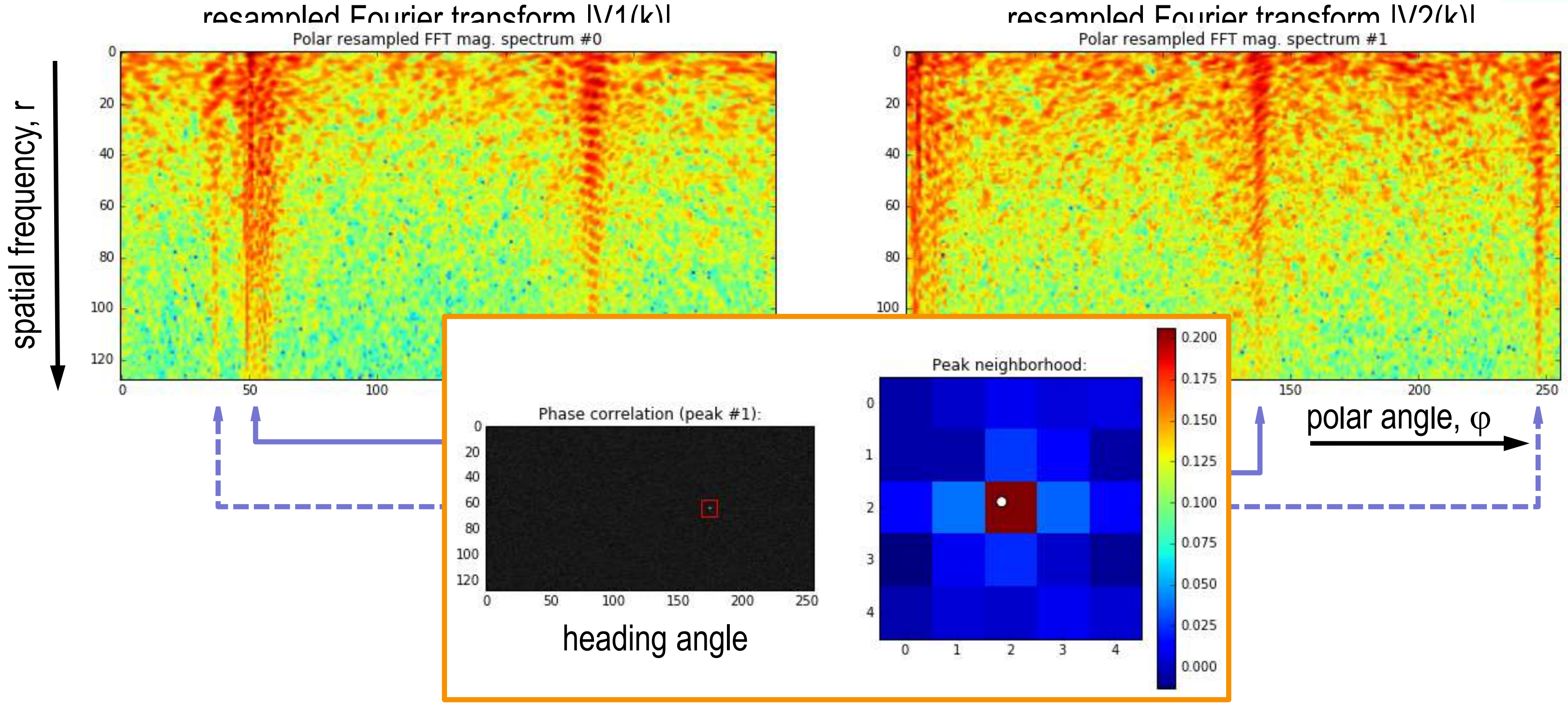
- resampling of irregular point cloud yields 3D voxel dataset: $v_1(\mathbf{x})$
- same „signal“ but rotated and shifted and denoted as $v_2(\mathbf{x})$: $v_2(\mathbf{x})=v_1(R\mathbf{x}+\mathbf{t})$
- Fourier transform of $v_1(\mathbf{x})$ and $v_2(\mathbf{x})$: $V_1(\mathbf{k})$ and $V_2(\mathbf{k})$
- ***Fourier Rotation Theorem*** **und** ***Shift Theorem***
  $V_2(\mathbf{k}) = V_1(R\mathbf{k})\ exp(i2\pi\,\mathbf{k}^T R^{-1}\mathbf{t})$
- analysing only magnitudes yields rotation R
  $|V_2(\mathbf{k})| = |V_1(R\mathbf{k})|$

Fourier transform |V1(k)|



Fourier transform |V2(k)|




resampled Fourier transform |V1(k)|
Polar resampled FFT mag. spectrum #0
resampled Fourier transform |V2(k)|
Polar resampled FFT mag. spectrum #1
spatial frequency, r
polar angle, φ
Phase correlation (peak #1):
heading angle
Peak neighborhood:

spectral registration – phase-only matched filtering

- resampling of irregular point cloud yields 3D voxel dataset: $v_1(\mathbf{x})$
- same „signal“ but rotated and shifted and denoted as $v_2(\mathbf{x})$: $v_2(\mathbf{x})=v_1(R\mathbf{x}+\mathbf{t})$
- Fourier transform of $v_1(\mathbf{x})$ and $v_2(\mathbf{x})$: $V_1(\mathbf{k})$ and $V_2(\mathbf{k})$
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  $V_2(\mathbf{k}) = V_1(R\mathbf{k})\, exp(i2\pi\, \mathbf{k}^T R^{-1}\mathbf{t})$
- analysing only magnitudes yields rotation R
  $|V_2(\mathbf{k})| = |V_1(R\mathbf{k})|$
- after applying rotation ($V_2'(\mathbf{k})$), analysis yields shift $\mathbf{t}$
  $V_2'(\mathbf{k}) = V_1(\mathbf{k})\, exp(i2\pi\, \mathbf{k}^T \mathbf{t})$

example:

- parking garage (multi-storey car park)
- 4 storeys, upper most with open sky access
- indoors area
  140.000 ft² / 13.000 m²

acquisition

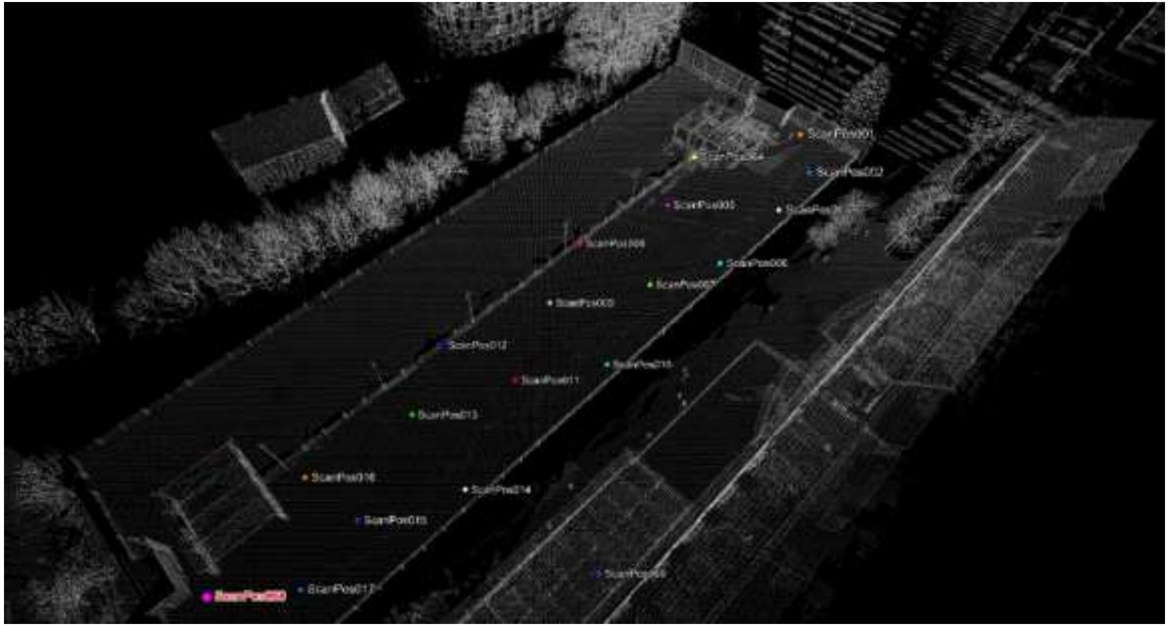
- *RIEGL* VZ-400i, 165 scan positions
- spatial sampling 0.04 deg / 7 mm @ 10 m
- 5 images / scan positions
- total time: 3h 42 min
- average time: 81 sec/scan position

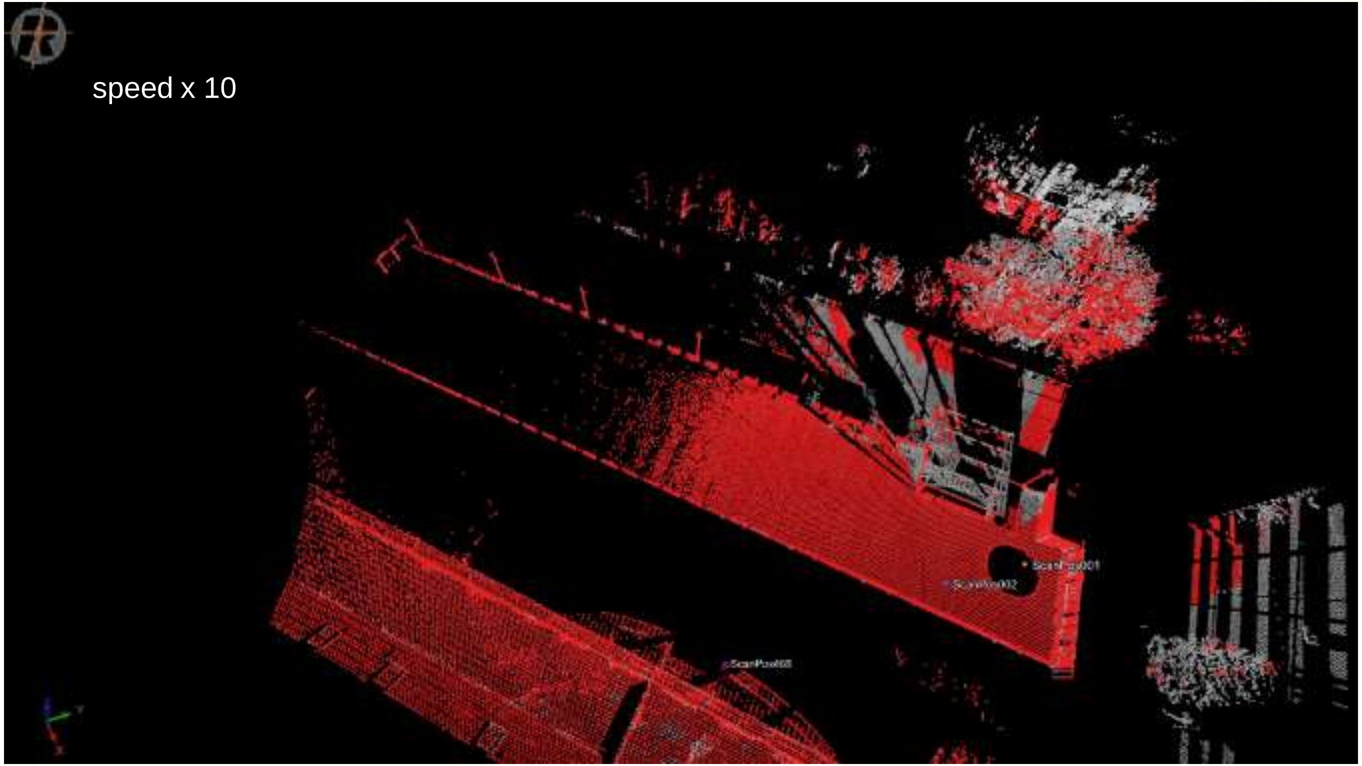
example:

- parking garage
  (multi-storey car park)
- 4 storeys, upper most with
  open sky accessibility
- indoors area
  140.000 ft² / 13.000 m²

registration

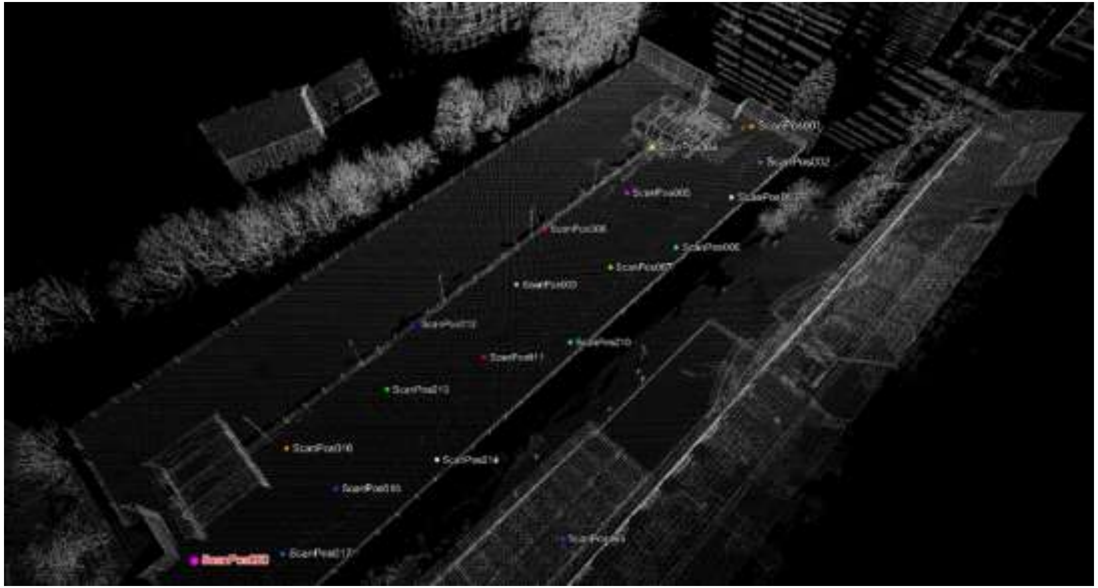
- automatic registration
- no user interaction required
- total time (standard PC): 1h 2 min
- average time 23 sec/scan position




speed x 10

example:

- parking garage
  (multi-storey car park)
- 4 storeys, upper most with
  open sky accessibility
- indoors area
  140.000 ft² / 13.000 m²



registration

- automatic registration
- no user interaction required
- total time (standard PC): 1h 2 min
- average time 23 sec/scan position

registration

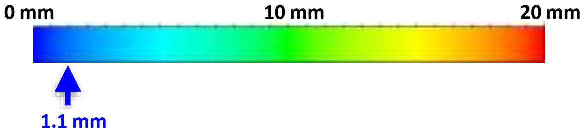
- automatic registration
- no user interaction required
- total time (standard PC): 1h 2 min
- average time 23 sec/scan position

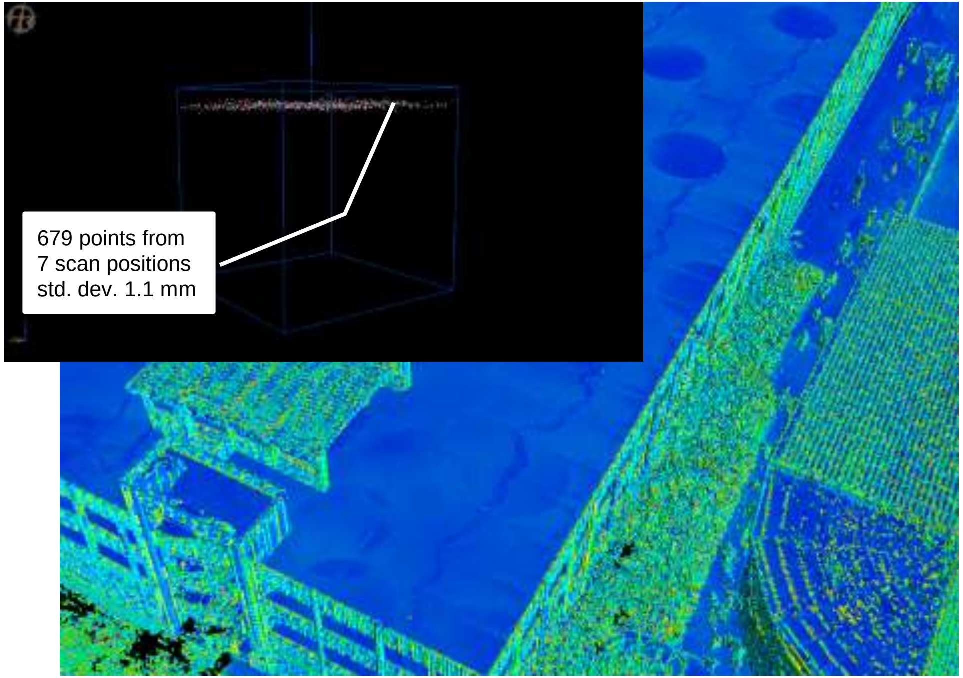
multi-station adjustment

- rigorous adjustment
- utilizing GNSS, control points, all internal sensors data
- total time 38 min
- average time per scan position 14 sec
- automatic generation of detailed report

example:
- parking garage (multi-storey car park)
- 4 storeys, upper most with open sky accessibility
- indoors area
  140.000 ft² / 13.000 m²

multi-station adjustment
- rigorous adjustment
- visual inspection
  standard deviation within 10 cm voxels



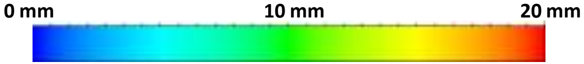


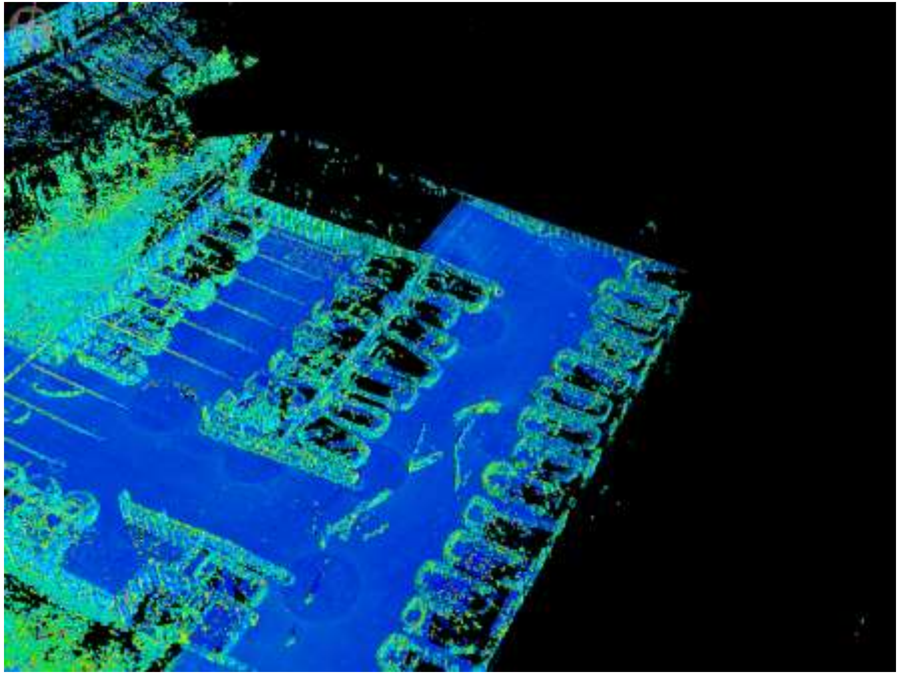
example:

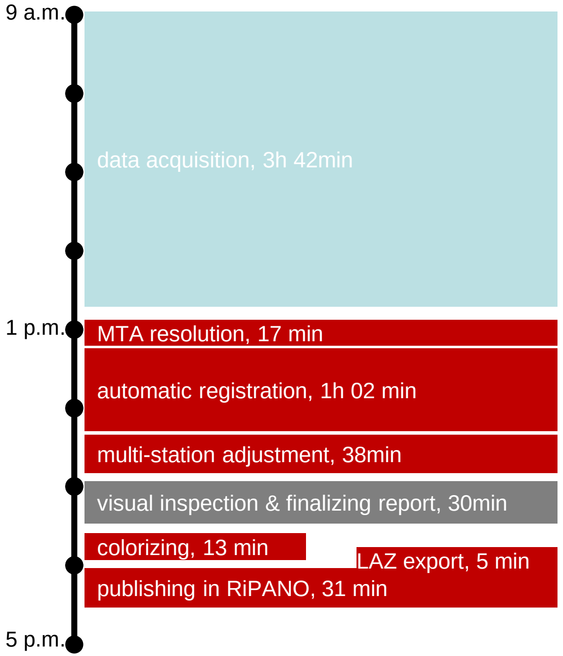
- parking garage
  (multi-storey car park)
- 4 storeys, upper most with
  open sky accessibility
- indoors area
  140.000 ft² / 13.000 m²

multi-station adjustment

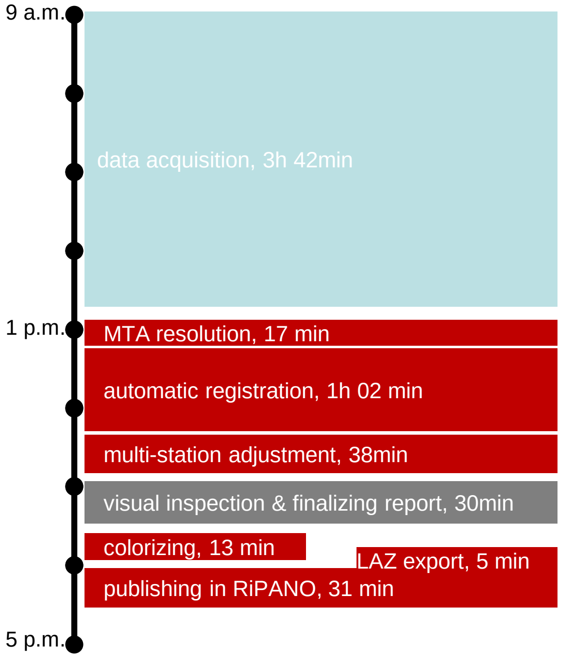
- rigorous adjustment
- visual inspection
  standard deviation within 10 cm voxels






9 a.m.
data acquisition, 3h 42min
1 p.m.
MTA resolution, 17 min
automatic registration, 1h 02 min
multi-station adjustment, 38min
visual inspection & finalizing report, 30min
colorizing, 13 min
LAZ export, 5 min
publishing in RiPANO, 31 min
5 p.m.


RiPANO
Eckartsau Castle
ScanPos001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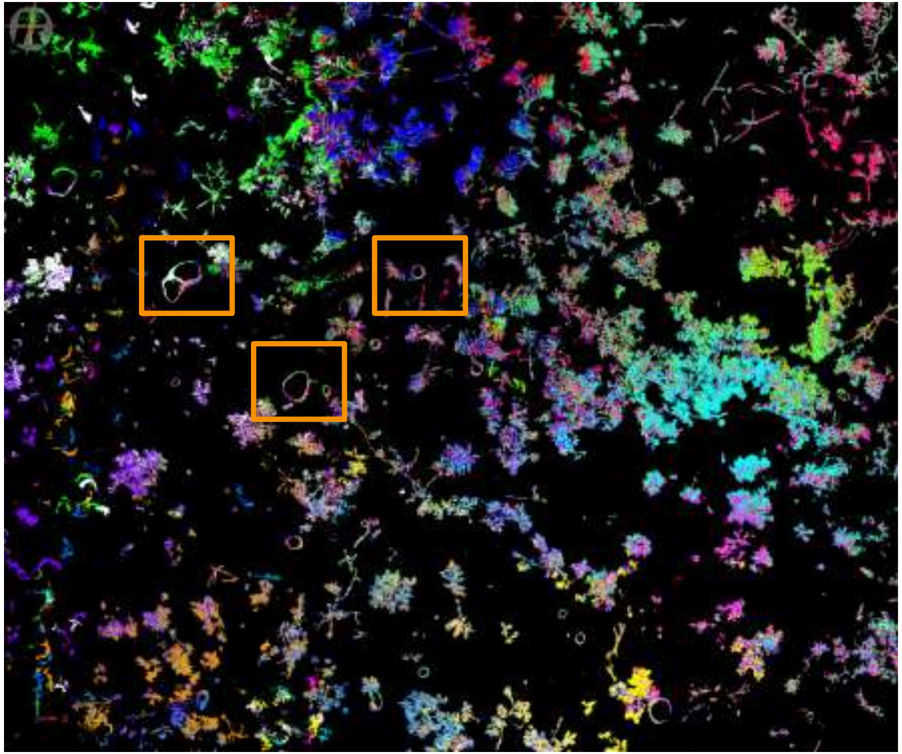
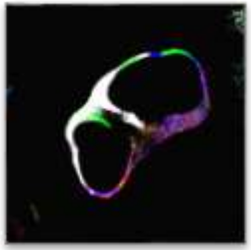
RiPANO
Eckartsau Castle
ScanPos001

2019 SILVI LASER
Iguazu Falls - October 8-10, 2019

SilviLaser benchmark test

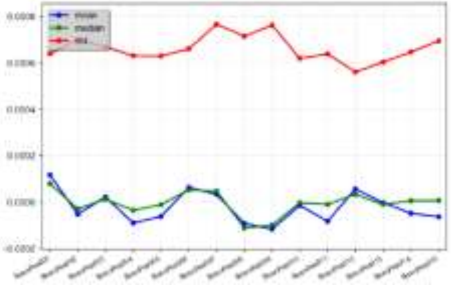
- 15 Scanpositions
- 23 minutes acquisition time
- 266 Mio points



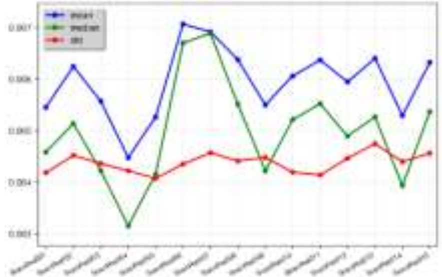


Plane patches

residuals in distance [m]



residuals in angle [deg]



Contents

Registration
finding initial estimate of all poses of the lidar sensor
for **each lidar measurement**, i.e., the **trajectory** of the platform

Adjustment
optimizing of all poses of the lidar sensor
for **each lidar measurement** in order to achieve
best consistency of final data with all measurements / observations

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  - Stop-and-Go Data Acquisition
  - **Kinematic Data Acquisition**

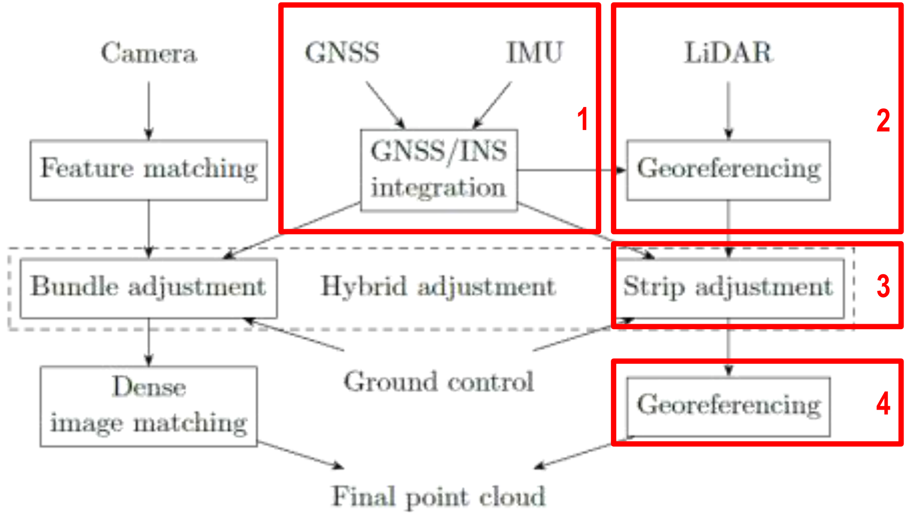


Figure 1: Standard kinematic mapping processing pipeline with trajectory-level error modelling

Integrated Trajectory Estimation for 3D Kinematic Mapping with GNSS, INS and Imaging Sensors: A Framework and Review

Florian Pöppl[a], Norbert Pfeifer[a], Hans Neuner[a]

[a]Department of Geodesy and Geoinformation, TU Wien, Wiedner Hauptstraße 8/E120, 1040 Wien, Austria

Project ZAP-ALS

Improving reliability, automation and precision through integrated estimation of trajectories and point clouds from GNSS, INS and ALS

Project no. 883660, supported by the Austrian Research Promotion Agency, FFG

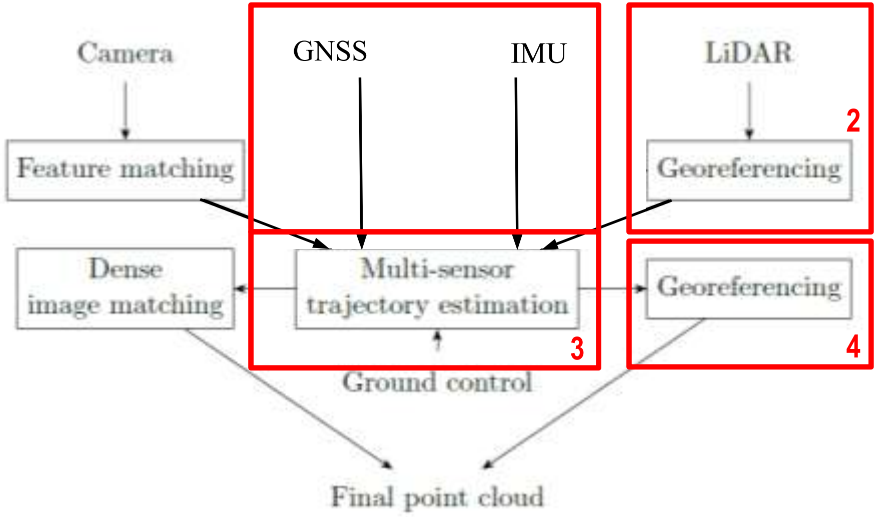


Figure 2: Holistic kinematic mapping processing pipeline with sensor-level error modelling

Integrated Trajectory Estimation for 3D Kinematic Mapping with GNSS, INS and Imaging Sensors: A Framework and Review

Florian Pöppl[a], Norbert Pfeifer[a], Hans Neuner[a]

[a]Department of Geodesy and Geoinformation, TU Wien, Wiedner Hauptstraße 8/E120, 1040 Wien, Austria

1. calculating initial trajectory
2. initial georeferencing of lidar data
3. re-calculating trajectory from IMU **raw** data, GNSS positions, and lidar/image observations
4. final georeferencing of lidar data

RIEGL VZi GNSS RTK Receiver
L1+L2 receiver, real-time
base station correction data

low € high

RIEGL VZ-2000i
long range (up to 2.5 km)
high speed (up to 500k Meas/sec)

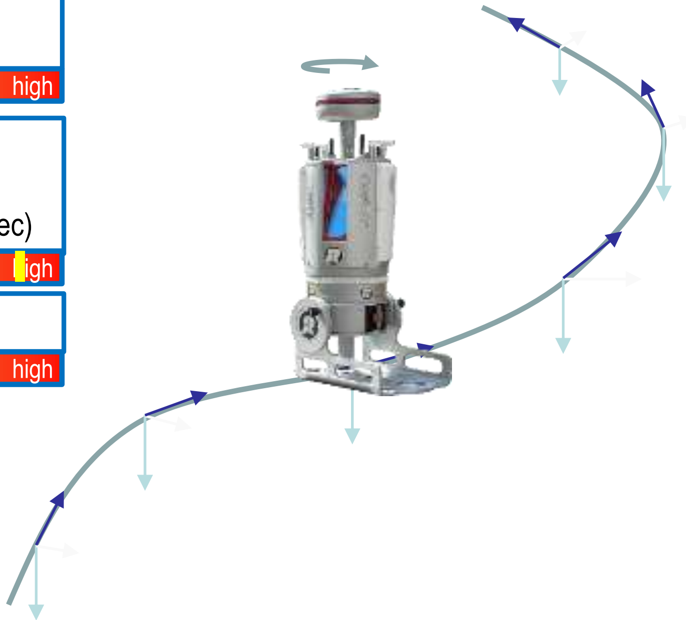
low € high

Internal IMU

low € high

Internal data processing and storage

RIEGL Add-On Battery
3x Li-Ion batteries

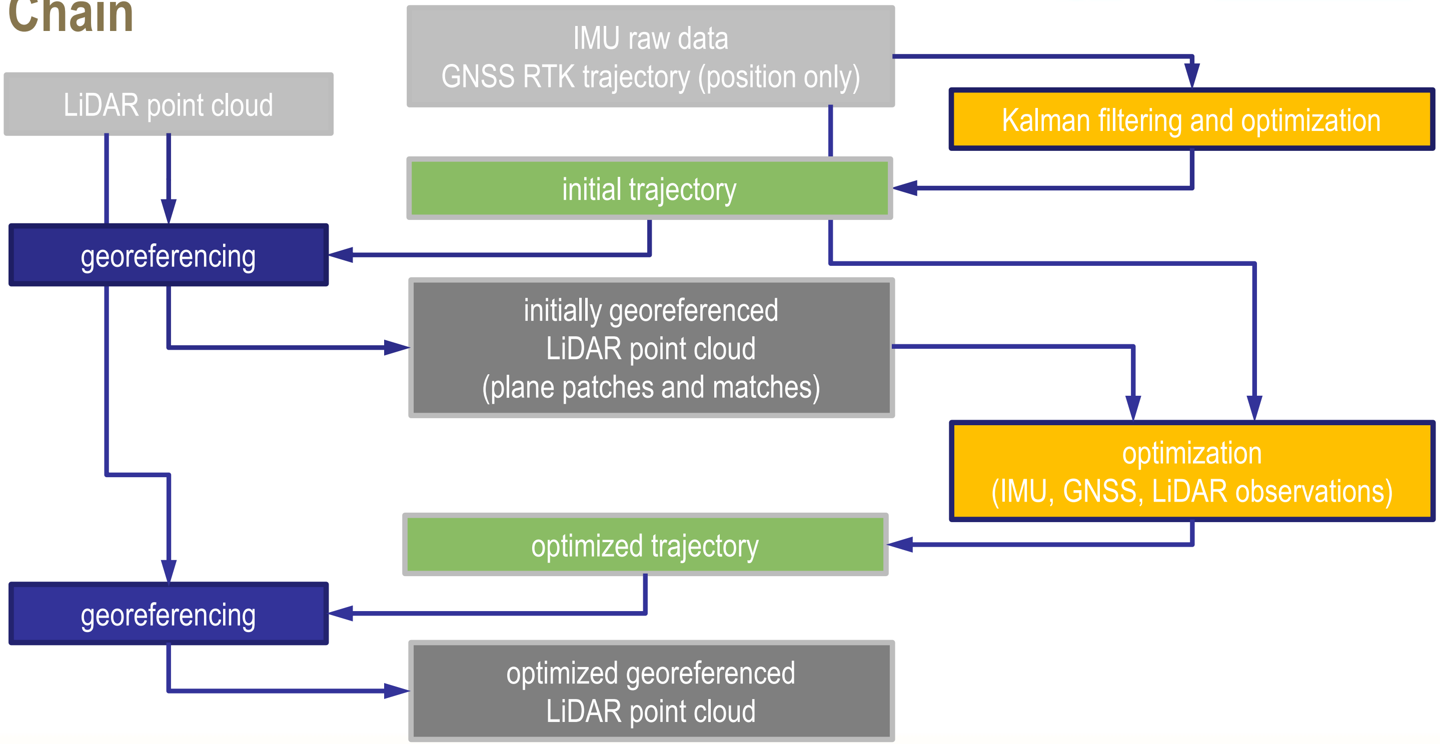


Kinematic Scanning with RIEGL VZ-2000i from Car Roof

Line Scan Mode

Radar Mode

Processing Chain



Kinematic Scanning with *RIEGL* VZ-2000i from Car Roof

Line Scan Mode

Radar Mode

Kinematic Scanning with *RIEGL* VZ-2000i from Car Roof

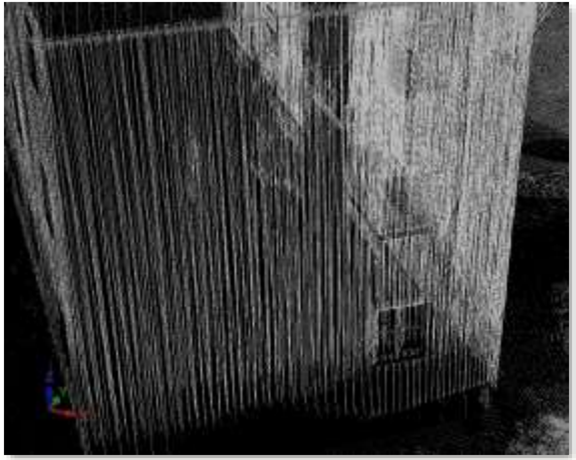
Pros Line Scan Mode
- higher resolution
- regular scan pattern

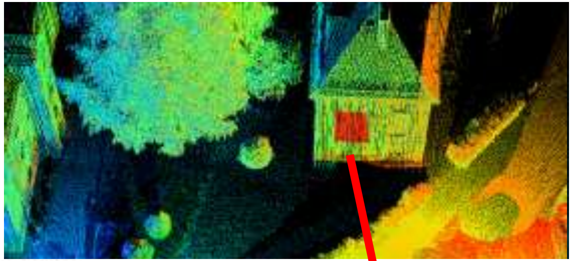
Cons Line Scan Mode
- more scan shadows
- 2 passes necessary to cover both sides of the street

Kinematic Scanning with *RIEGL* VZ-2000i from Car Roof

Pros of Radar Mode
- higher overall accuracy of trajectory
- only one single pass is necessary
- less scan shadows

Cons of Radar Mode
- less small details due to irregular scan pattern





PLANE

	Min	Max	Max - Min	StdDev	Mean
Range:	-0.03655	0.01560	0.05215	0.00468	0.00000

	X	Y	Z
Plane position:	63.73174	75.42955	477.58438
Plane normal vector:	-0.62816	0.77808	-0.00137
Inclination angle:	87.885		

- same object is covered multiple times
- the facade is covered 9 times
- platform speed approx. 10 km/h
- scanner rotation speed 150°/sec.
- noise of data close to static TLS data

***RIEGL* VZ-400i**
Stop & Go Acquisition

- June 2022
- 315 scan positions
- about 10 m apart
- forth and back
- in about 7h10min

→ ground truth

***RIEGL* VZ-400i**
Stop & Go Acquisition

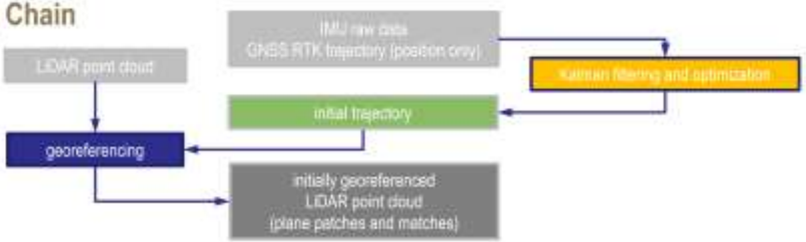
- June 2022
- **180 scan** positions
- about 10 m apart
- forth and back
- in about **4 hours**

→ ground truth

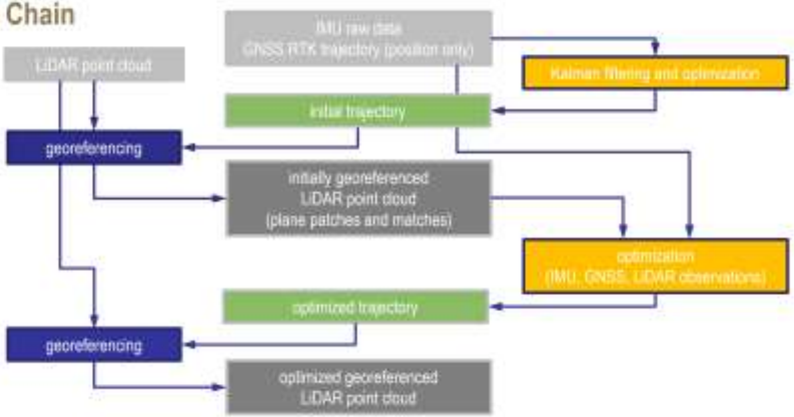
***RIEGL* VZ-400i on**
Cargo Bike
Kinematic Acquisition

- September 2022
- 2 acquisitions
- 7 min + 5 min

Processing Chain



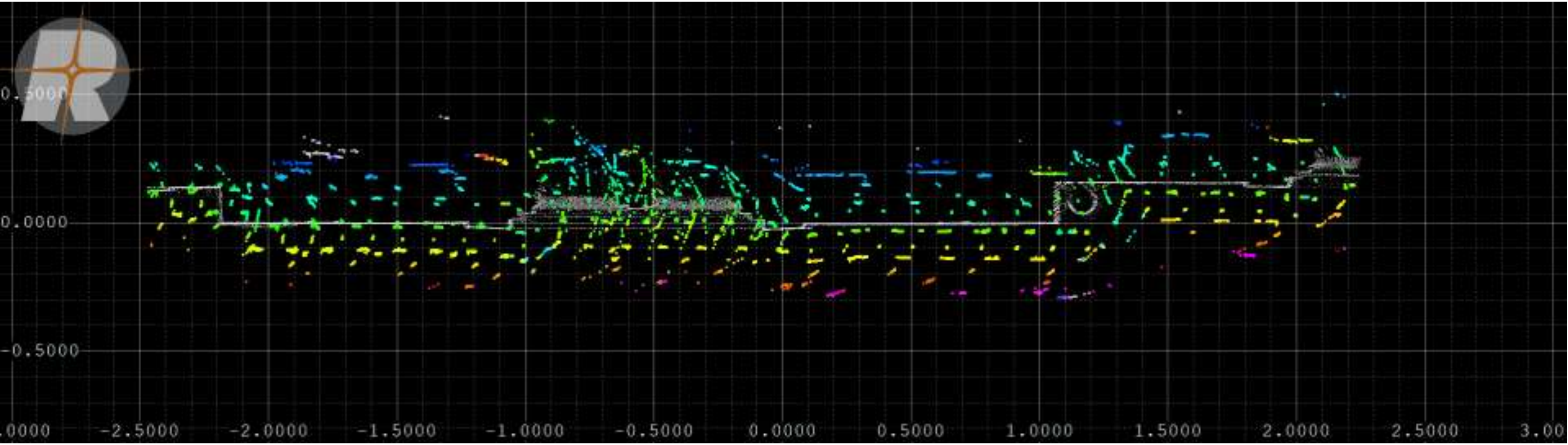
Processing Chain



reflectance - colorized point cloud from **kinematic acquisition** September 2022

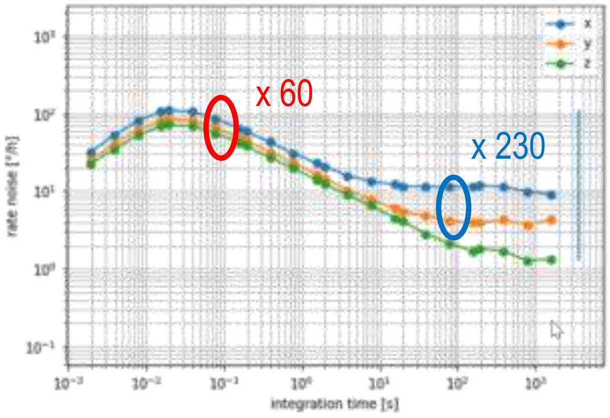
cross section from TLS stop & go acquisition

-0.25 m initial point cloud from kinematic acquisition with trajectory from IMU and GNSS only +0.25 m

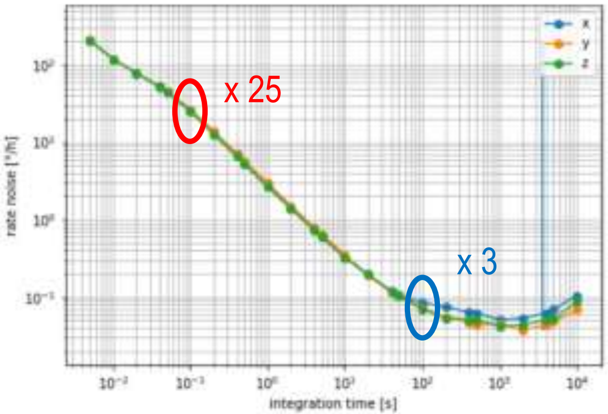


Angular Rate Noise – Allan Deviation

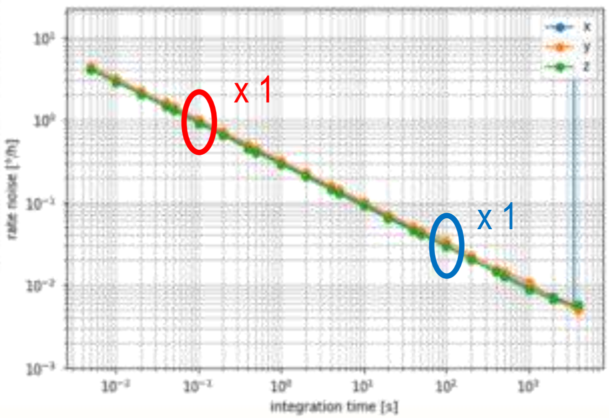
Low-Grade MEMS IMU



High-Grade MEMS IMU



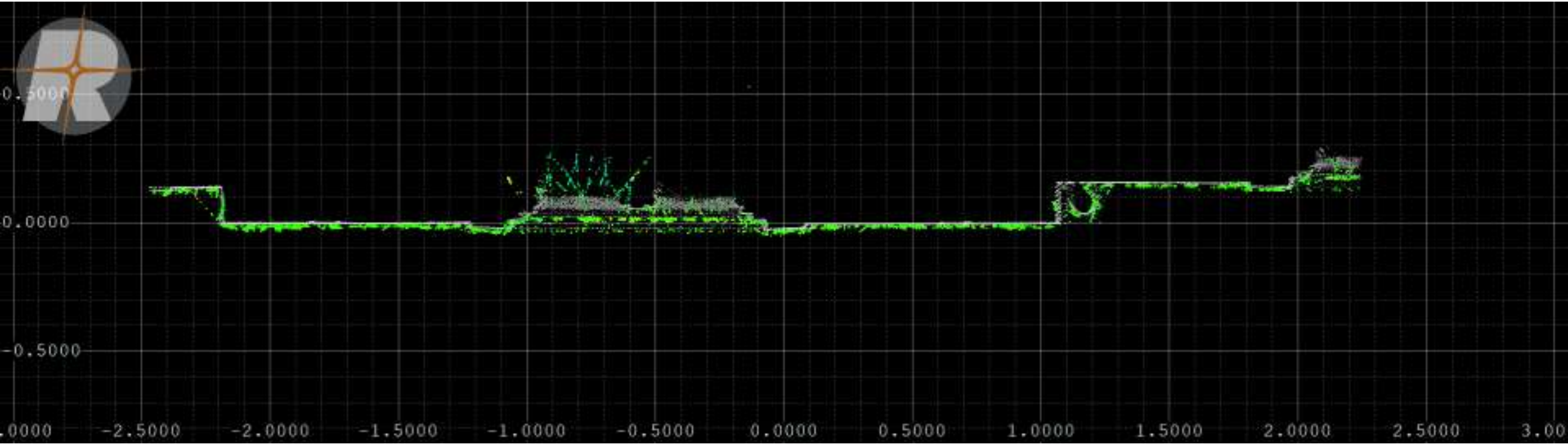
High-Grade FOG IMU

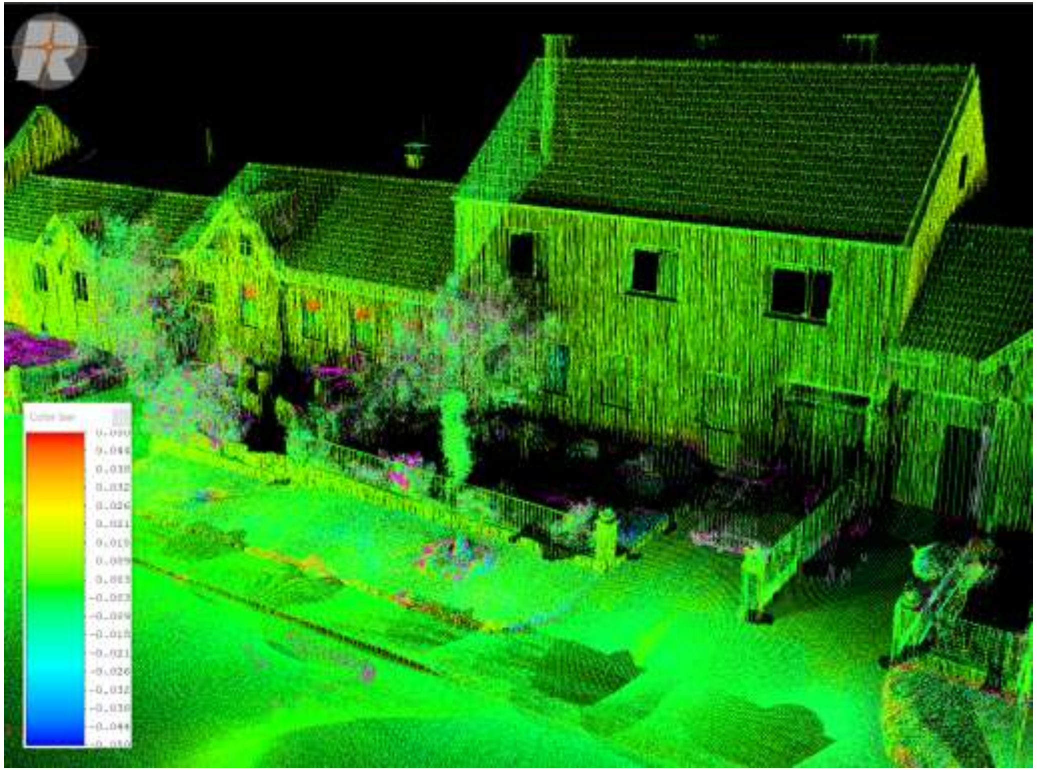


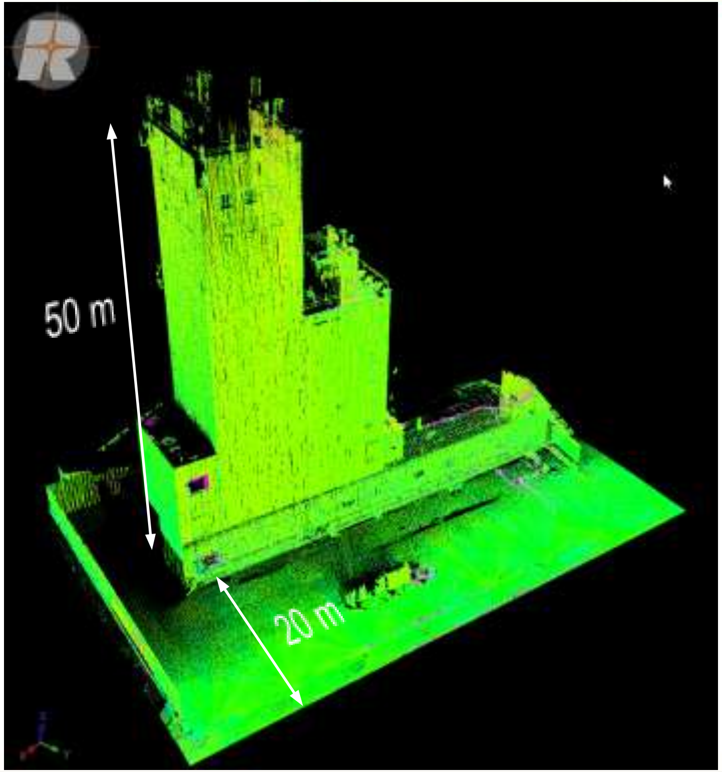
0 … 0.1 sec 0 … 100 sec

cross section from TLS stop & go acquisition

-0.05 m final point cloud from kinematic acquisition from IMU, GNSS and lidar observations +0.05 m






50 m
20 m

Survey-grade Lidar Systems utilizing Sensor Fusion for Static and Kinematic Lidar Data Acquisition

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Thank you for your kind attention

Scientific Workshop on Uncertainty and Quality of Multi-Sensor Systems

Session 4: Quality of Terrestrial Laser Scanning, 11.9.2022