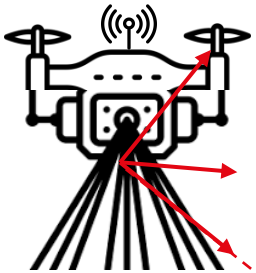
Rigorous approach to bore-sigh self-calibration in airborne laser scanning

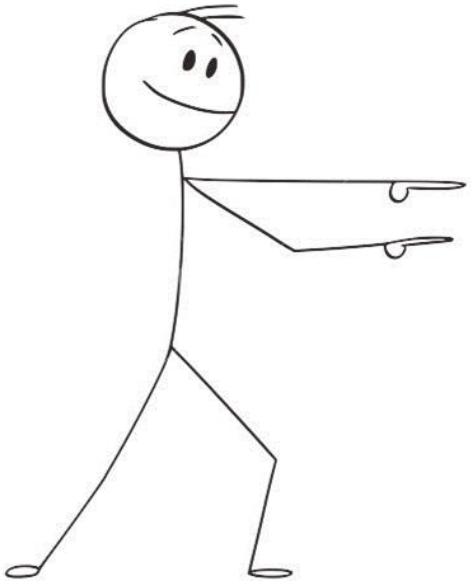
What's new after 20 years?



Jan Skaloud

Eurocow, June 16. 2025

EPFL



- **Why this title?**
- Legacy
- Limits & mis-understandings
- Where are better matches?
- How to cook it in a big pot?
- Is it better?

Why this title ?

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Article • *Open access*

Rigorous approach to bore-sight self-calibration in airborne laser scanning

238
Citations

Skaloud, J., Lichti, D.

ISPRS Journal of Photogrammetry and Remote Sensing, 2006, 61(1), pp. 47–59

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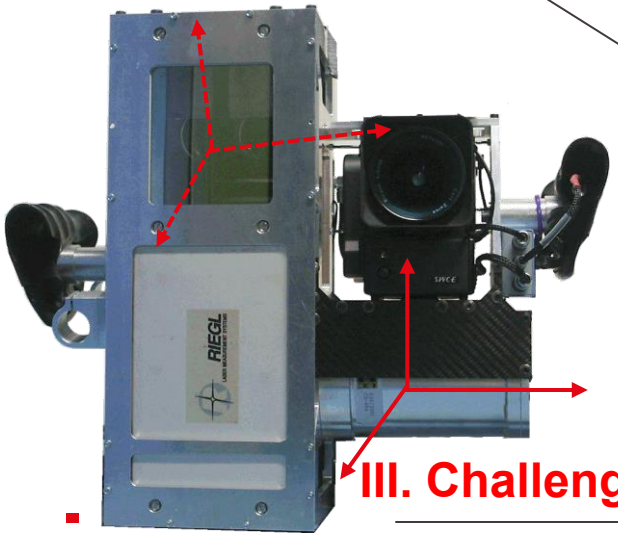
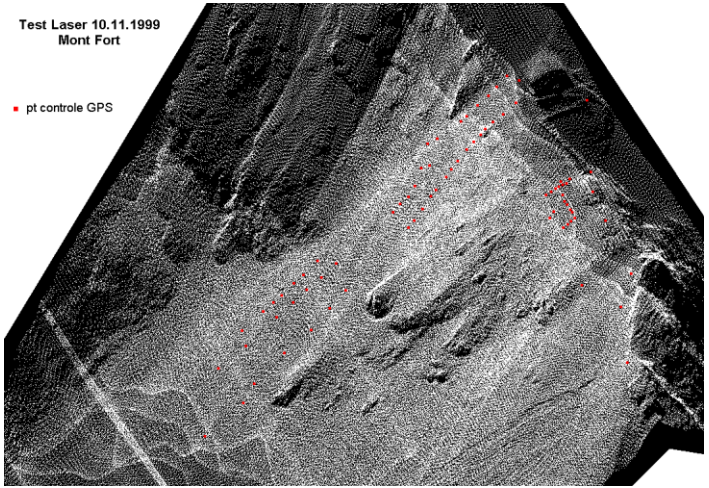
GOAL: REPAIR IT !

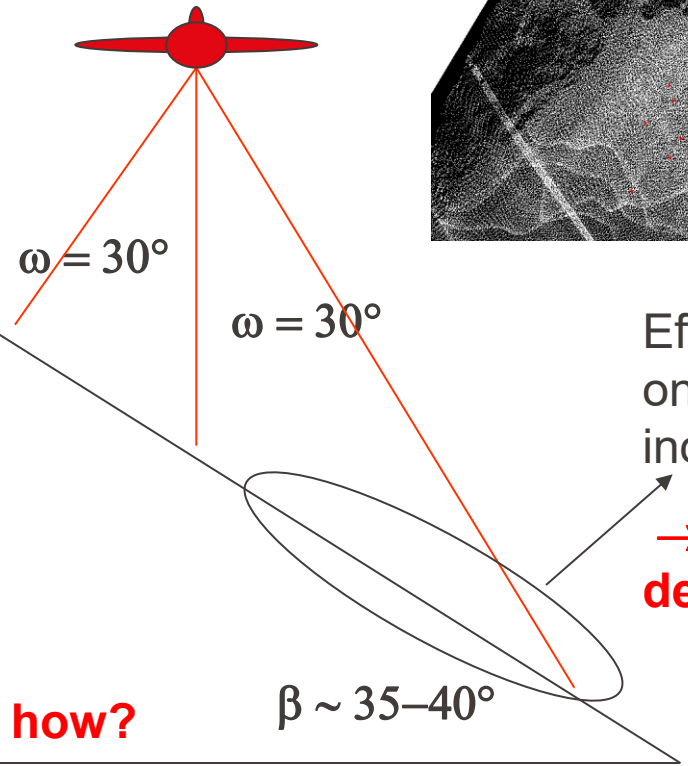
Why this title ?

II. solution



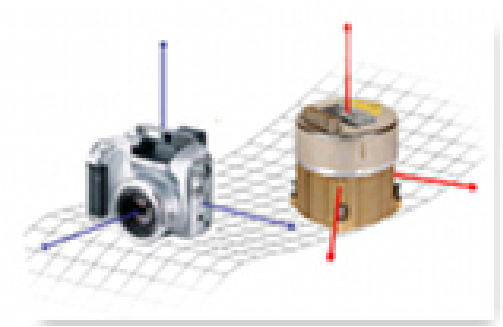
III. Challenge – how?





Effect of a steep slope on the angle of incidence:

→ **I. accuracy degradation!** (40 cm)



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Legacy - background "AAT" 2003

Approach	Adjustment Space	Additional Observations	Considering time correlations in IMU data?	Remark
"No step"	Global	IMU, GPS, AT, (GCP)	Yes	Not developed, optimal but cumbersome.
" 1 step"	AT	IMU/GPS, (GCP)	No (→Yes possible)	Too optimistic accuracy estimate. Biased mean?
" Reversed 1 step"	IMU	/GPS, /Attitude_AT	Yes	Not developed, may lead to KF divergence.
"2 steps"	Additional /Independent	IMU/GPS, AT (Attitude only)	Yes	Developer independent, presented method.

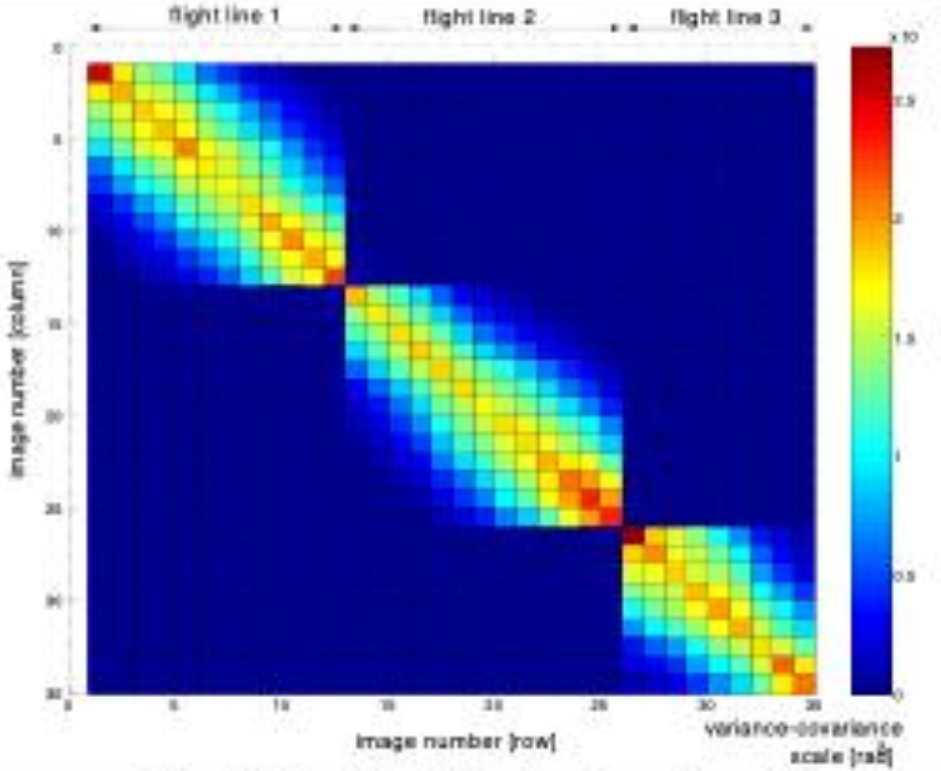
later

✓

$$R_{b_i}^{c} = R_{\mathrm{cmr}_i}^{c} \left(R_{\mathrm{cmr}_i}^{b} \right)^{T} , i = 1, 2, \ldots, n$$

Skaloud, J. , Schaer, P. (2003) Towards a more rigorous boresight calibration
ISPRS Int. Workshop on Theory Technology and Realities of Inertial/GPS/Sensor Orientation, IG, Spain

Legacy - background "AAT"
covariance matrix of INS/GPS attitude



$$R_{b_i}^{c} = R_{cam_i}^{c} \left(R_{cam_i}^{b} \right)^{T}, i = 1, 2, \ldots, n$$

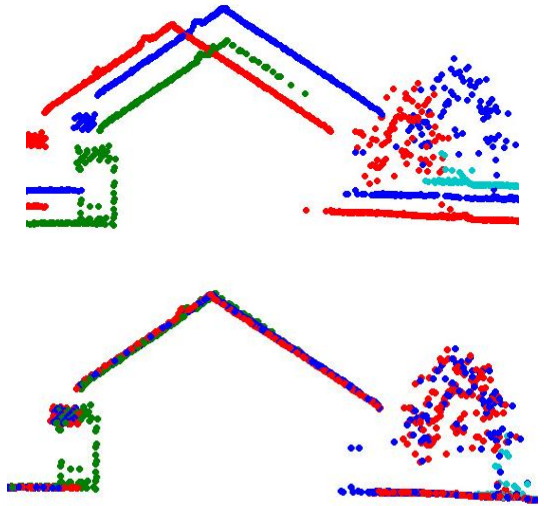
AT INS/GPS

- Flight-lines of <u>similar duration</u>
  - Limited impact on mean
  - **Large** impact on **confidence**

Skaloud, J. / Schaer, P. (2003) Towards a more rigorous boresight calibration
ISPRS Int. Workshop on Theory Technology and Realities of Inertial/GPS/Sensor Orientation, IG, Spain

Legacy – SOTA 2004

- Physical boundaries or cross-section (Schenk, 2001) [Optech]
- DTM Gradients (Burman, 2000) [Terrascan]
- Intensity (Morin,2002) [Leica]
- Homologous planes
  - Filin (2023) – plane param. known!
  - Kager (2024) – part of strip adj., no report on resolving boresight



after terramatch

- Summary:
  - Nothing suitable for all angles, no QA
  - Correlation with unknown terrain shape
  - Impractical w. absolute control, or no results

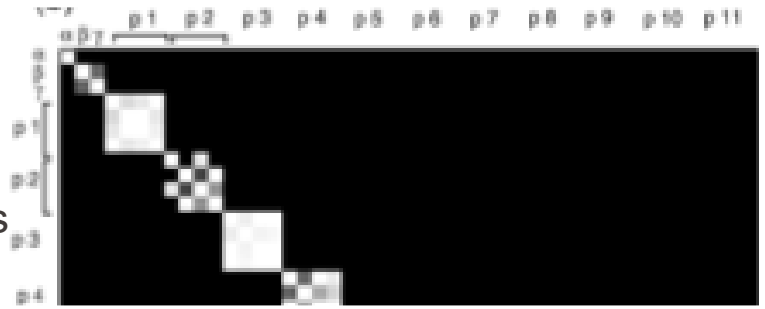
Legacy approach 2005

- Approach
  - Unknowns: boresight+plane-param (aux.)
  - Observations: poses + lidar vectors
  - Conditions: 3D points on planes ➔
  - Check sensitivity, prove consistency

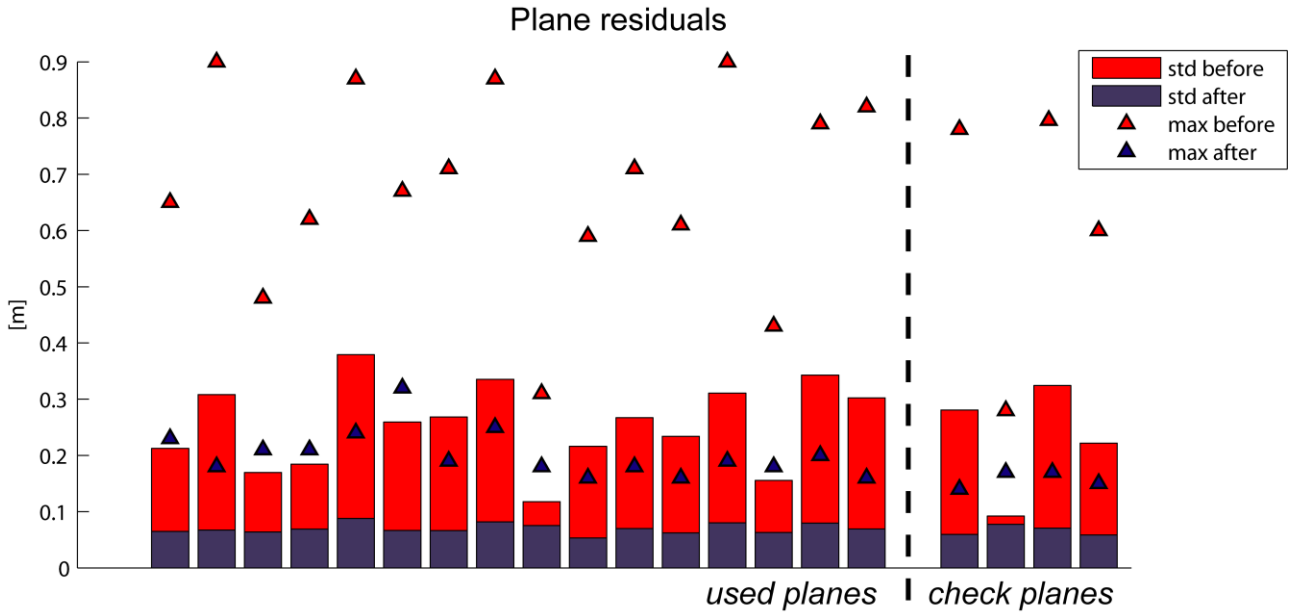
$$\left\langle \vec{s}_j, \begin{bmatrix} \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} + R_{b_i}^m \left(\begin{bmatrix} u_i \\ v_i \\ w_i \end{bmatrix} + U_i \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} + \vec{a} \right) \\ 1 \end{bmatrix} \right\rangle = 0$$

- Control
  - Zone/area
  - Flight geometry
  - INS/GPS accuracy (PPK, dynamic)

Legacy - approach 2005



- If planes varies in aspect & inclination
  - No correlation: boresight / plane-parameters
  - Insensitive to initial boresight up to 30 deg.



J. Skaloud, D. Lichti / ISPRS Journal of Photogrammetry & Remote Sensing 61 (2006) 47–59

Legacy - approach 2007

- Applied to*
  - Optech's ALTM 3100 – yaw!
  - Leica's ALS 50 – yaw + encoder scale
  - Riegl (many) – earlier systems (range + angle), later laser vectors

- Concurrent development
  - P. Fries, Institute Geomatica, Optech
  - TUW, Riegl (system + scanner internal calibration)
  - :

*Skaloud, J., Schaer, P., (2007) Towards automated LiDAR boresight self-calibration *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* , Vol. 36, No. 5

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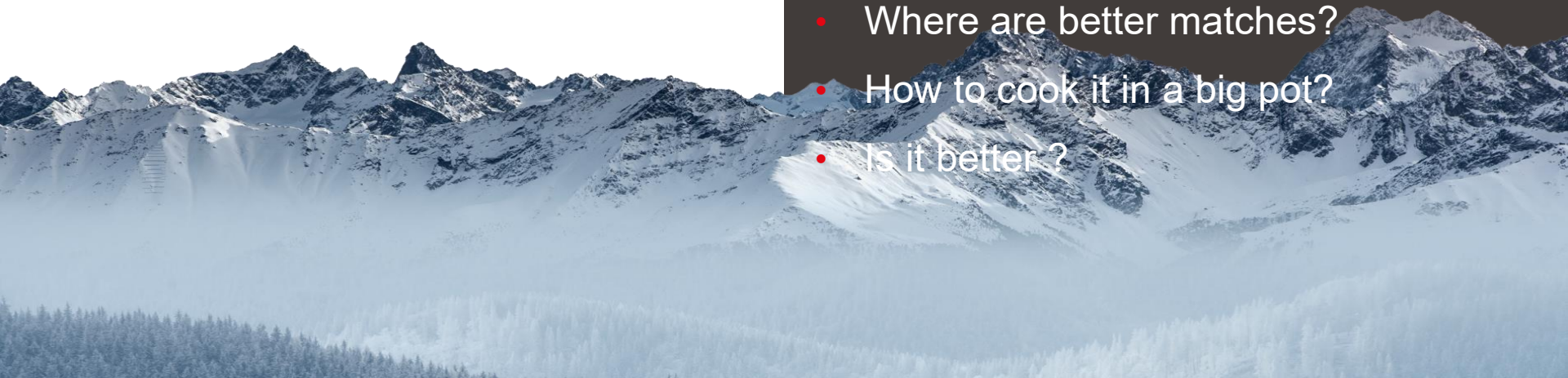
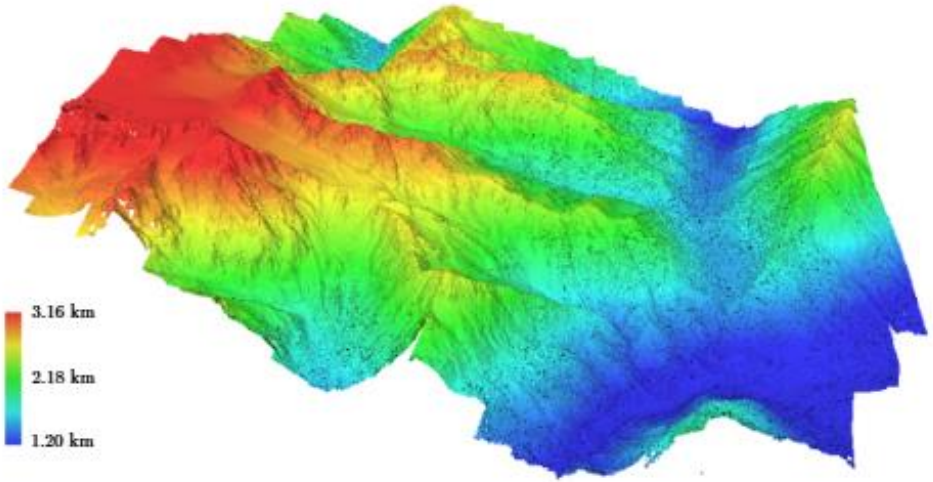


Limits - assumptions



Limits - assumptions

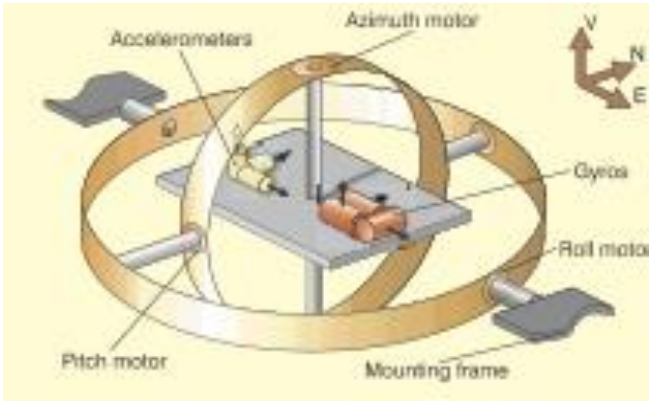
$$T = 2\pi\sqrt{\frac{L}{g}} \approx 2\pi\sqrt{\frac{6371000}{9.81}} \approx 5063 \text{ seconds} \approx 84.4 \text{ min}$$

The Perturbation of Pendulum and Gyroscope Instruments by Acceleration of the Vehicle

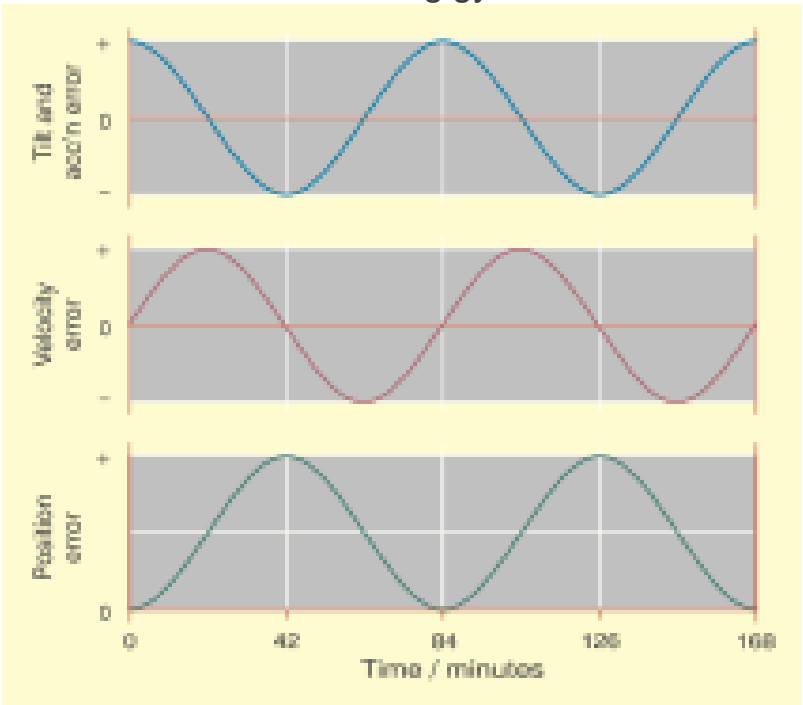
Die Stoerung von Pendel-und Kreiselapparaten dutch die Beschleunigung des Fahrzeuges

Schuler, M. 1923 14pp. table, diagrs, drwg

Physikalische Zeitschrift, Deutschland (Vol. 24, No. 344)



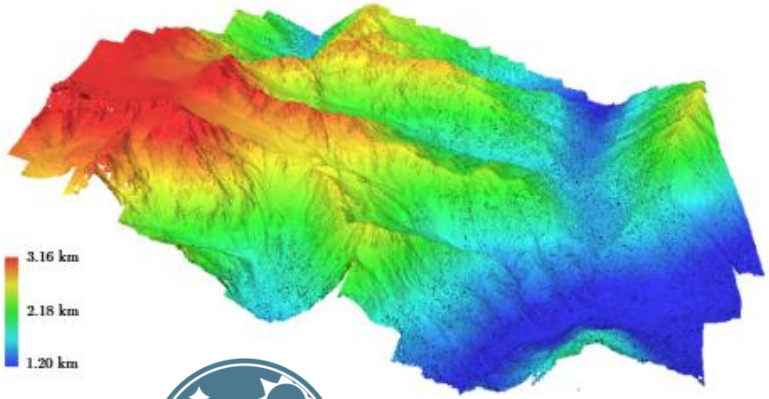
Non-drifting gyro case



After King, A.D. (1998). "Inertial Navigation - Forty Years of Evolution" (PDF). GEC Review. 13 (3): 141

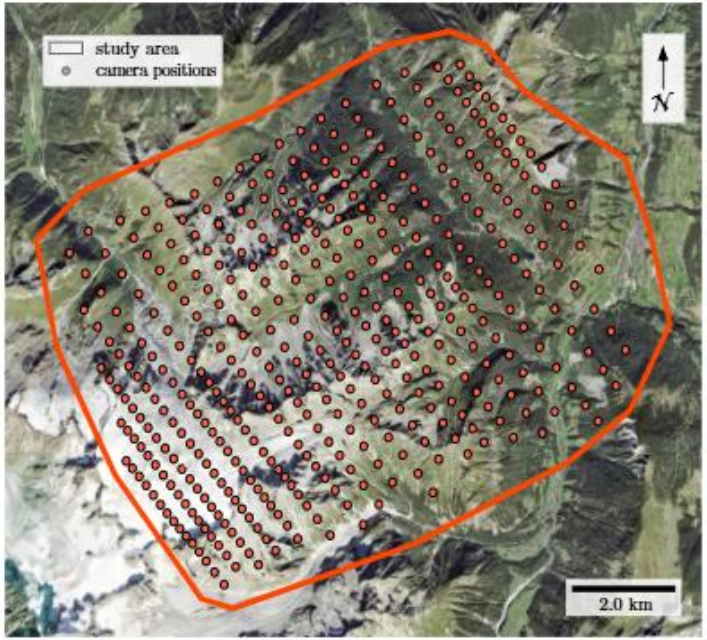
Limits - assumptions

$$f_x \sim f_y \approx 0 \qquad f_z \approx g$$

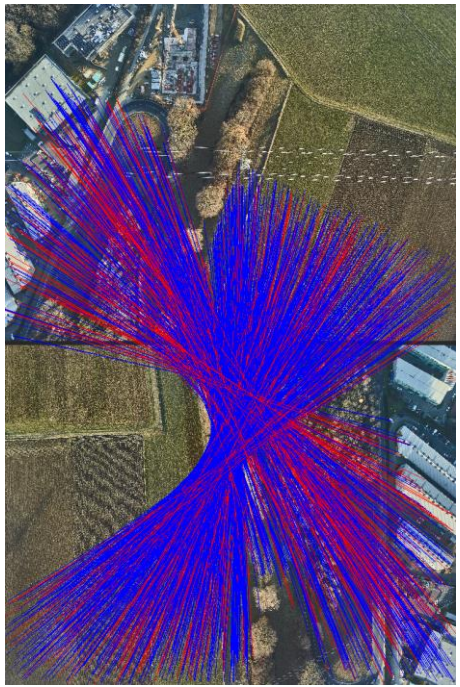


The FLAT EARTH SOCIETY

+



Photogrammetric tie-points



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Point to point correspondences – why?

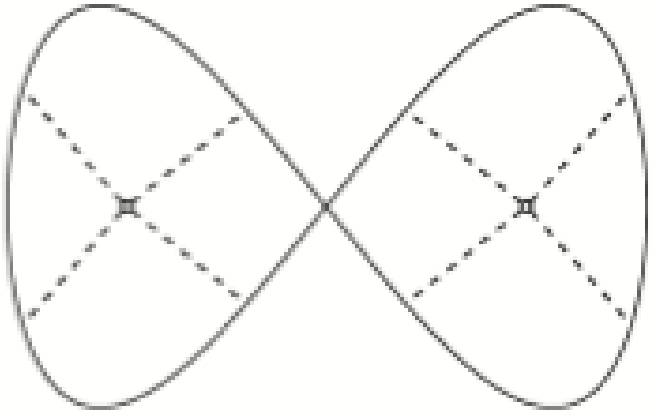
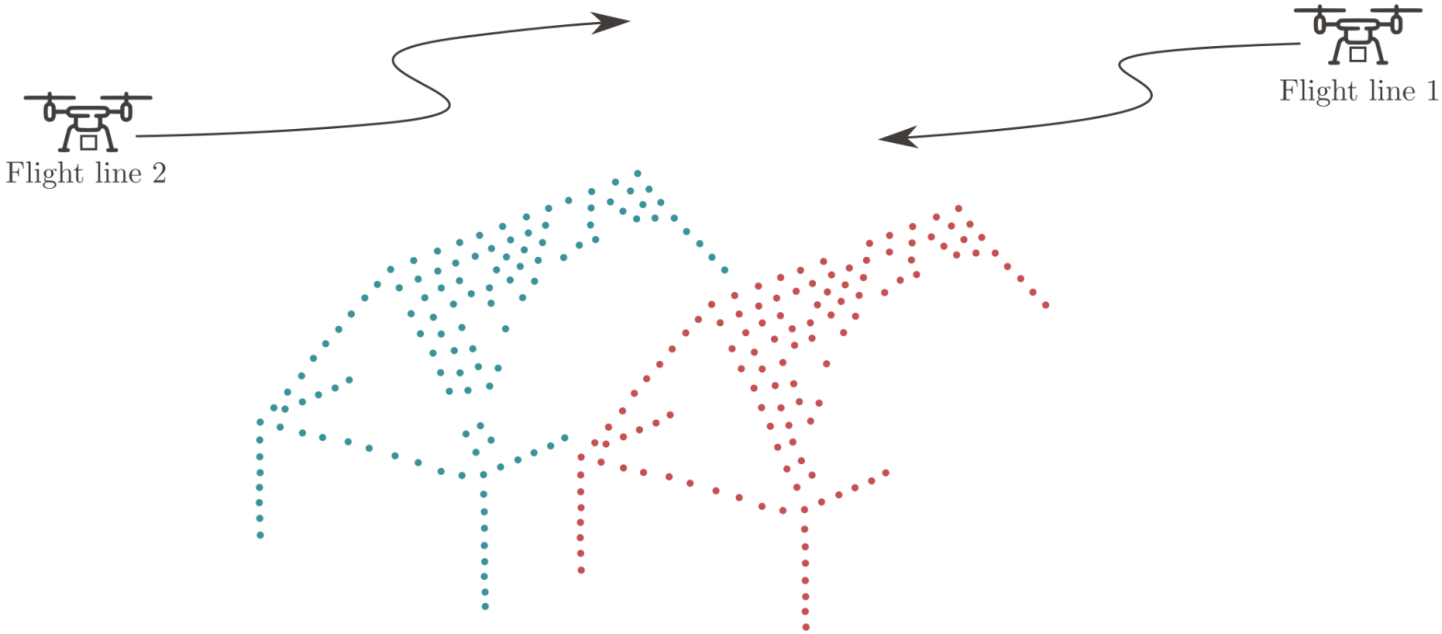


Fig. 8–Motion along a closed trajectory with one tie-feature located in each loop

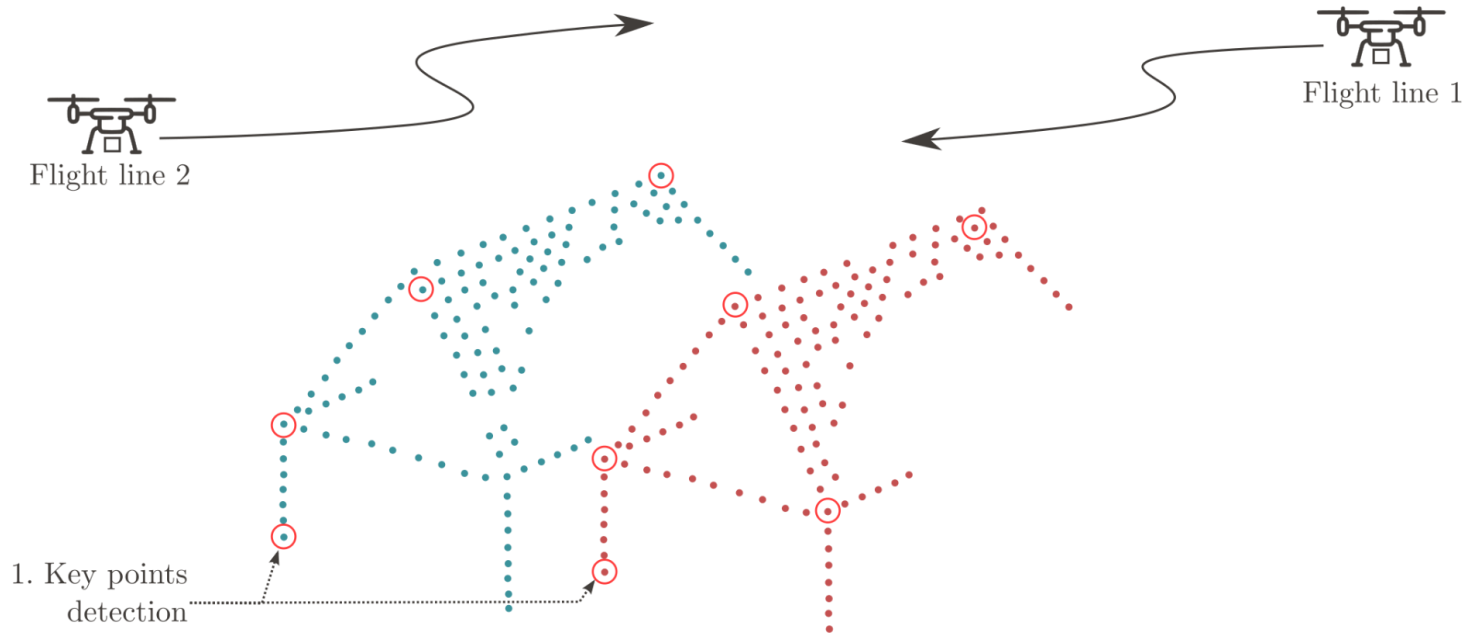
- Simulation 2D
  - Tactical IMU <u>without</u> GNSS during 3 min
  - **1 range** (1σ = 2 cm) every 6 s to a TP
  - RMSE pos drift = 0.05 m

Rouzaud, Skaloud (2011) Rigorous integration of inertial navigation with optical sensors by dynamic networks NAVIGATION, Journal of The Institute of Navigation , Vol. 58, No. 2

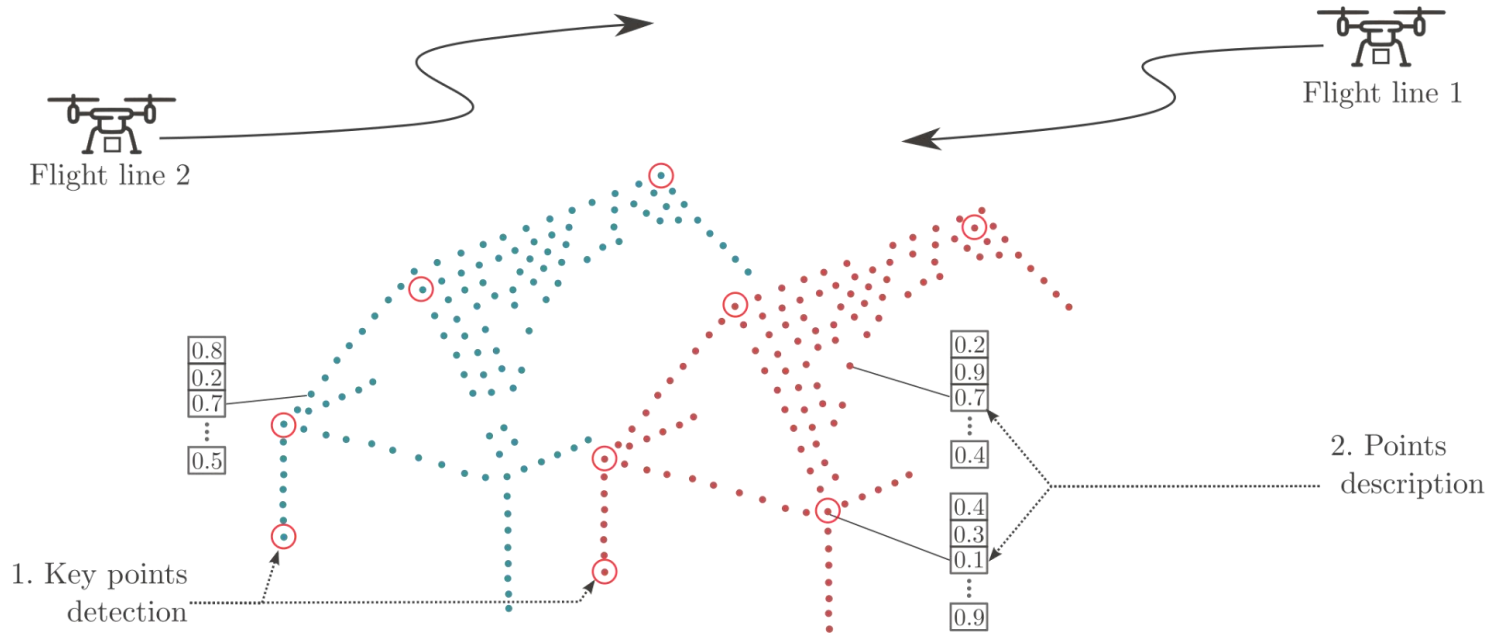
Point to point correspondences – how?



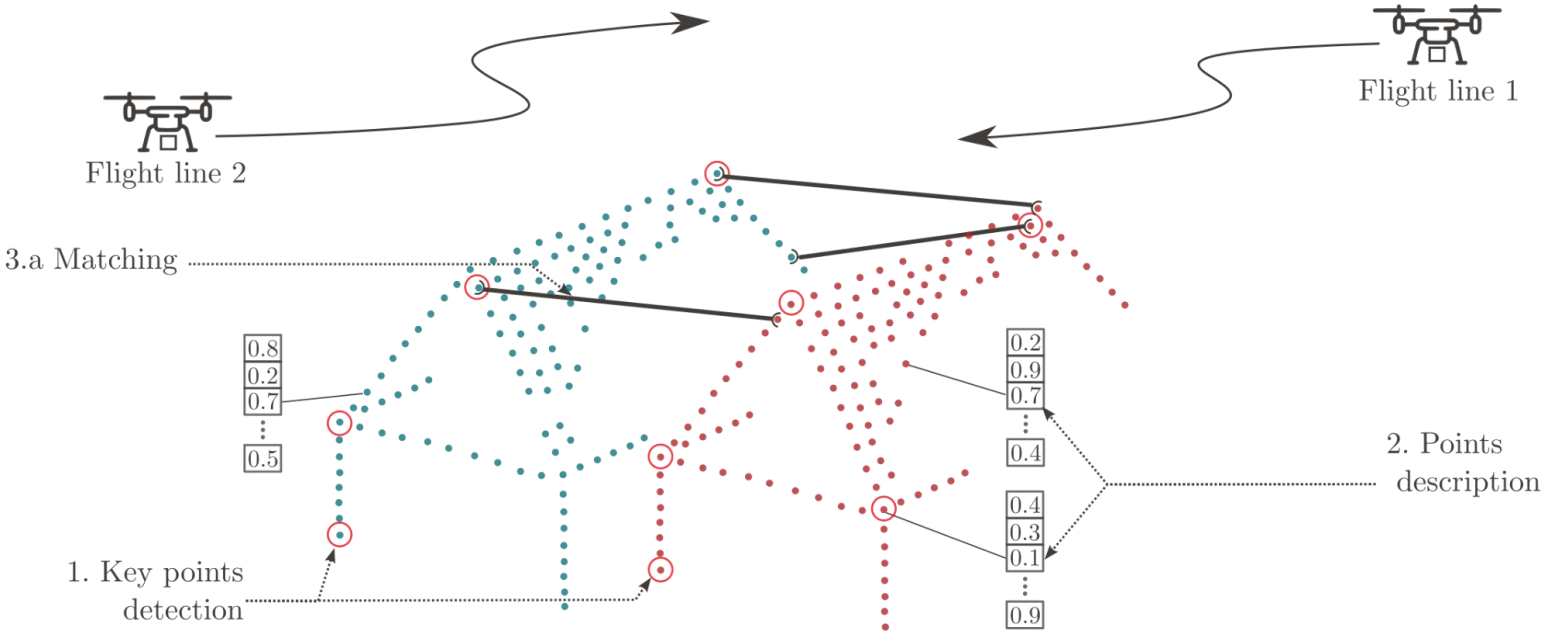
Point to point correspondences – how?



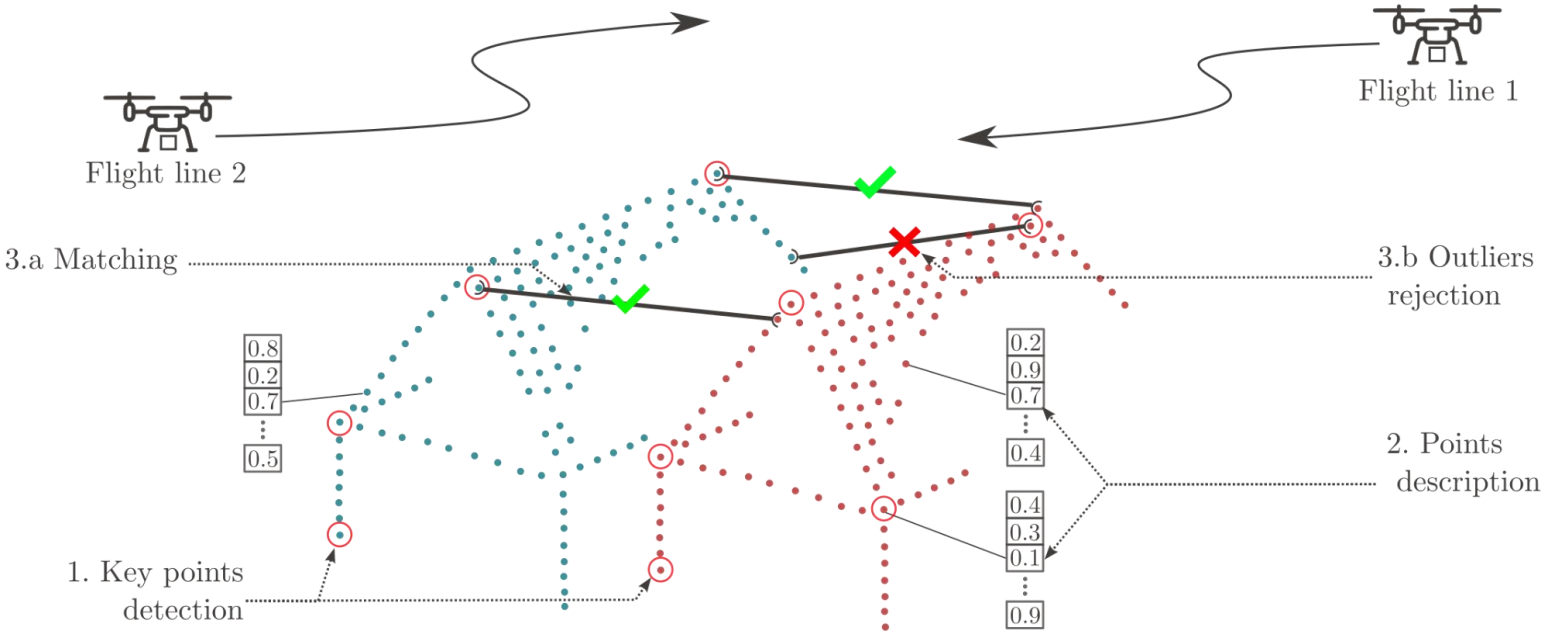
Point to point correspondences – how?



Point to point correspondences – how?



Point to point correspondences – how?

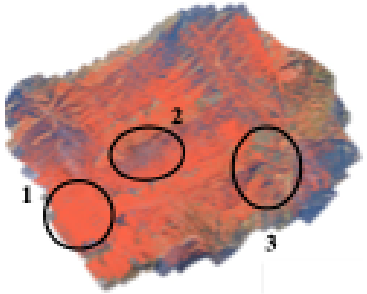


Brun, A., et al. (2022) Lidar point–to–point correspondences for rigorous registration of kinematic scanning in dynamic networks, J. ISPRS

Point to point correspondences – how?

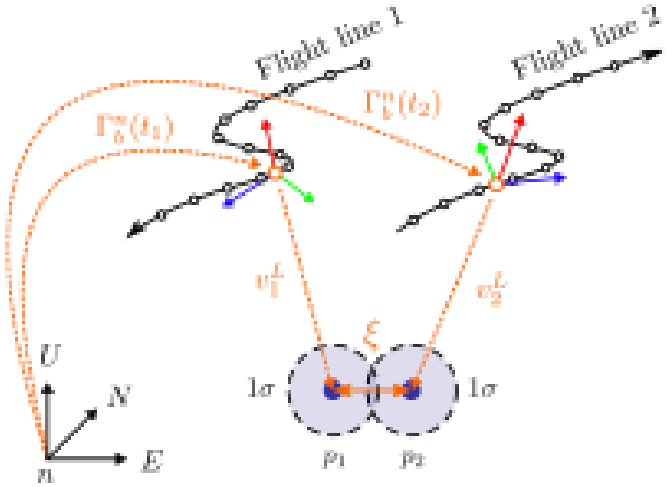
Descriptors parameters, run-time and performances.

Descriptor	Dim.	Parameters	Computation time [s]	Match time [s]	Inlier ratio @30 cm [%]
SHOT	352	$r_s = 15 * GSD$	49	73	13.3
FPFH	32	$r_s = 15 * GSD$	16	1,4	5.7
USC	1980	$r_s = 15 * GSD$	82	612	5.2
FCGF	32	vox. size = 0.2 kernel size = 7	0,21	1,3	27.3
SpinNet	32	$r_s = 2$, $rad_s = 9$, $ele_s = 30$, $azi_s = 60$ vox. = 0.3, $vox_s = 30$	1410	2	30.7
LCD	256	$r_s = 2$ m patch pts N = 1024	128	31	53.7



Brun, A., et al., 2022. Lidar point–to–point correspondences for rigorous registration of kinematic scanning in dynamic networks. J. ISPRS

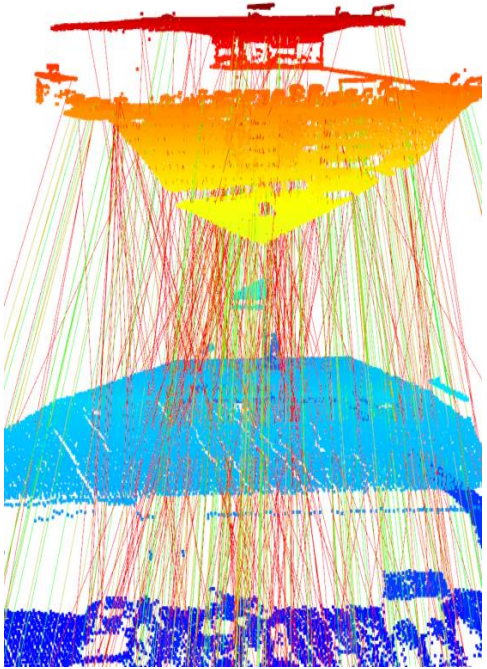
Point to point correspondences - constrain



$$R_L^b v_1^L - \underbrace{\left[\Gamma_{k,t_1}^{abs}\right]^{-1} \Gamma_{k,t_2}^{abs}}_{\Delta T_L^b} R_L^b v_2^L = 0 + \xi$$

relative pose!

LiDAR point to point (3D-3D)



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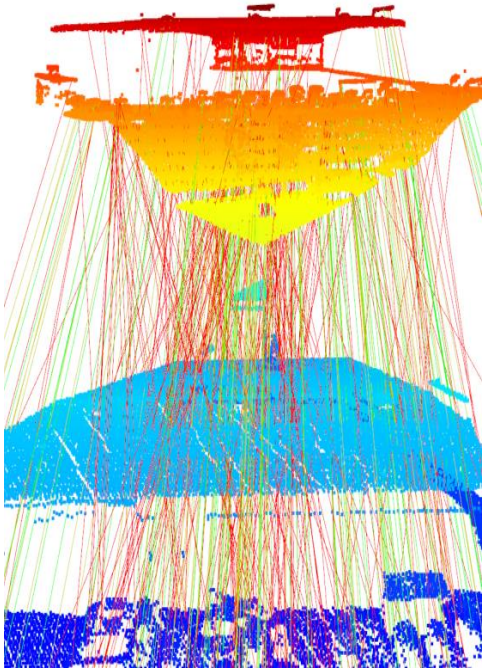

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" 1 step"	AT	IMU/GPS, (GCP)	No (→Yes possible)	Too optimistic accuracy estimate. Biased mean?
" Reversed 1 step"	IMU	/GPS, /Attitude_AT	Yes	Not developed, may lead to KF divergence.
"2 steps"	Additional /Independent	IMU/GPS, AT (Attitude only)	Yes	Developer independent, presented method.

→ later

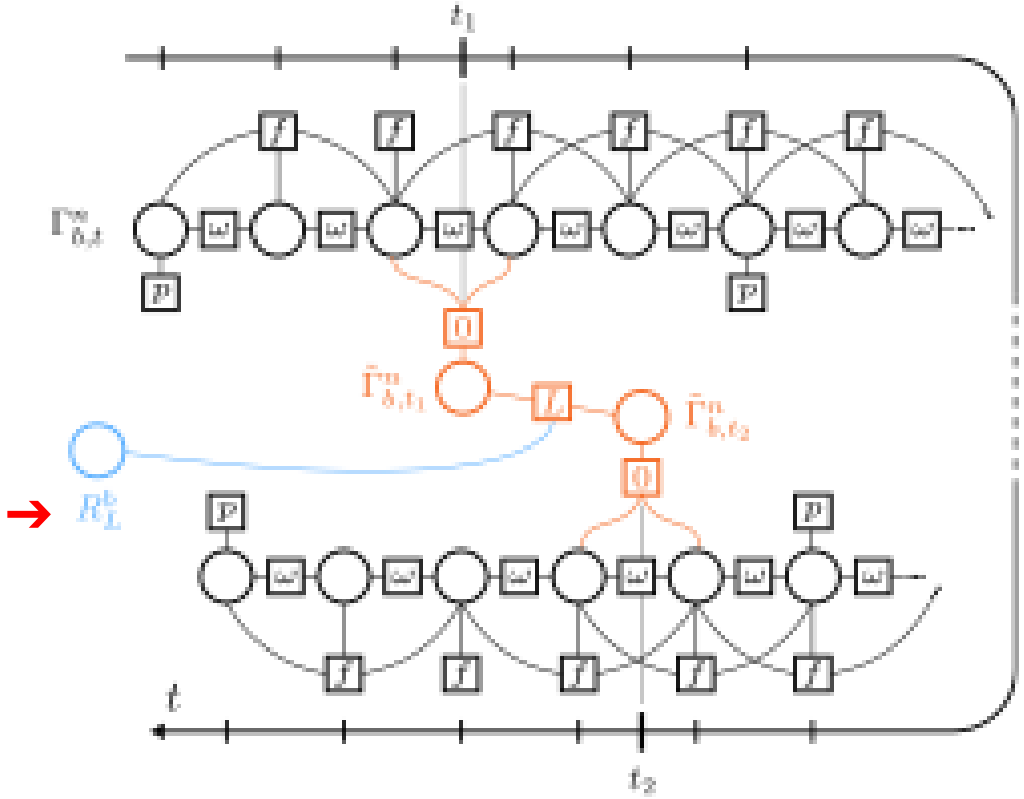
✓

✓

✓

Cucci, Rehak, Skaloud (2017) J. Bundle adjustment with raw inertial observations in UAV applications, J. ISPRS

The big pot of estimation – extended for 3D-3D TP

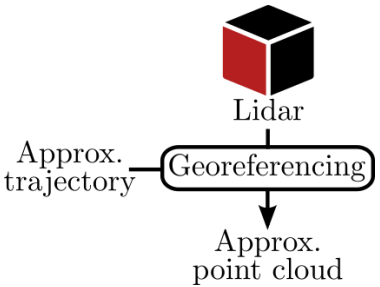


ODyN

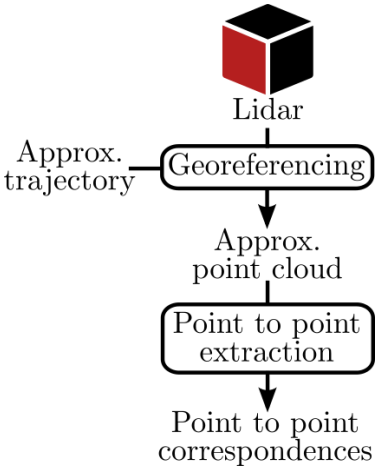
Free online service of
Dynamic Networks solver

Brun, A., et al., 2022. Lidar point–to–point correspondences for rigorous registration of kinematic scanning in dynamic networks. J. ISPRS

The big pot of estimation with 3D-3D constraints



The big pot of estimation with 3D-3D constraints



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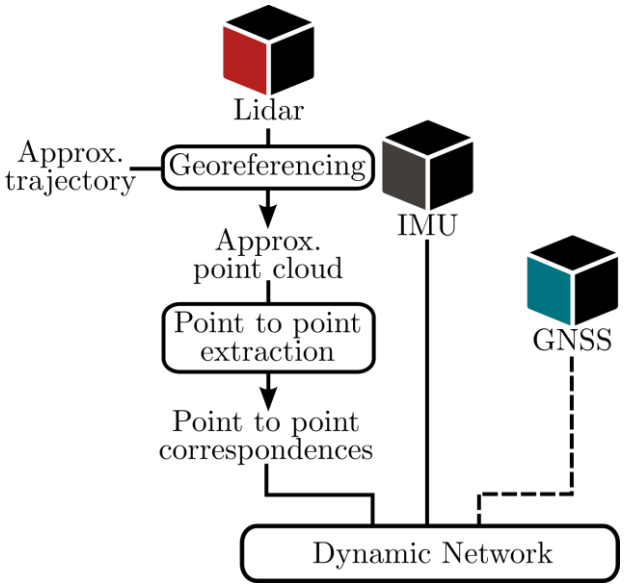
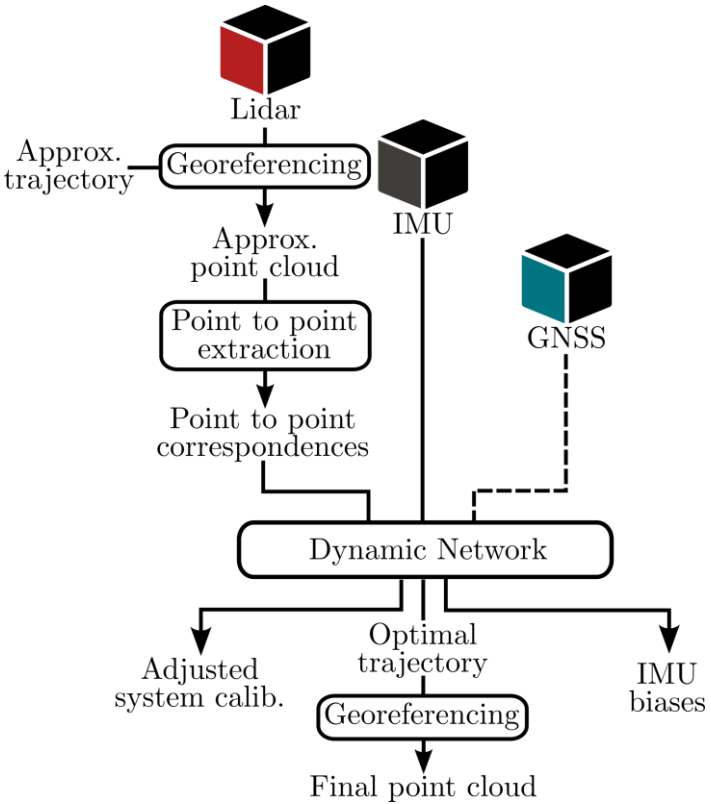
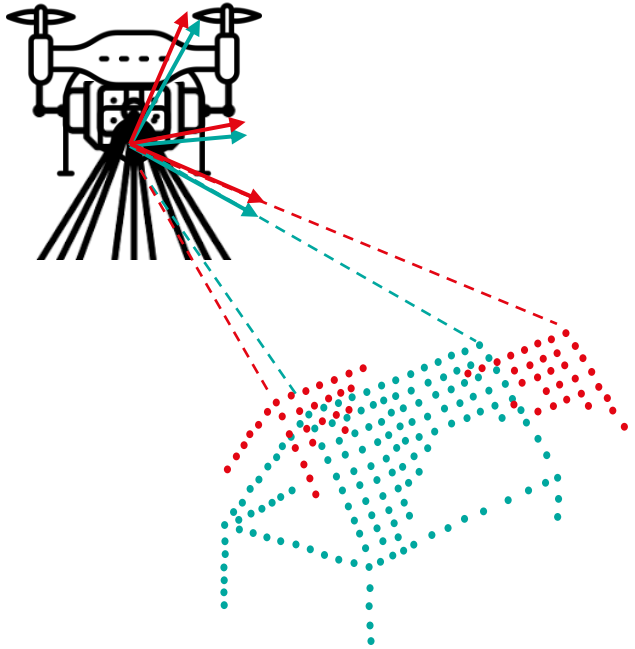


The big pot of estimation with 3D-3D constraints





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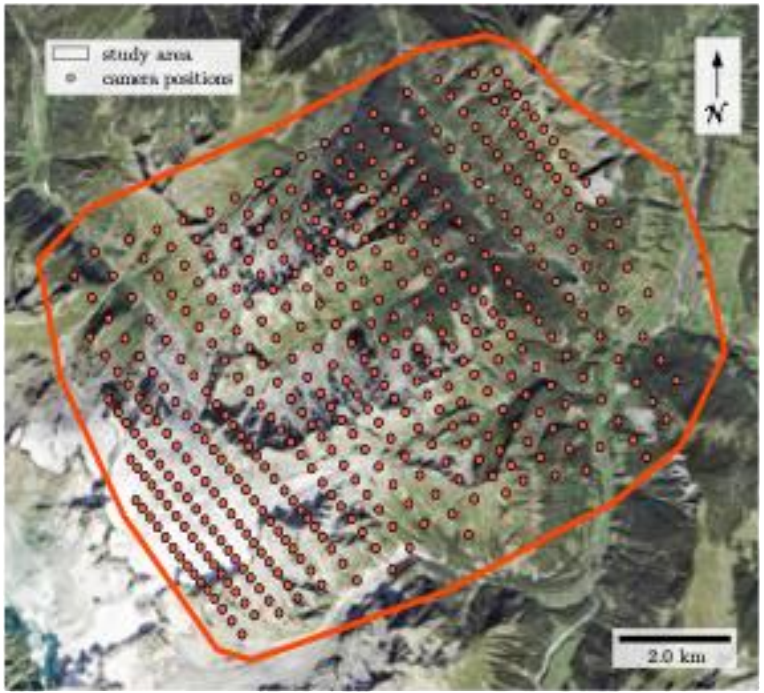
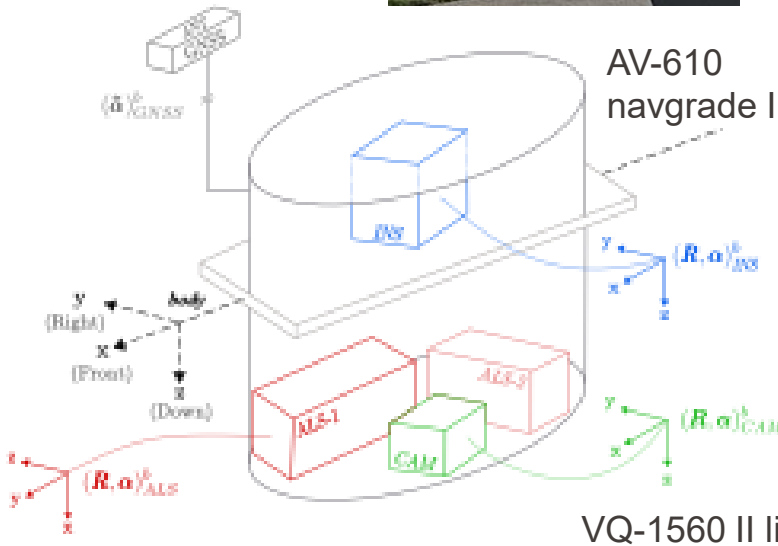
Airborne laser scanning (ALS)

Case – long-range, “lawn-mover” pattern



Ranges ± 700 – 2000 m



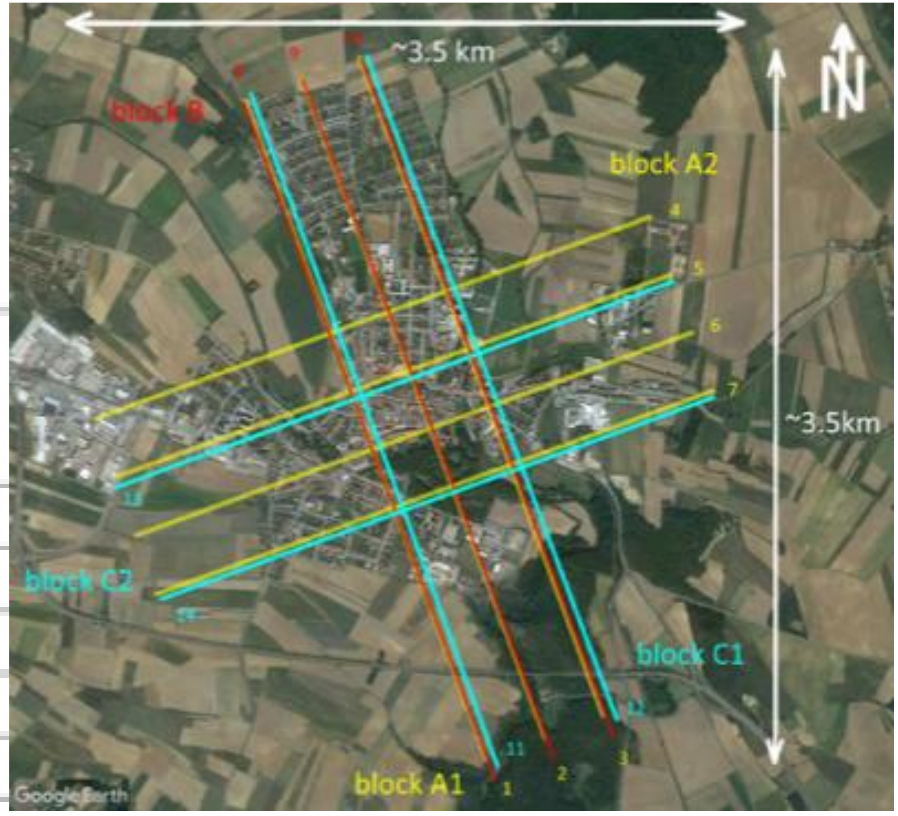
AV-610
navgrade INS

VQ-1560 II lidar
IXU-100 RS cam

ALS long range

Reference boresight – calibration certificate / pattern

Block	AGL [m] 1)
A1	550
A2	550
B	720
C1	1981
C2	1981



ALS long range

On job boresight estimation (from zero)

1. Using planes, factory method (with our without shift/drift for 21 flight lines)

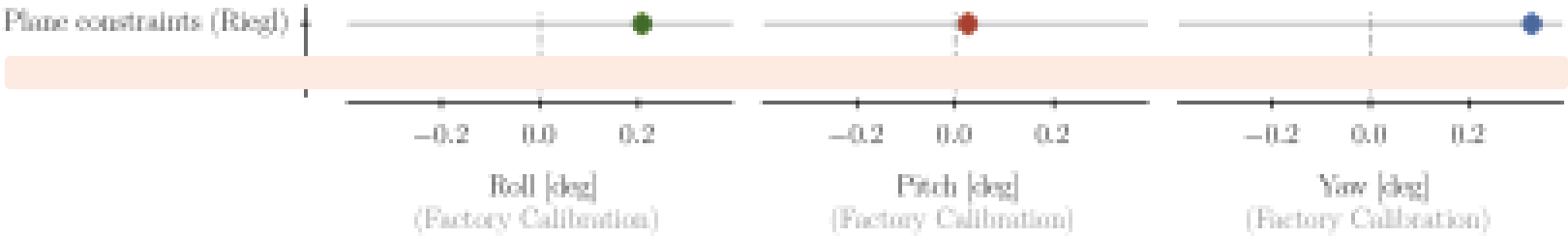
Calculation parameters	
Calculation mode:	Adjustment
Calculation time:	7 mins, 39 secs
Calculation mode:	Least Square Fit
Tolerance:	0.000100
Use Manual Tie Objects:	False
Search corresp. planes:	True

Calculation results	
Number of free parameters:	3
Number of observations:	18999
Error (Std. deviation) [m]:	0.1130

← 3 angles
← planes

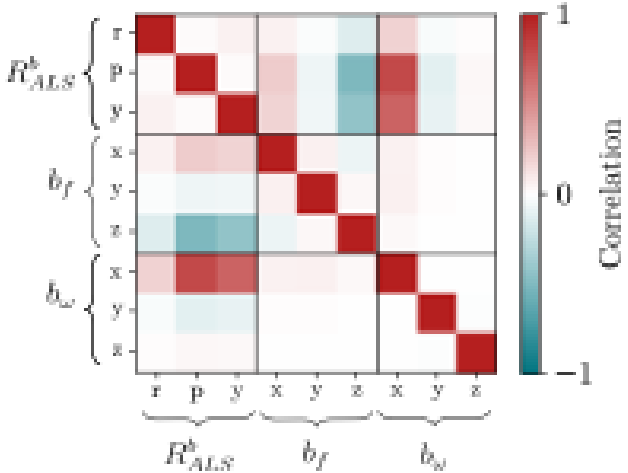
Laser devices			
Name	Roll [deg]	Pitch [deg]	Yaw [deg]
1560II_CH1 (VQ-1560II, S2223550)	0.00981	0.00102	0.01712
- Confidence	0.000135	0.000025	0.000233

ALS long range
On job boresight estimation (from zero)



- Plannar surfaces
  - Not recovered, irealistically low confidences
  - (not recommeded by the manufacturer!)

- 3D to 3D
  - Recovered correctly
  - Correlated with inertial biases (absorbing) ➔



Airborne laser scanning (ALS)
Case – corridor mapping

Setup

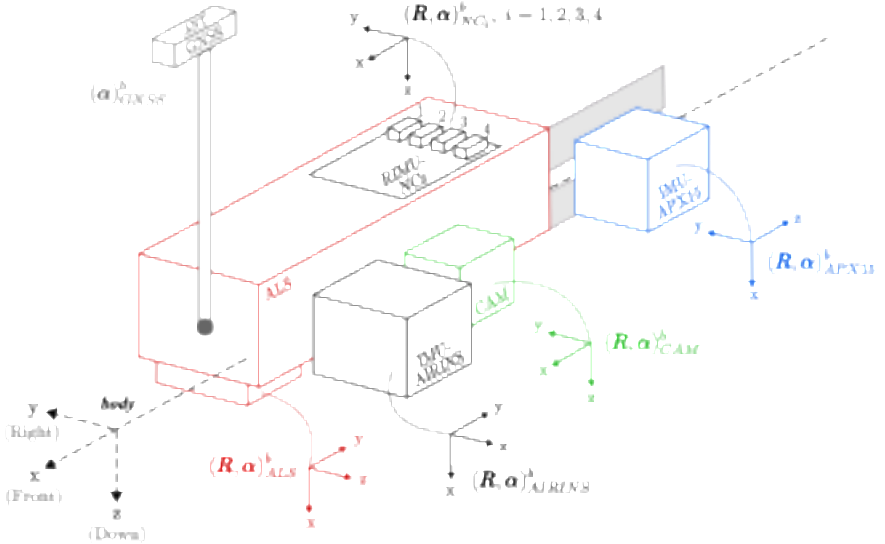
navigation grade IMU + 3 lower quality IMUs:
APX 15, 1x navchip (NC) v. 2010, 4x NC

↓

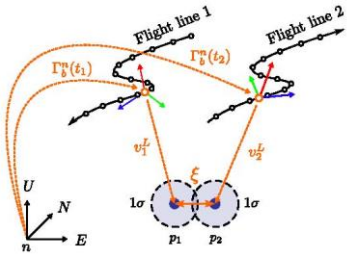
Complex orientation errors within flight-lines,
amplified by 200- 250 m ranges

↓

on job estimated -- reference boresight
(via legacy calib. area/pattern + Riprocess)



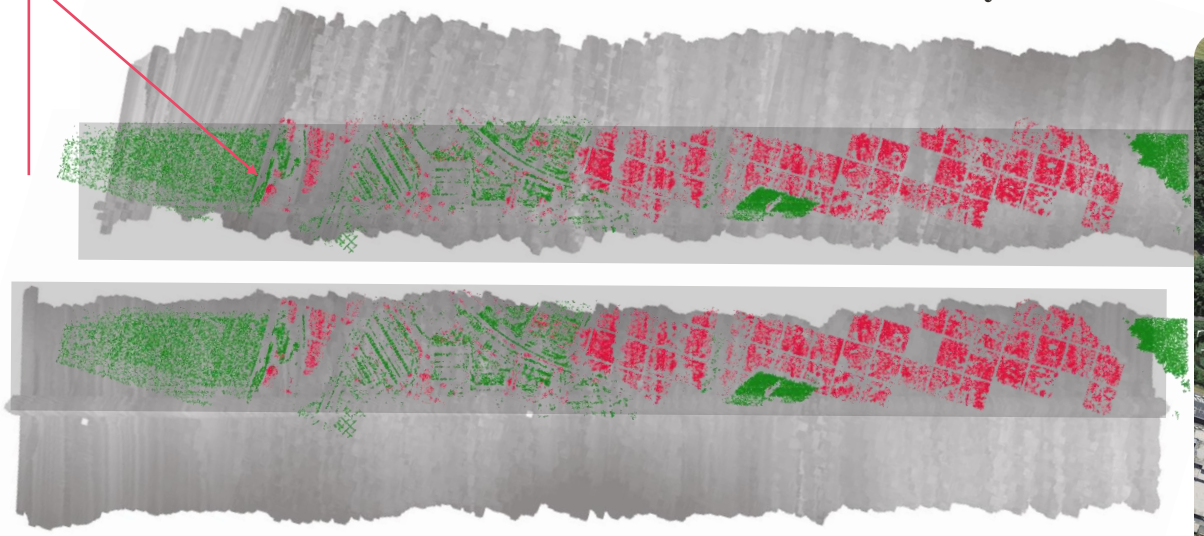
Corridor - distribution of optical constraints

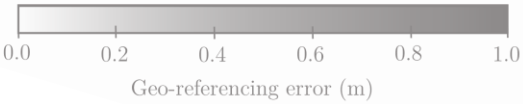


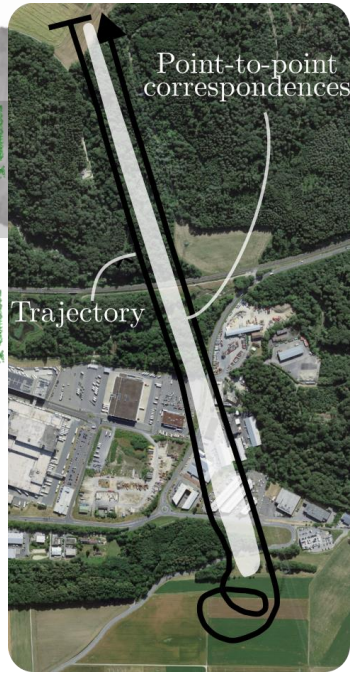
Brun, A., et al. 2022. ISPRS Journal

MEMS-IMU + GNSS

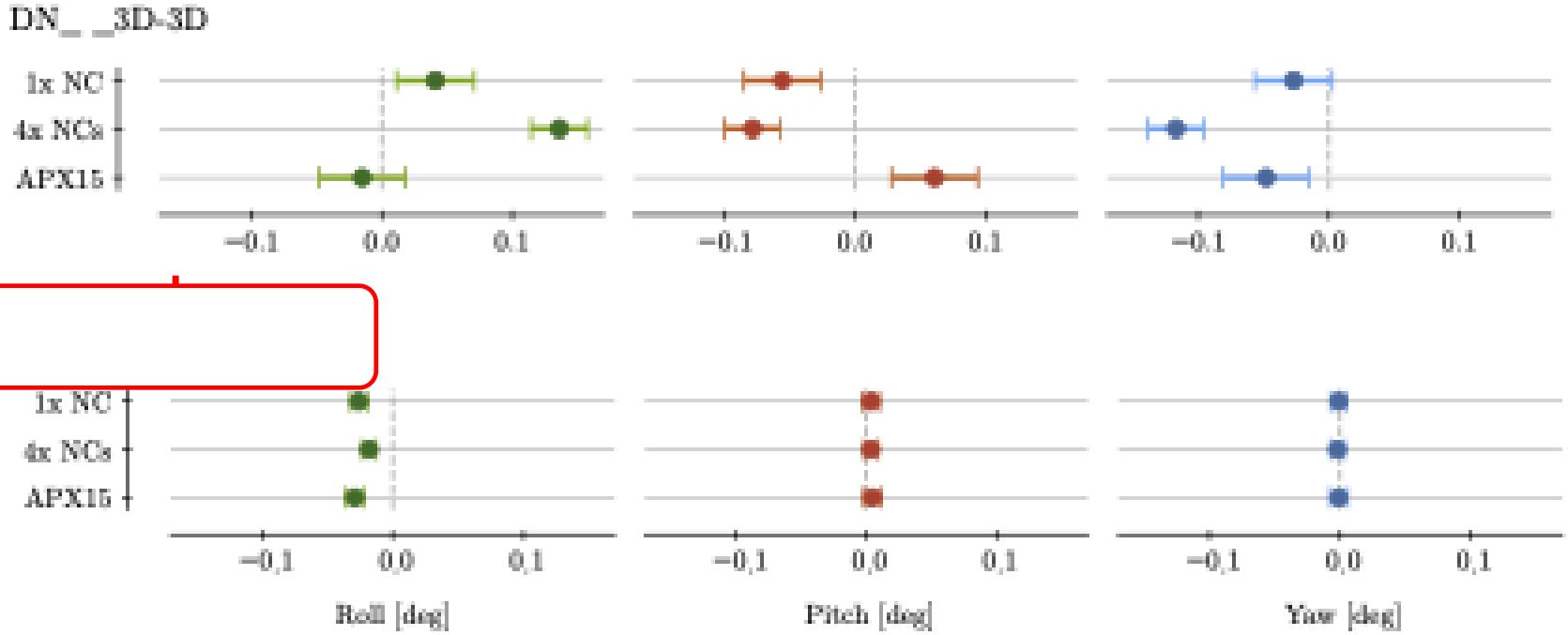
+ Lidar 3D tie-points
+ Camera 2D tie-points
+ within Dynamic Networks







ALS corridor – on job estimated boresight



Mouzakidou et al. (2024) Airborne sensor fusion: Expected accuracy and behavior of a concurrent adjustment, Open J. ISPRS

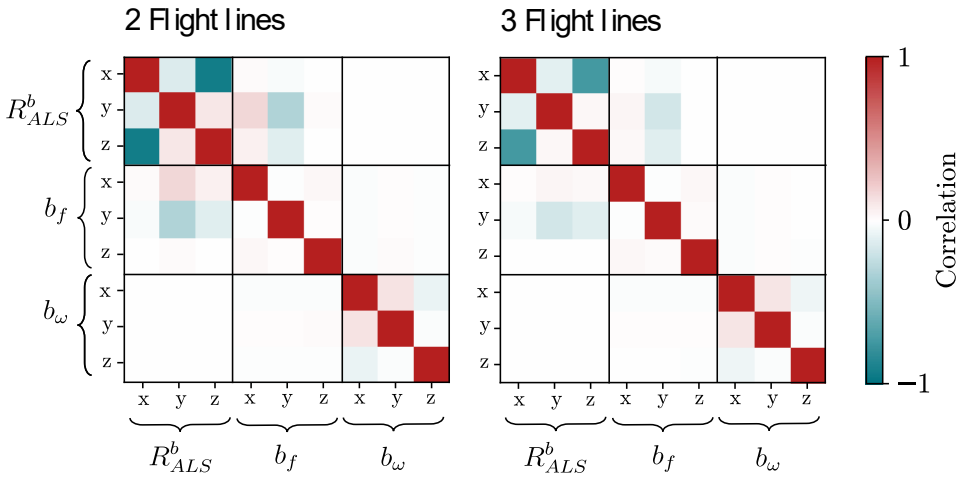
Aerial dataset

Estimated parameters uncertainty – Lidar Boresight

Correlation matrix

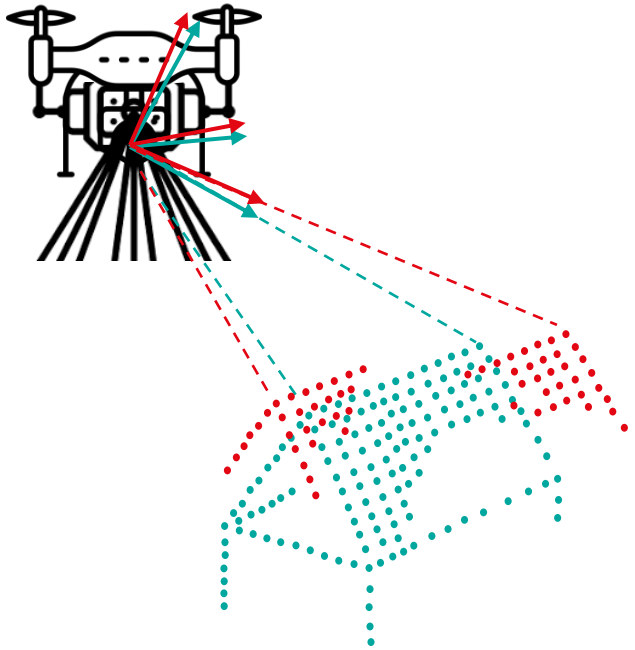
GNSS INS ALS CAM

R^b_{ALS} : Lidar boresight
b_f : IMU accelerometer bias
b_ω : IMU gyroscope bias



- cross-flight towards the decorrelation R^b_{ALS} - b_f
- remaining correlation in roll (y-axis)

Mouzakidou et al. (2024) Airborne sensor fusion: Expected accuracy and behavior of a concurrent adjustment, Open J. ISPRS



Take

- Why this title? - update legacy
- Legacy – still OK under assumptions
- Limits – really flat? 1924!
- Where are better matches? – all over!
- How to cook it in a big pot? ✓
- Is it better? ✓ + absorbing

Acknowledgements

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TOWARDS EFFICIENCY OF OBLIQUE IMAGES ORIENTATION

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