Airborne laser scanning for corridor mapping: Georeferencing with tightly-coupled multi-view LiDAR

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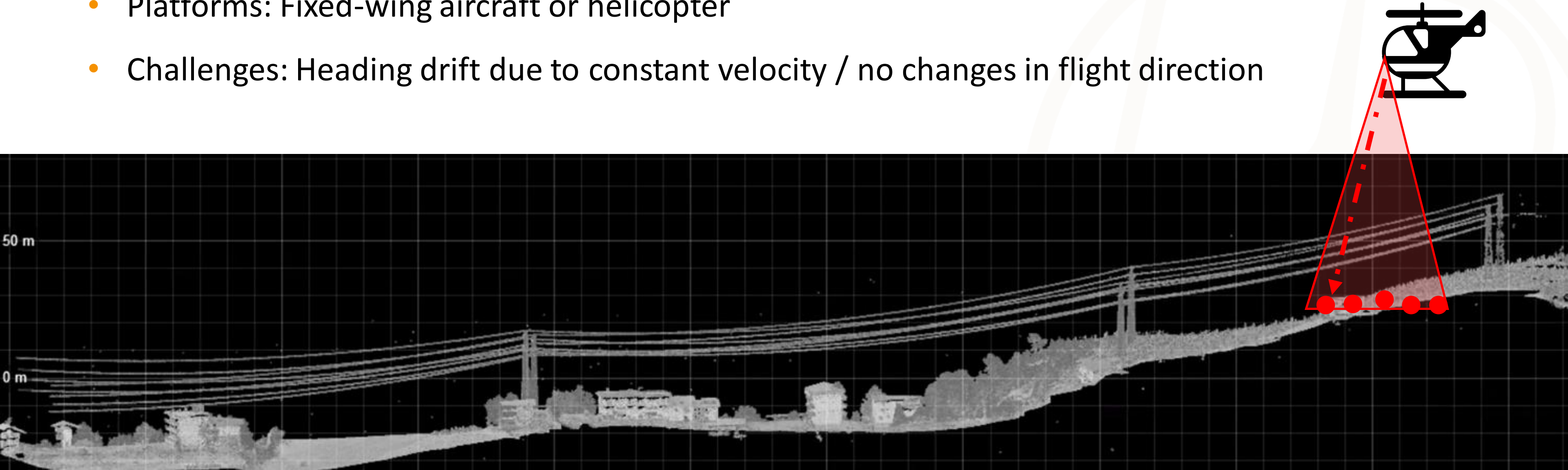
Airborne laser scanning for corridor mapping

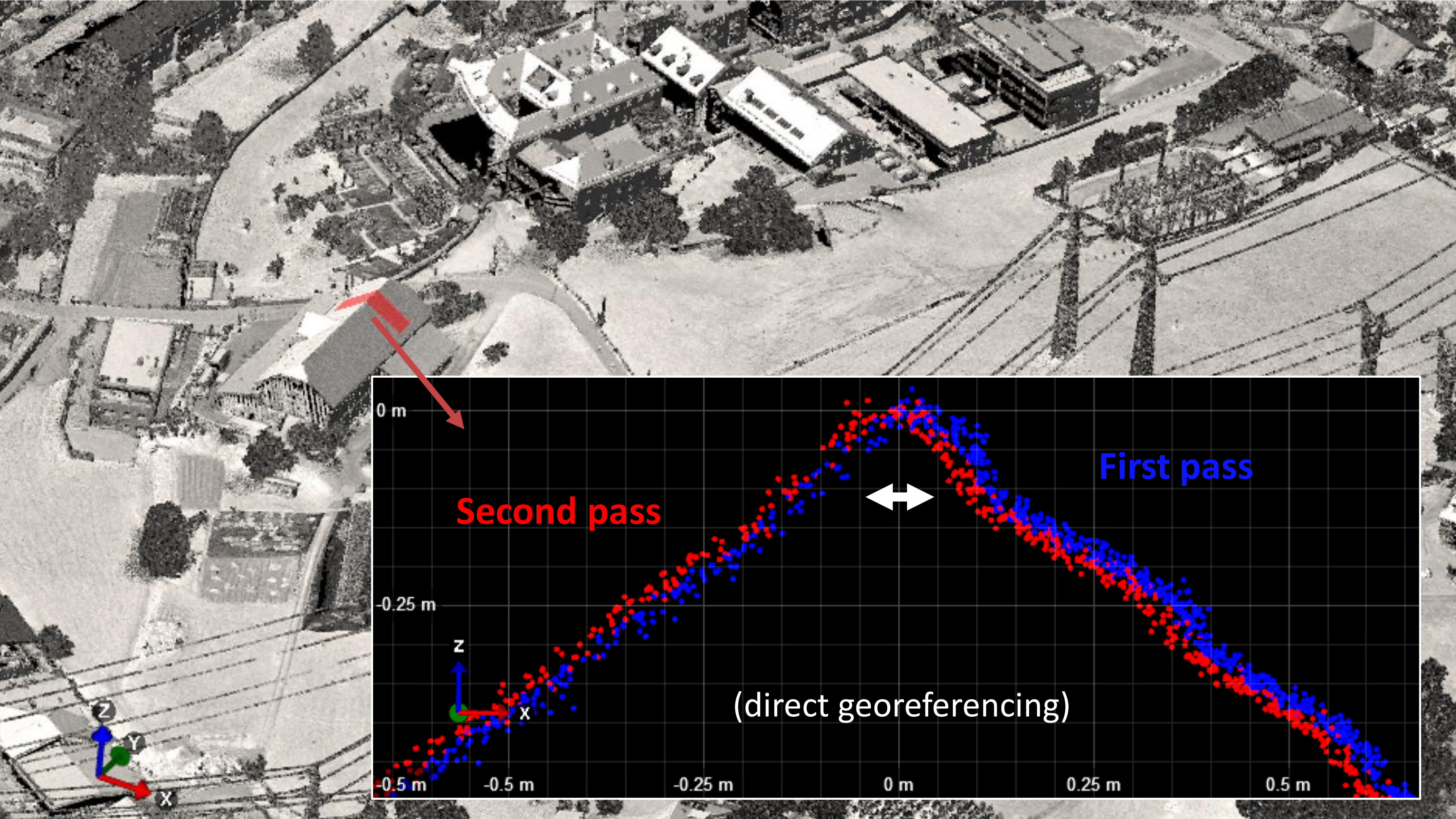
- Mapping of linear structures, e.g., power lines, railways, etc.
- Overlap often undesired, single-pass data acquisition more efficient/economical

- Laser scanners: „survey grade“, high precision, small footprint, high point density
- Platforms: Fixed-wing aircraft or helicopter
- Challenges: Heading drift due to constant velocity / no changes in flight direction

RIEGL VUX-160[23]



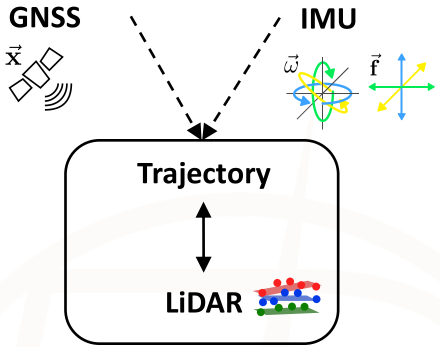

Z
Y
X



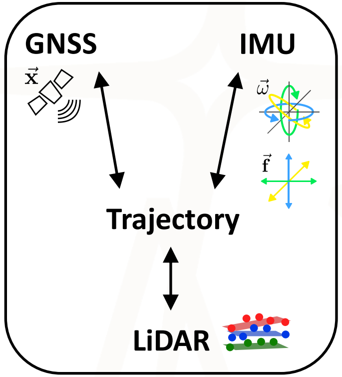
0 m
-0.25 m
-0.5 m
-0.5 m
-0.25 m
0 m
0.25 m
0.5 m
First pass
Second pass
(direct georeferencing)
z
x
Z
Y
X

Trajectory estimation with tightly-coupled LiDAR

Instead of standard "*Kalman filter followed by strip adjustment*":



Joint adjustment of all data, modelling of errors at the sensor level, tight coupling of IMU and LiDAR.

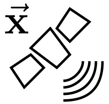


Pöppl, F., Ullrich, A., Mandlburger, G., Pfeifer, N., 2024. *A Flexible Trajectory Estimation Methodology for Kinematic Laser Scanning. ISPRS Journal of Photogrammetry and Remote Sensing*.
Pöppl, F., Ullrich, A., Mandlburger, G., Pfeifer, N., 2025. *Precise and Efficient High-Frequency Trajectory Estimation for LiDAR Georeferencing*. ISPRS Journal of Photogrammetry and Remote Sensing, 223, 344–361.

Trajectory estimation with GNSS/IMU/LiDAR data

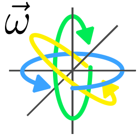
Non-linear least-squares adjustment (optimization) with GNSS, IMU and LiDAR measurements

GNSS

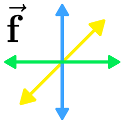


Position

IMU

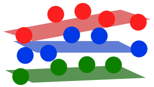


Angular velocity



Specific force

LiDAR



Correspondences
(here: plane-to-plane)

Minimize discrepancy (*sum of squared residuals, SSR)* between model and measurements

min! SSR(GNSS) +

SSR(IMU) +

SSR(LiDAR)

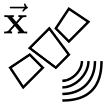
→ Frequency of IMU defines trajectory model, redundancy stems from GNSS and LiDAR observations.

→ Tight coupling of LiDAR & IMU!

Trajectory estimation with GNSS/IMU/LiDAR data

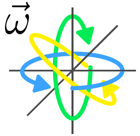
Non-linear least-squares adjustment (optimization) with GNSS, IMU and LiDAR measurements

GNSS

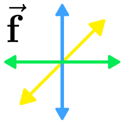


Position

IMU

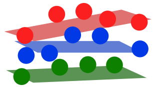


Angular velocity



Specific force

LiDAR



Correspondences
(here: plane-to-plane)

$$\underbrace{\widetilde{\boldsymbol{p}}}_{\text{measurement}} = \underbrace{\boldsymbol{x}^e_{eb}(t) + \boldsymbol{R}^e_b(t)\left(\boldsymbol{x}^b_{bm} + \boldsymbol{R}^b_m(t)\boldsymbol{x}^m_{ma}\right)}_{\text{model}} + \underbrace{\boldsymbol{\epsilon}_p}_{\text{error}}$$

$$\underbrace{\begin{matrix} \widetilde{\Delta\boldsymbol{v}}^s_{is}\,\frac{1}{\Delta t} \\ \widetilde{\Delta\boldsymbol{\theta}}^s_{is}\,\frac{1}{\Delta t} \end{matrix}}_{\text{measurement}} \begin{matrix} = \\ = \end{matrix} \underbrace{\begin{matrix} (\boldsymbol{I} + \boldsymbol{S}_v)\,\Delta\boldsymbol{v}^s_{is}(t)\,\frac{1}{\Delta t} + \boldsymbol{b}_v(t) \\ (\boldsymbol{I} + \boldsymbol{S}_\theta)\,\Delta\boldsymbol{\theta}^s_{is}(t)\,\frac{1}{\Delta t} + \boldsymbol{b}_\theta(t) \end{matrix}}_{\text{model}} \begin{matrix} + \\ + \end{matrix} \underbrace{\begin{matrix} \boldsymbol{\epsilon}_v \\ \boldsymbol{\epsilon}_\theta \end{matrix}}_{\text{noise}}$$

$$\underbrace{(\boldsymbol{\mu} - \widetilde{\boldsymbol{\mu}}) \cdot \widetilde{\boldsymbol{n}}}_{\text{normal distance } d} = \boldsymbol{0} + \epsilon_d$$

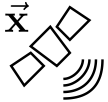
$$\underbrace{\frac{\boldsymbol{n} \cdot \widetilde{\boldsymbol{k}}_1}{\boldsymbol{n} \cdot \widetilde{\boldsymbol{n}}}}_{\text{slope } s_1} = \boldsymbol{0} + \epsilon_{s_1}$$

$$\underbrace{\frac{\boldsymbol{n} \cdot \widetilde{\boldsymbol{k}}_2}{\boldsymbol{n} \cdot \widetilde{\boldsymbol{n}}}}_{\text{slope } s_2} = \boldsymbol{0} + \epsilon_{s_2}$$

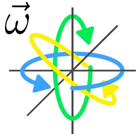
Trajectory estimation with GNSS/IMU/LiDAR data

Non-linear least-squares adjustment (optimization): $|z - f(x)|$ -> min

GNSS

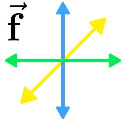


Position



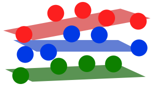
Angular velocity

IMU

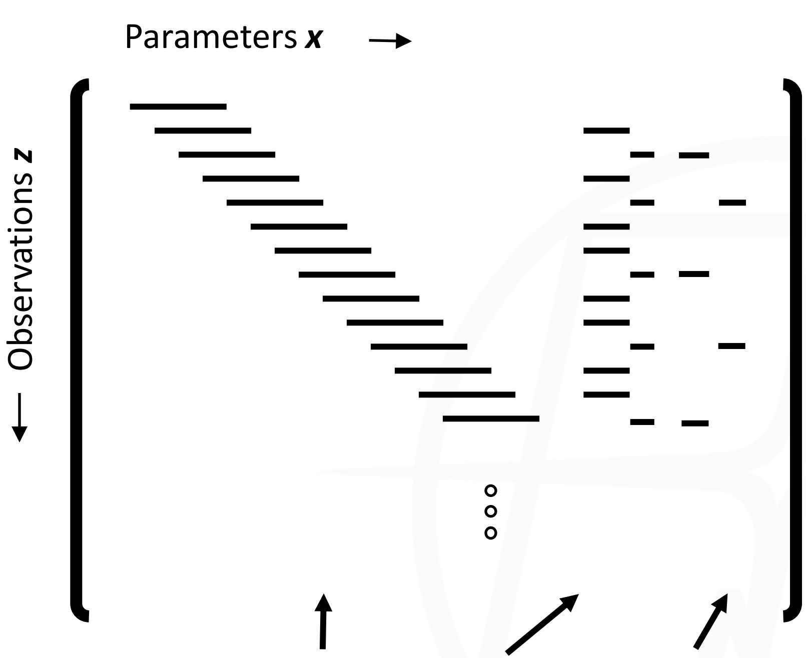


Specific force

LiDAR



Correspondences
(here: plane-to-plane)



Design
matrix
d*f(x)*

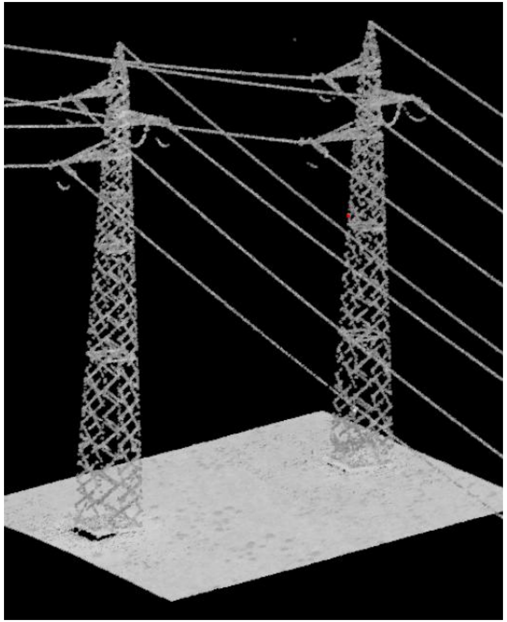
Joint
Adjustment of Trajectory-, calibration- and object parameters

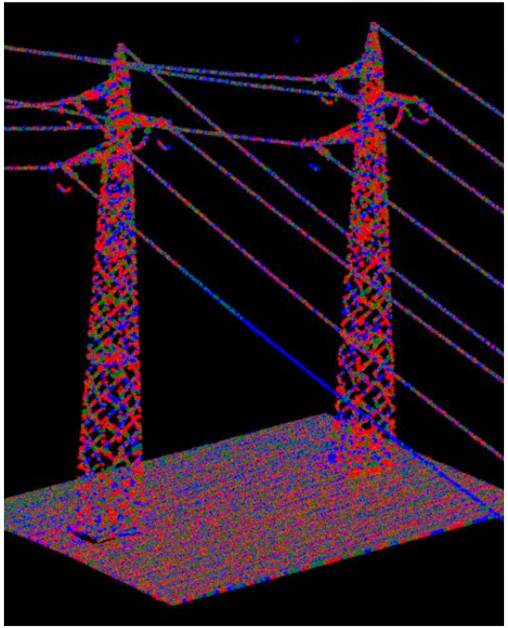
Multi-view LiDAR: *NFB* scanning

- *RIEGL* VUX-160²³ (with RiLOC-E-25 GNSS/IMU) features nadir/forward/backward (NFB) scanning for
  - reduced scan shadows
  - **in-strip overlap**

Accuracy [6) 8)] / Precision [7) 8)]	10 mm / 5 mm
Laser Pulse Repetition Rate [1) 9)]	up to 2400 kHz
Max. Effective Measurement Rate [1)]	up to 2,000,000 meas./sec.

For details see RIEGL VUX-160²³ datasheet.



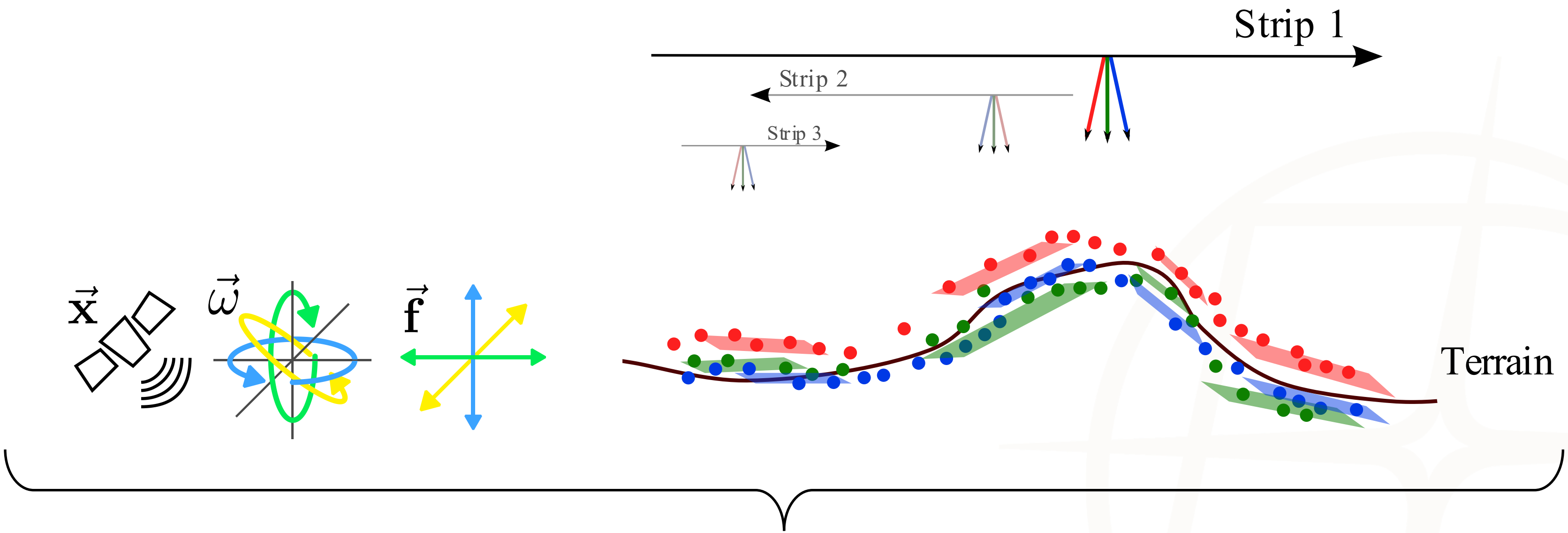


Multi-view LiDAR: *NFB* scanning

- *RIEGL* VUX-160[23] (with RiLOC-E-25 GNSS/IMU) features nadir/forward/backward (NFB) scanning for
  - reduced scan shadows
  - **in-strip overlap**

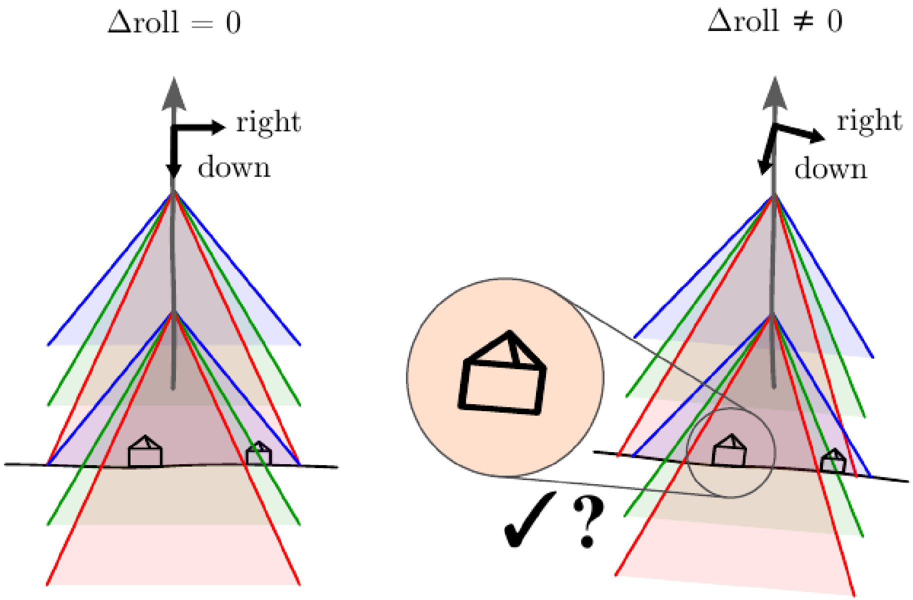
Does multi-view scanning aid estimation of platform heading?

LiDAR correspondences from NFB scanning



Least-squares adjustment

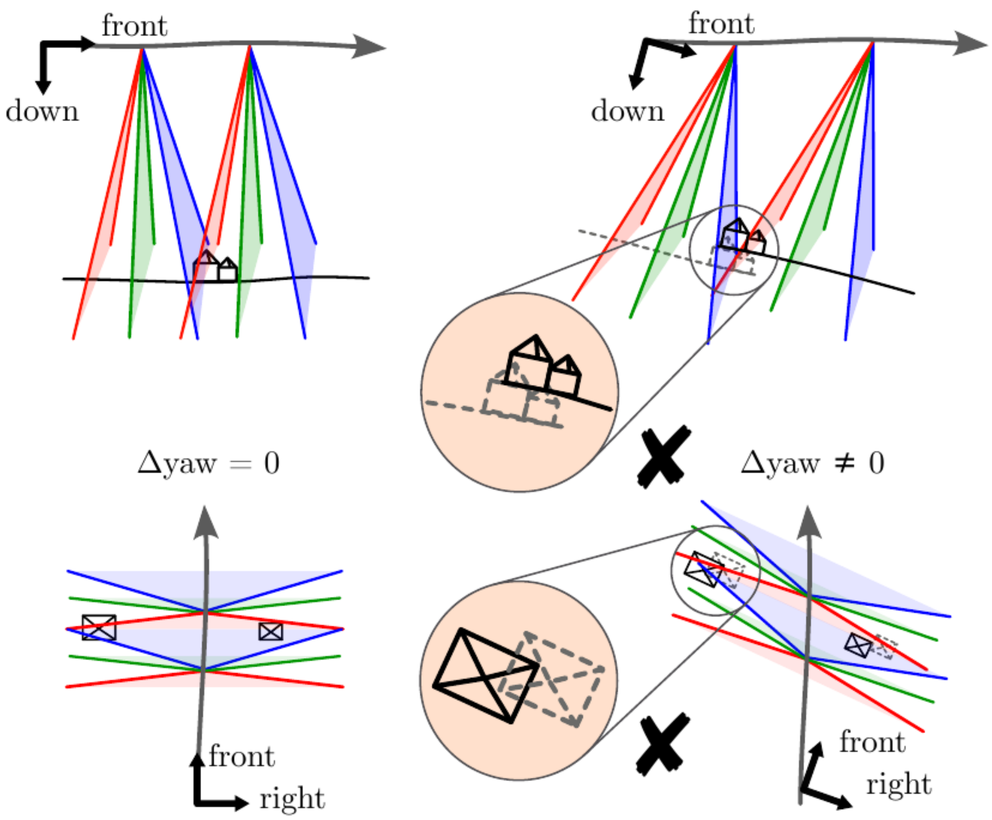
LiDAR correspondences from NFB scanning



Does multi-view scanning aid estimation of platform heading?

Roll errors effect all view directions equally and are not observable this way!

LiDAR correspondences from NFB scanning

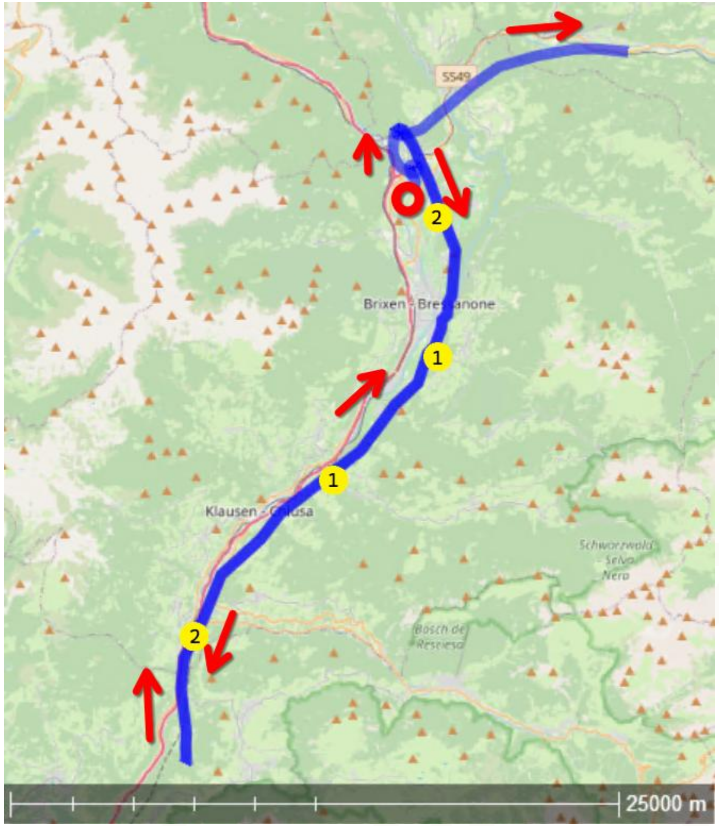


Does multi-view scanning aid estimation of platform heading?

Overlap from NFB scanning makes pitch and yaw errors immediately apparent from only one pass!

Results: Powerline mapping in the the Eisacktal (Valle Isarco)

RIEGL VUX-160²³ with RiLOC-E-25 GNSS/IMU navigation system
(data acquisition performed by Alto Drones GmbH)



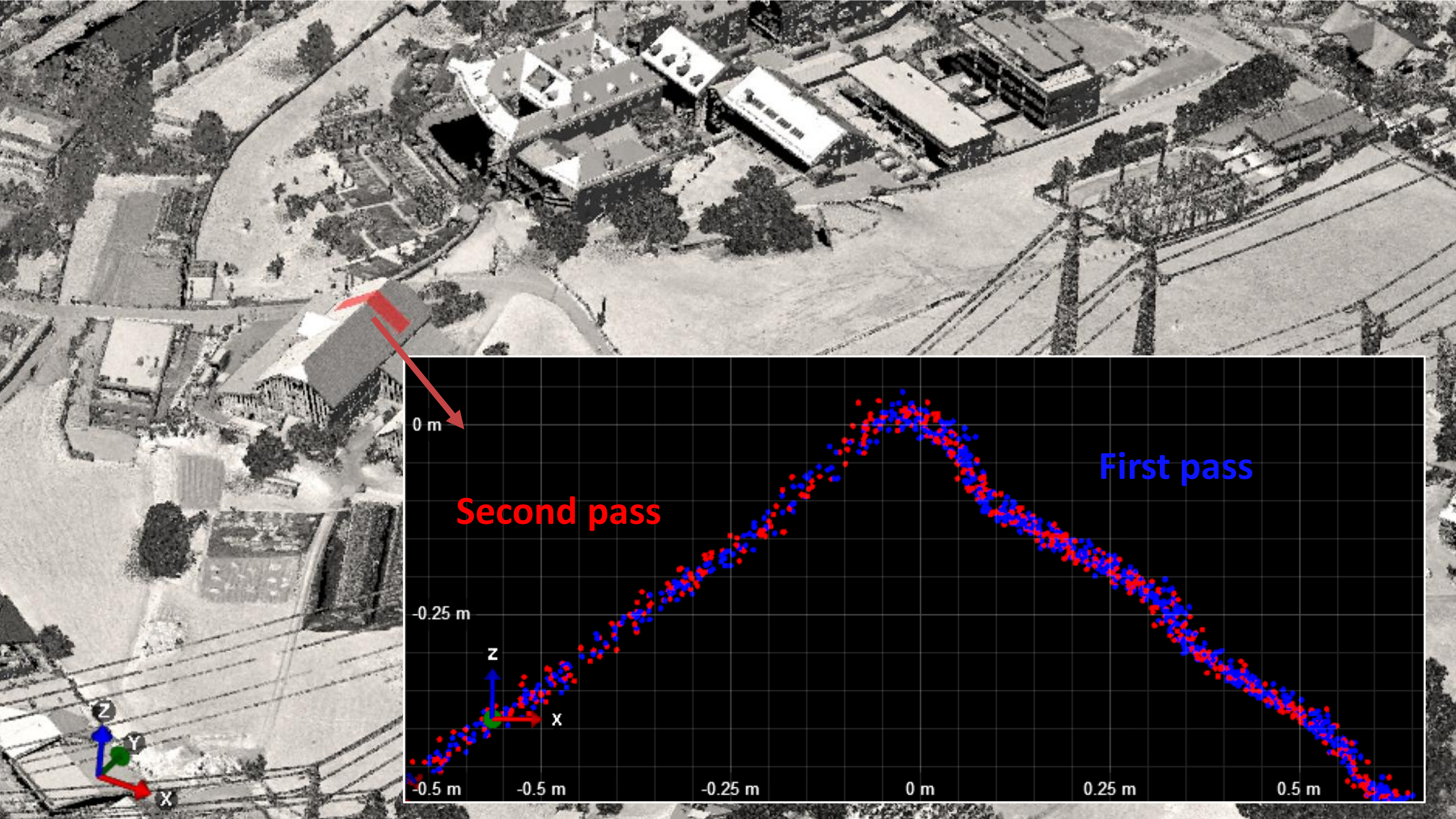
Results / Evaluation

Does multi-view scanning aid estimation of platform heading?

- No „higher-grade“ reference from other sources available

1. Verify full-overlap LiDAR-integrated results [**Full G/I/L**] are suitable as reference by
   - checking precision / consistency / strip differences
   - checking accuracy w.r.t. independent reference on the ground

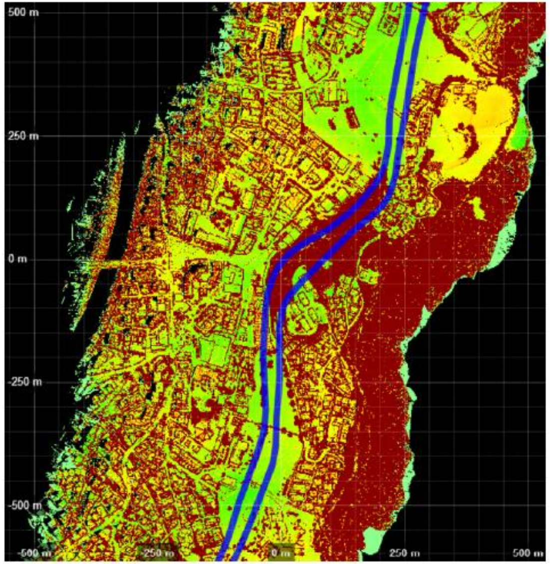
2. Use full overlap LiDAR-integrated results as reference / baseline and
   - compare with GNSS/IMU trajectory [**Full G/I**],
   - compare with *single-pass* GNSS/IMU/LiDAR trajectory [**N-to-S G/I/L**].



0 m
First pass
Second pass
-0.25 m
Z
X
Y
-0.5 m
-0.5 m
-0.25 m
0 m
0.25 m
0.5 m

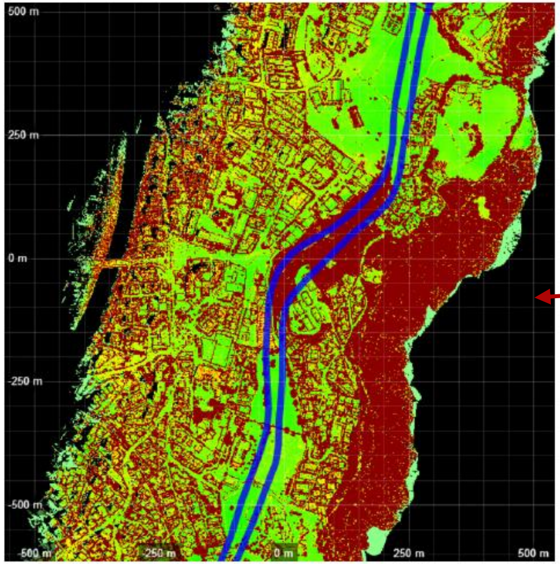
Strip differences and comparison to reference surfaces

NLS adjustment with
IMU/GNSS [G/I]

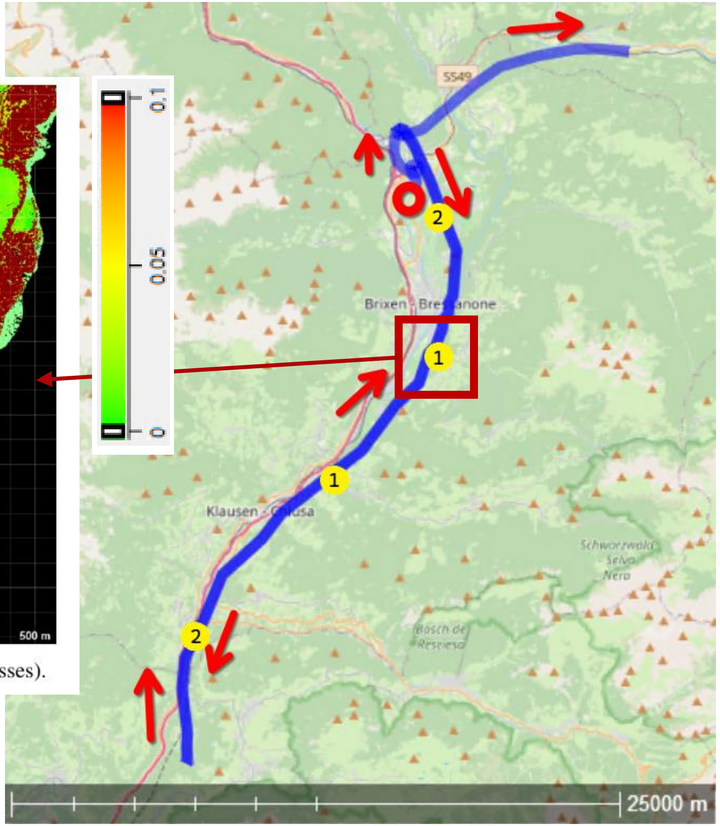


(a) Strip differences for all G/I point clouds (both passes).

NLS adjustment with
IMU, GNSS, LiDAR [G/I/L]

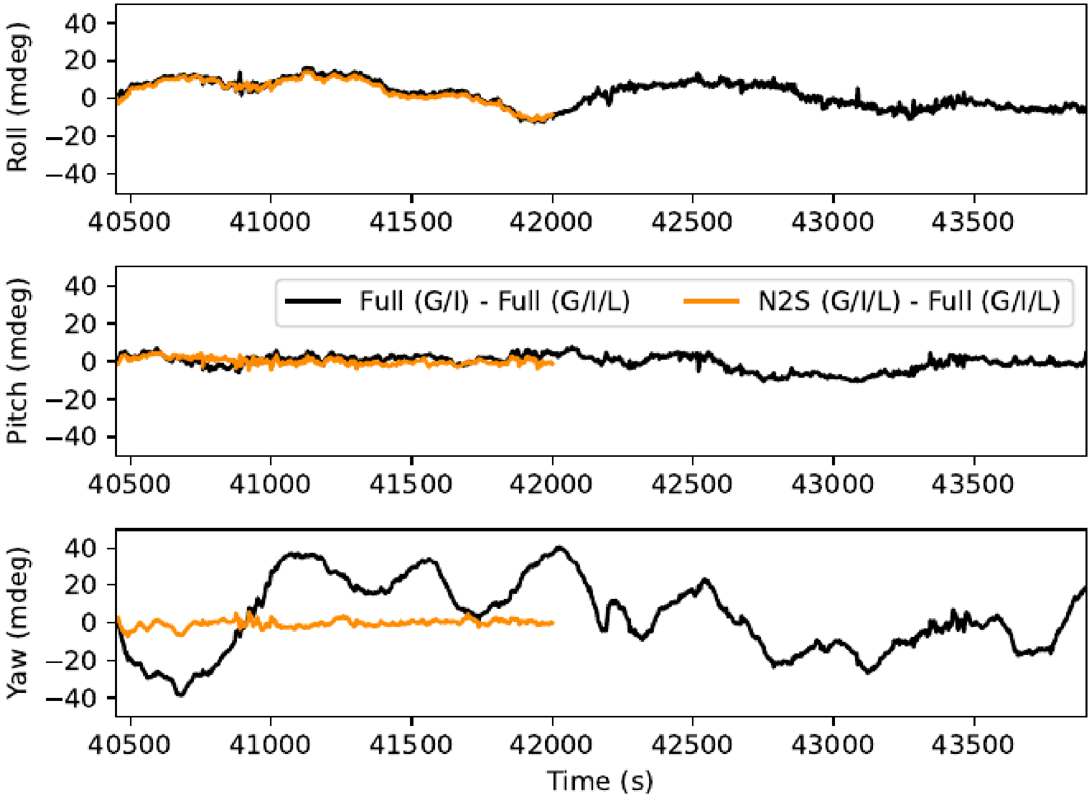


(b) Strip differences for all G/I/L point clouds (both passes).



	Mean (cm)	**RMSE** (cm)	**AVG-SD** (cm)
G/I	-0.36	2.13	1.01
G/I/L	-0.36	2.17	0.33

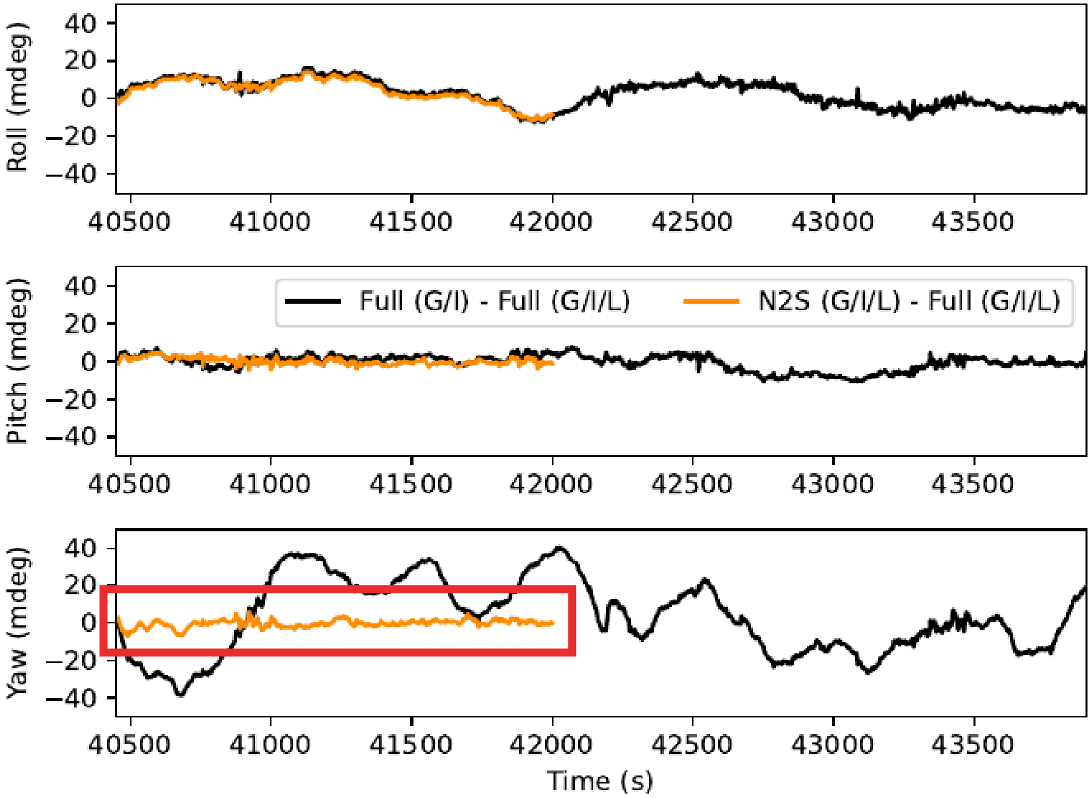
VUX-160[23] on helicopter: single-pass vs. dual-pass



Use full overlap LiDAR-integrated results **as reference / baseline** [Full G/I/L] and

- compare with GNSS/IMU trajectory [**Full G/I**]
- compare with *single-pass* GNSS/IMU/LiDAR trajectory **[N2S G/I/L]**.

VUX-160[23] on helicopter: single-pass vs. dual-pass



Use full overlap LiDAR-integrated results **as reference / baseline** [Full G/I/L] and

- compare with GNSS/IMU trajectory [**Full G/I**]
- compare with *single-pass* GNSS/IMU/LiDAR trajectory **[N2S G/I/L]**.

Multi-view LiDAR correspondences improve heading estimation, with few-mdeg difference to fully overlapping data!

Conclusion

- Georeferencing approach based on NLS adjustment with
  - Tight coupling of IMU and LiDAR
  - **Correspondences from multiple LiDAR scan directions (NFB scanning)**
- Evaluation of consistency/precision and accuracy
  - RMSE < 2 cm w.r.t. Independent reference surfaces
  - Strip differences at cm-level (terrain-dependent)
- Evaluation of the impact of multi-view correspondences in corridor mapping
  - **Heading improved by up to a factor of 10 w.r.t. pure GNSS/IMU solution when compared to the dual-pass (full overlap) solution**