MSC GEODETIC ENGINEERING

MSR-02: ADVANCED TECHNIQUES FOR MOBILE SENSING AND ROBOTICS (GEODESY TRACK)

03: SYSTEM CALIBRATION

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ADVANCED TECHNIQUES FOR MOBILE SENSING AND ROBOTICS – LECTURE CONTENT

(1) Mobile Laser Scanning

(2) Trajectory Estimation

(3) System Calibration

(4) Sensor Synchronisation

(5) From Images to Point Clouds (SfM)

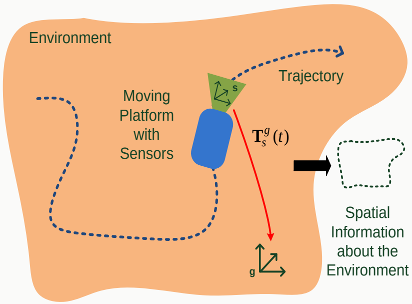
(6) Accuracy of Point Clouds I

(7) Accuracy of Point Clouds II

(8) Deformation Analysis with Point Clouds I

(9) Deformation Analysis with Point Clouds II

CHAPTER 1:
MOBILE LASER SCANNING



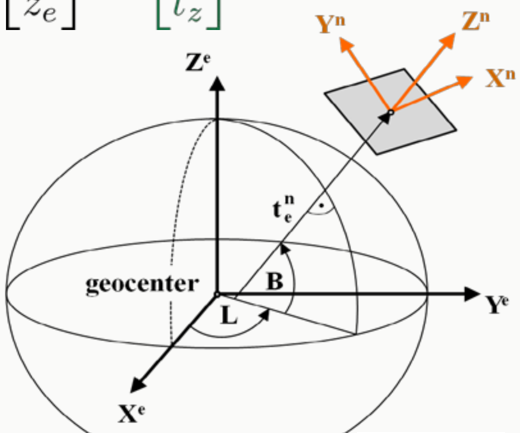
$$\mathbf{p}_{object}^{global}(t_s) = \mathbf{T}_{body}^{global}(t_s) \cdot \mathbf{T}_{sensor}^{body} \cdot \mathbf{p}_{object}^{sensor}(t_s)$$

- Review of involved **coordinate systems /frames**
- Derivation of detailed **georeferencing equation** for the example of **mobile laser scanning**

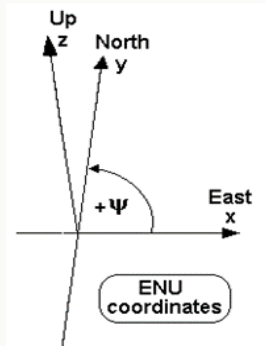
$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma) \cdot \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix} \right]$$

CHAPTER 2: TRAJECTORY PARAMETERS

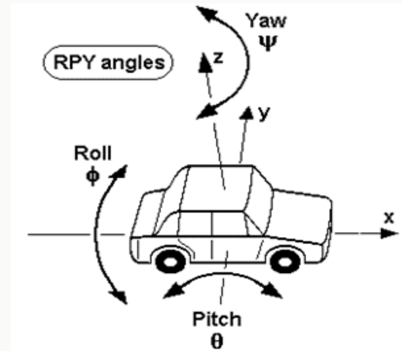
$$\begin{bmatrix}x_e\\y_e\\z_e\end{bmatrix} = \begin{bmatrix}t_x\\t_y\\t_z\end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi)\cdot\left[\begin{bmatrix}\Delta x\\\Delta y\\\Delta z\end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma)\cdot\begin{bmatrix}0\\d\cdot\sin b\\d\cdot\cos b\end{bmatrix}\right]$$



Earth frame



Navigation frame



"body frame"

- Review of inertial navigation, strapdown integration and Kalman Filtering
- Introduced **Kalman Smoothing**
- Evaluation of **trajectory estimation**

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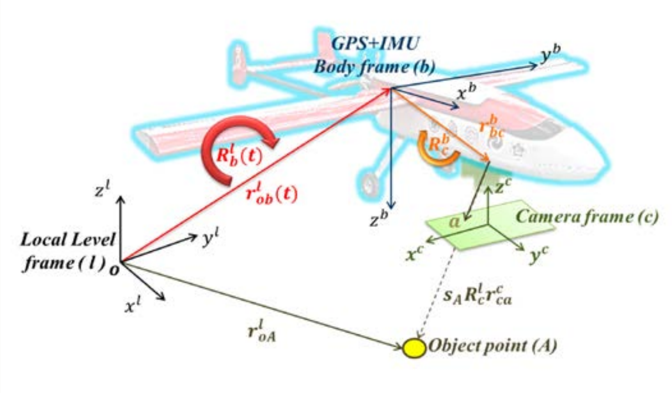
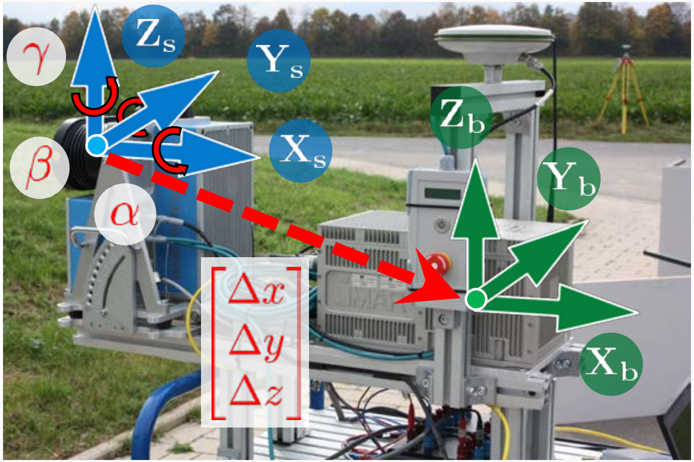
CHAPTER 3: SYSTEM CALIBRATION

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma) \cdot \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix} \right]$$



From: Chiang, K.-W.; Tsai, M.-L.; Naser, E.-S.; Habib, A.; Chu, C.-H. New Calibration Method Using Low Cost MEM IMUs to Verify the Performance of UAV-Borne MMS Payloads. Sensors 2015, 15, 6560-6585.



- Overview of **system calibration** methods
- Detailed derivation of **plane based calibration**

CALIBRATION

FORMAL DEFINITION

Indication: quantity value provided by a measuring instrument or a measuring system

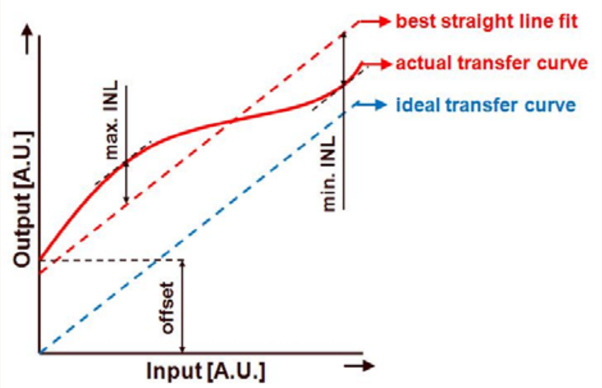
Operation that, under specified conditions, in a first step, establishes a **relation between the quantity values** with measurement uncertainties provided by measurement standards **and corresponding indications** with associated measurement uncertainties (of the calibrated instrument or secondary standard) and, in a second step, uses this information to establish **a relation for obtaining a measurement result from an indication**

International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM 3rd edition)
https://jcgm.bipm.org/vim/en/index.html

CALIBRATION

WHAT DO WE USUALLY MEAN BY CALIBRATION

- Derive necessary parameters to receive useful information from a measurement system
- Prodedure to minimize systematic errors in a measurement system



Calibration parameters:

- Constants
- Paramaters of functional relationships
- Look up tables

CALIBRATION EXAMPLES

INERTIAL SENSORS

noise

$$a_{P,k} = \mathbf{MS}(a_{S,k} - b_a) + \epsilon$$

True value ($a_{P,k}$)

Sensor readings ($a_{S,k}$)

Offset/Bias (b_a)

Temperature

$$\mathbf{M} = \begin{pmatrix} 1 & -\alpha_{yz} & \alpha_{zy}(t) \\ 0 & 1 & -\alpha_{zx} \\ 0 & 0 & 1 \end{pmatrix}$$

Axis Misalignment

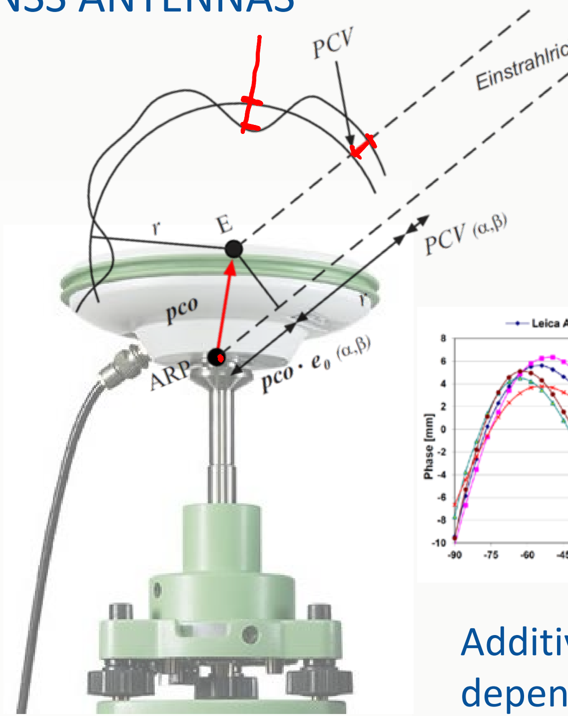
$$\mathbf{S} = \begin{pmatrix} s_{xx} & 0 & 0 \\ 0 & s_{yy} & 0 \\ 0 & 0 & s_{zz} \end{pmatrix}$$

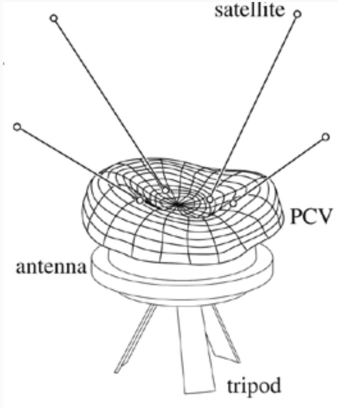
Scale factors

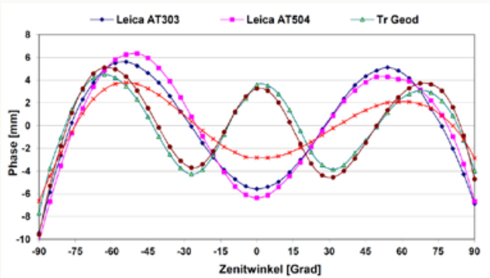
Parameters can be also „calibrated over temperature“

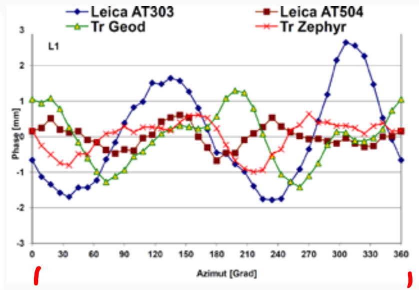
CALIBRATION EXAMPLES

GNSS ANTENNAS





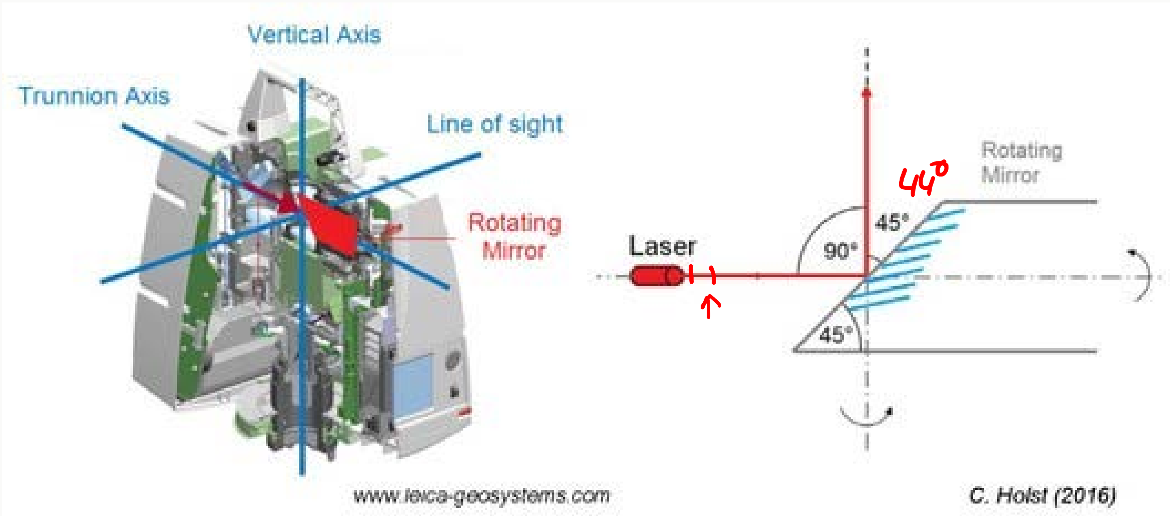




Additive corrections to phase observations depending on azimuth and zenitth angles of the satellites

CALIBRATION EXAMPLES

LASER SCANNER



- Determination of misalignements between various internal components
- distance measurement offsets of laser
- …

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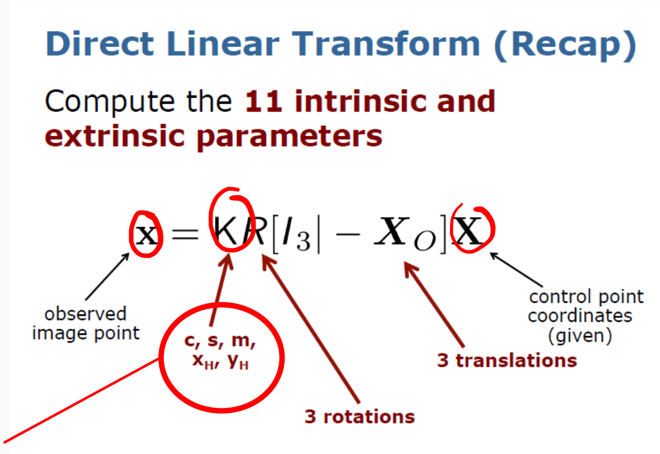
CALIBRATION EXAMPLES

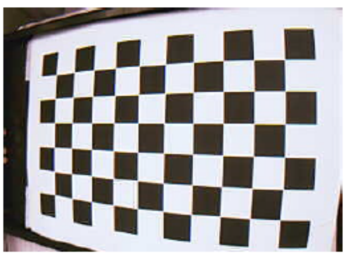
CAMERA CALIBRATION

- See camera calibration lecture by C. Stachniss in this course

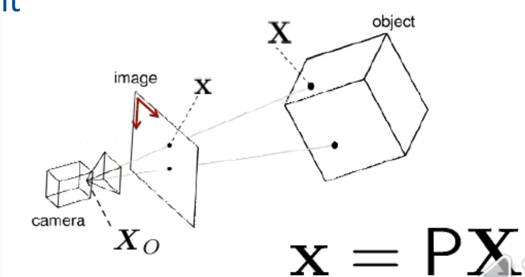


Intrinsic camera parameters
- principal point
- camera constant
- scale
- sheer

Slides by Cyrill Stachniss



Zhang, A Flexible New Technique for Camera Calibration, MSR-TR-98-71



CALIBRATION

- Examples so far:
  Individual calibration of single sensors or sensor groups (Inertial sensors, scanner, camera, GNSS antenna, …)

  → **Component calibration**

- Also necessary in complex multi-sensor systems:
  Calibration of geometric relationships between the sensors

  → **System Calibration**

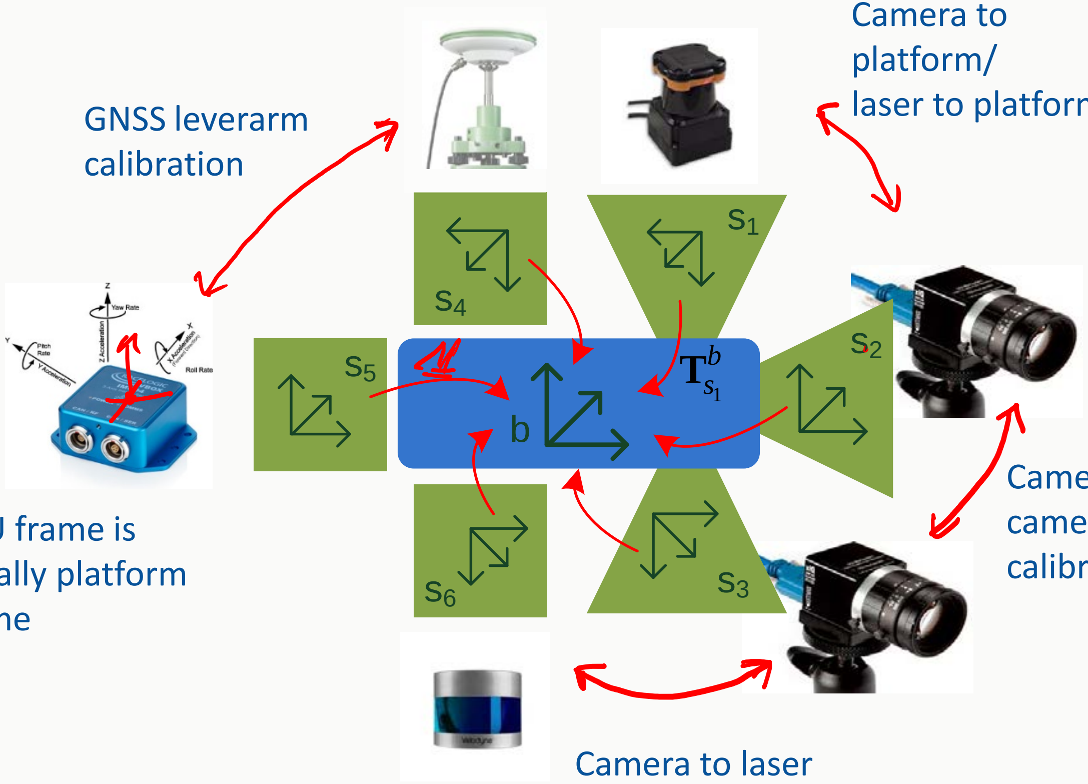
- Establishing a temporal relationship between sensor reading can also be considered as a calibration procedure

  → **Sensor sychronization (next lexture)**

SYSTEM CALIBRATION

Camera to platform/ laser to platform

GNSS leverarm calibration



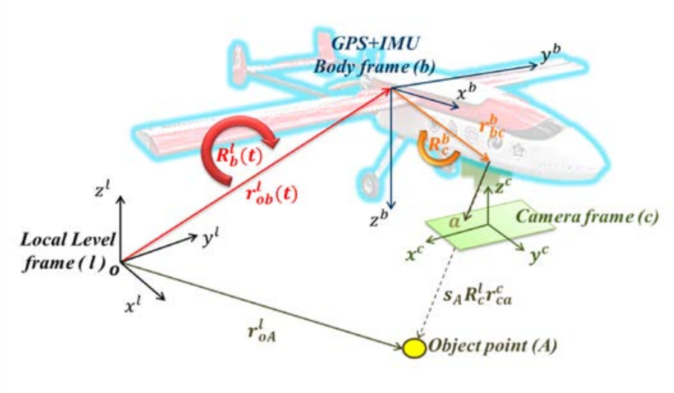
IMU frame is usually platform frame

Camera to camera calibration

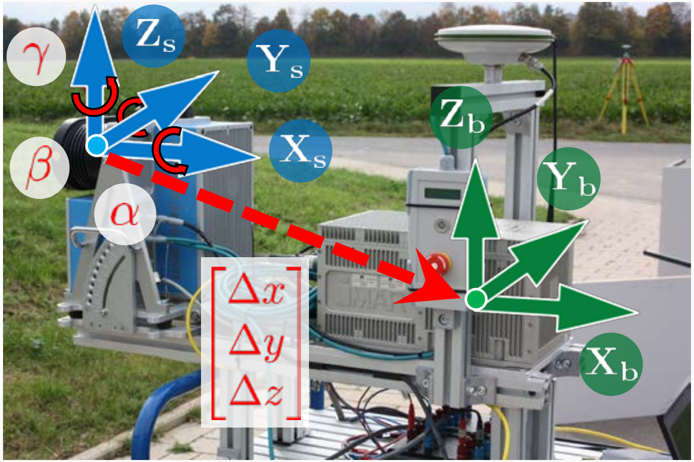
Camera to laser calibration

CHAPTER 3: SYSTEM CALIBRATION

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi)\cdot\left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma)\cdot\begin{bmatrix} 0 \\ d\cdot\sin b \\ d\cdot\cos b \end{bmatrix}\right]$$



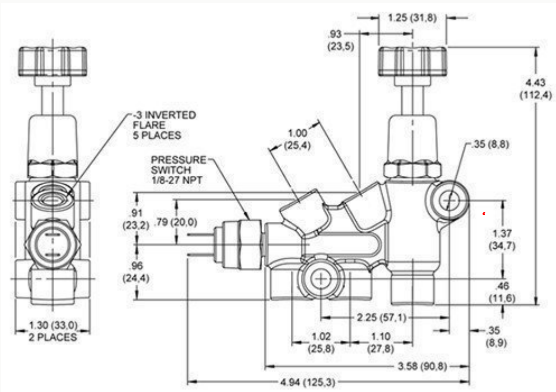
From: Chiang, K.-W.; Tsai, M.-L.; Naser, E.-S.; Habib, A.; Chu, C.-H. New Calibration Method Using Low Cost MEM IMUs to Verify the Performance of UAV-Borne MMS Payloads. Sensors 2015, 15, 6560-6585.

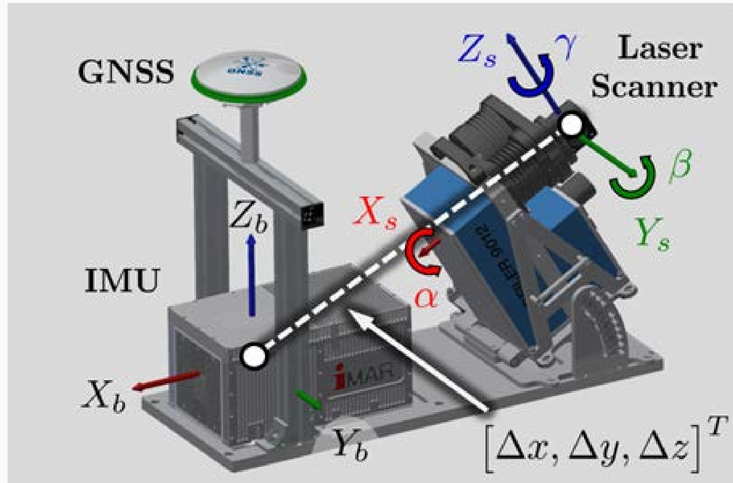


- Overview of **system calibration** methods
- Detailed derivation of **plane based calibration**

SYSTEM CALIBRATION - METHODS

PREVIOUS KNOWLEDGE





- Data from construction plan

➔ Might be wrong, especially for critical parameters such as angles

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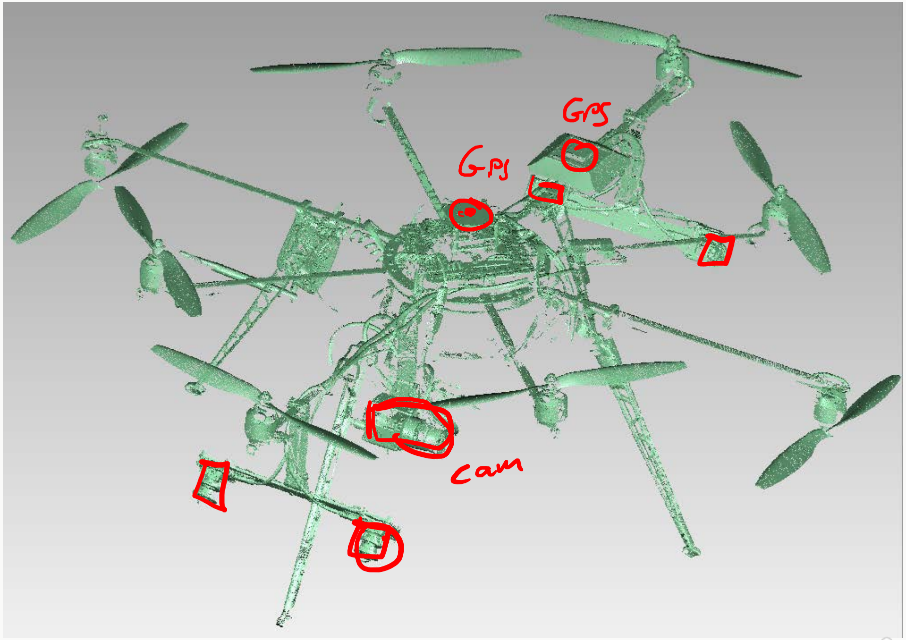
SYSTEM CALIBRATION - METHODS

DIRECT OBSERVATION

- Example:
  Get parameters from accurate laser scan
- Problem:
  Most points of interest are not physically visible/available, eg camera focal points
- How to deal with orientations?



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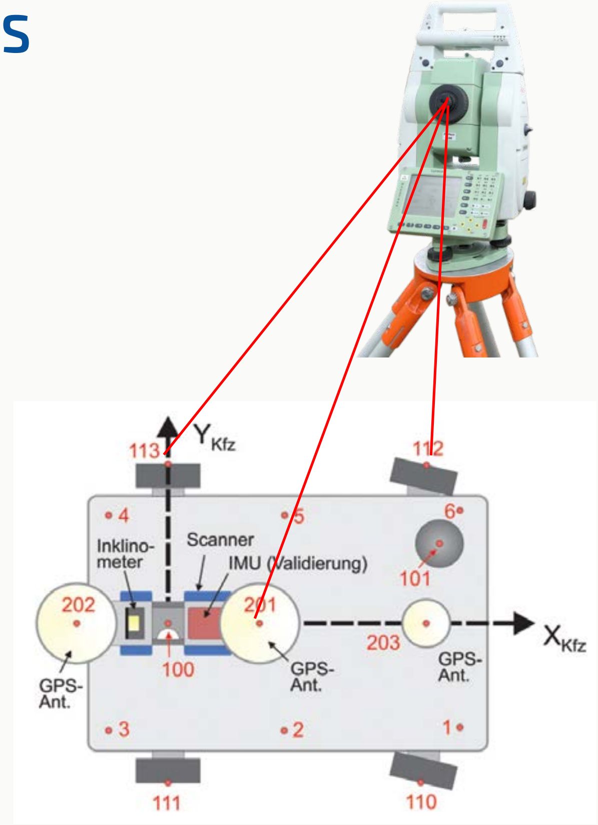
SYSTEM CALIBRATION - METHODS

DIRECT MEASUREMENT

- Example:
  Use geodetic measurement equipment and methods to derive parameters
- Accurate but lot of manual work
- Also problems with non physical points of interests and orientations (cameras)

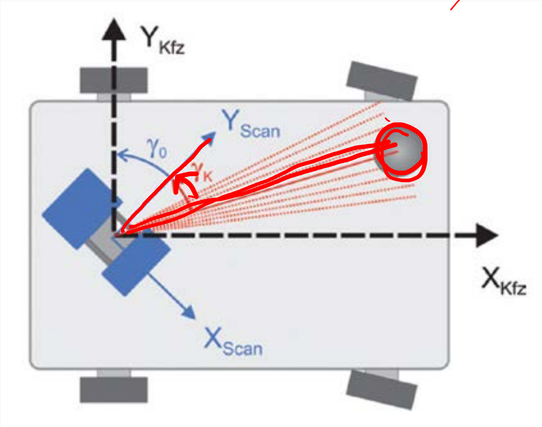


From: Christian Hesse (2007): Hochauflösende kinematische Objekterfassung mit terrestrischen Laserscannern. PhD Thesis. Uni Hannover

SYSTEM CALIBRATION - METHODS

INDIRECT MEASUREMENTS

- Use the **sensors**, which position/orientation parameters are needed (scanner or cameras), to **observe objects** (e.g. points, planes, spheres) **with known positions/orientations** in the or relative to the **body frame**.



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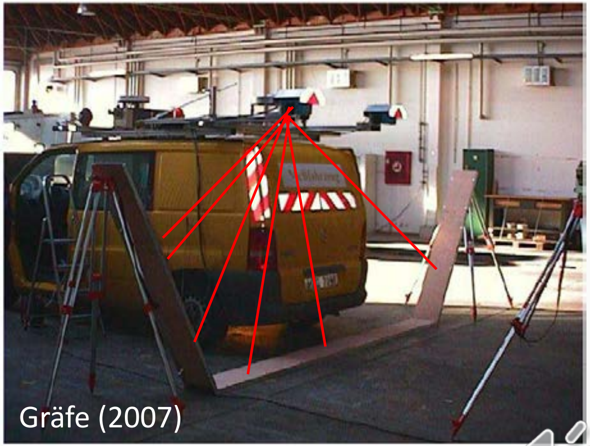
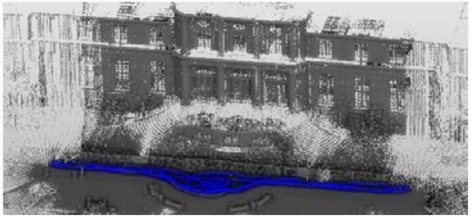
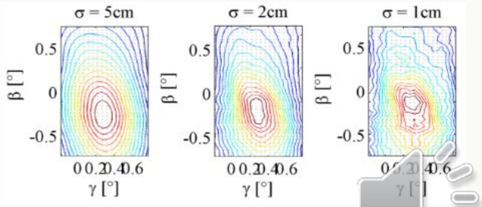


SYSTEM CALIBRATION - METHODS

ENTROPY BASED METHODS

- Formulate pointcloud as a Gaussian Mixture Model
- Find a measure for the ‚quality' or ‚compactness' or ‚crispness' of the point cloud ➔ Quadratic Renyi Entropy
- Generate a point cloud using the sensor system, trying to see same areas from multiple ‚viewing conditions'
- Assume the world not to be ‚too noisy'
- Minimize QRE by varying calibration parameters





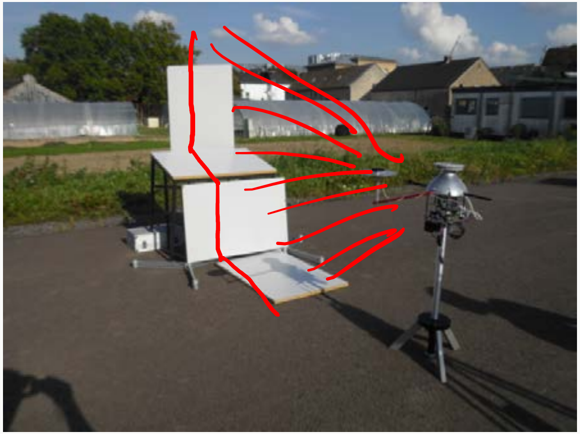
More details: W. Maddern, A. Harrison, and P. Newman, “Lost in translation (and rotation): Fast extrinsic calibration for 2D and 3D LIDARs,” in Proc. IEEE Int. Conf. Robot. Autom., May 2012

SYSTEM CALIBRATION - METHODS

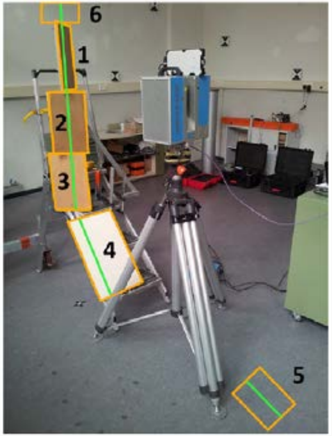
INDIRECT MEASUREMENTS – PLANE BASED

- Use arbitrary or dedicated plane setup together with an adjustment procedure to derive parameters

Dorndorf et al. (2015)



Heinz et al. (2015)



Hartmann et al. (2015)

PLANE BASED CALIBRATION

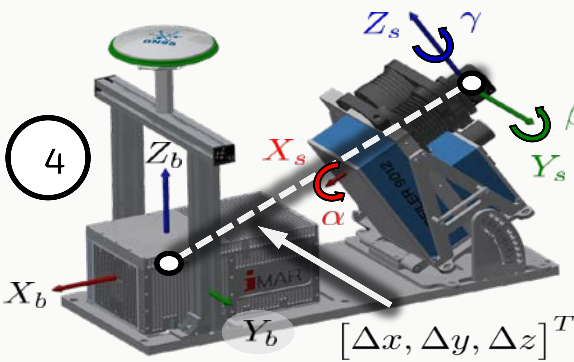
LASER TO GNSS/IMU
(= LASER TO BODY)

PLANE BASED CALIBRATION FOR MOBILE LASER SCANNING

Setup of planes

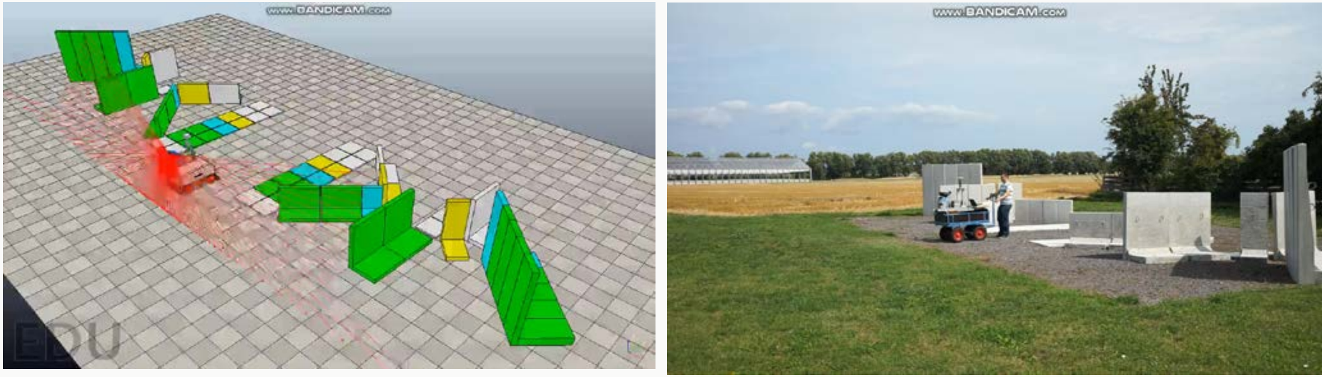
Reference scan of planes

Scan with mobile scanning system

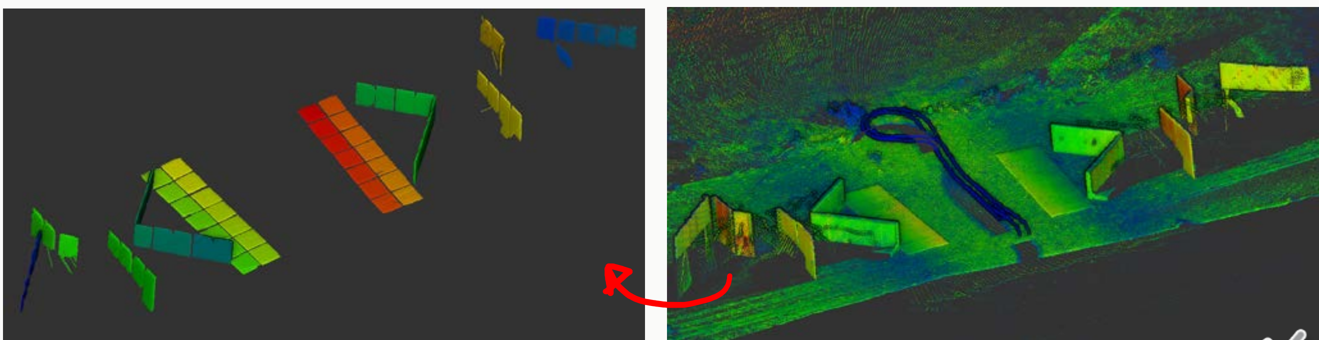


Adjustment to derive parameters

PLANE BASED CALIBRATION – MOBILE SCAN

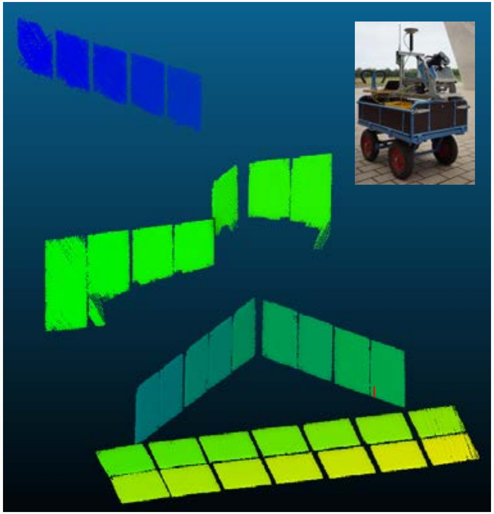


Aufnahme des Kalibrierfeldes mit zwei Durchfahrten (Hin- und Rück, ca 30 Sekunden)



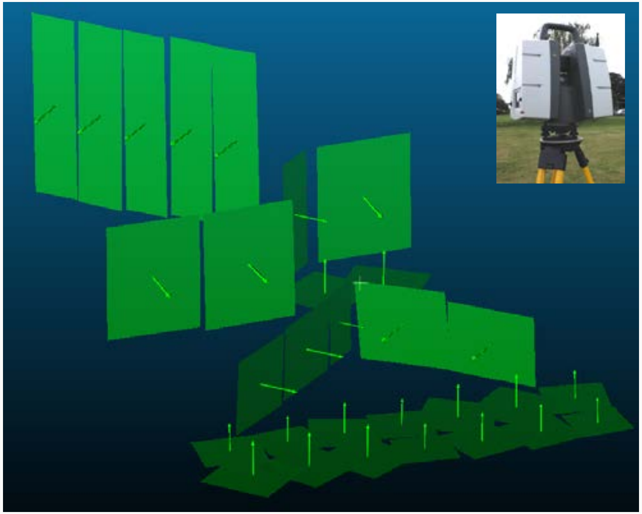
Automatisierte Zuordnung der Scanprofile zu den Referenzebenen (RANSAC)

PLANE BASED CALIBRATION



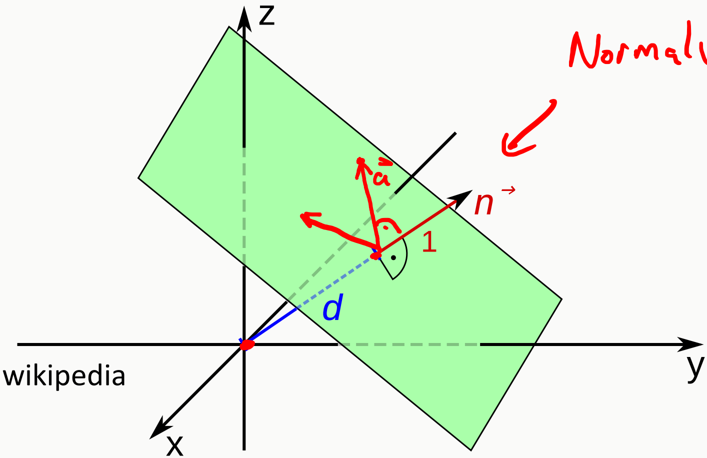
Planes extracted from mobile scan

$\stackrel{!}{=}$



Planes measured with static sacnner

PLANE BASED CALIBRATION



wikipedia

Normalvector

Scalarprodukt

$\vec{a} \cdot \vec{n} = 0$

$\vec{x} \cdot \vec{n} = d$

Hesse normal form

4 plane parameters

$\vec{n}, d$

PLANE BASED CALIBRATION

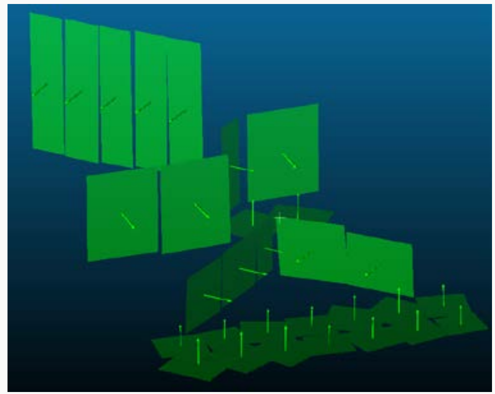
1) ESTIMATE PLANE PARAMETERS FROM TLS SCANS

$$\begin{bmatrix} x_{TLS} \\ y_{TLS} \\ z_{TLS} \end{bmatrix}^T \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} - d_p \stackrel{!}{=} \mathbf{0}$$

obs. param

observations

parameters



- Implicit functional relationship between parameters and observations

➔ Adjustment via Gauss-Helmert model / Least Squares to get n, d

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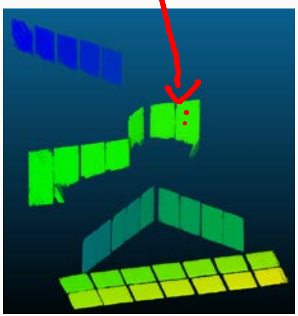
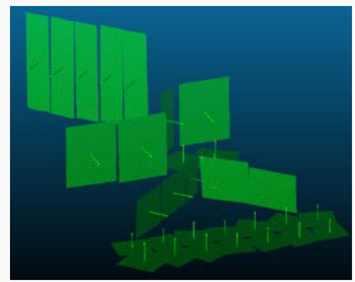
PLANE BASED CALIBRATION

2) MEASURE PLANES WITH MOBILE SYSTEM

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma) \cdot \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix} \right]$$

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix}^T \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} - d_p \stackrel{!}{=} \mathbf{0}$$




parameters from TLS plane adjustment

PLANE BASED CALIBRATION

3) ESTIMATE CALIBRATION PARAMETERS

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix}^T \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} - d_p \stackrel{!}{=} \mathbf{0}$$

$$\left[\begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi)\cdot\left(\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma)\cdot\begin{bmatrix} 0 \\ d\cdot\sin b \\ d\cdot\cos b \end{bmatrix}\right)\right]^T \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} - d_p \stackrel{!}{=} \mathbf{0}$$

TLS plane params

observations
parameters

- Implicit functional relationship between parameters and observations

→ Adjustment via Gauss-Helmert model / Total Least Squares to get Calibration parameters

PLANE BASED CALIBRATION

$$\left[\begin{bmatrix}t_x\\t_y\\t_z\end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi)\cdot\left(\begin{bmatrix}\Delta x\\\Delta y\\\Delta z\end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma)\cdot\begin{bmatrix}0\\d\cdot\sin b\\d\cdot\cos b\end{bmatrix}\right)\right]^T \begin{bmatrix}n_x\\n_y\\n_z\end{bmatrix} - d_p \stackrel{!}{=} \mathbf{0}$$

observations

parameters

unknown parameters

- The plane parameters could also be part of the estimated parameter vector
- A dedicated plane setup is not necessary
- **Disadvantage**: general success and accuracy is not guaranteed, some parameters may not be observable

More details in: Jan Skaloud, Derek Lichti. Rigorous approach to bore-sight self-calibration in airborne laser scanning. ISPRS Journal of Photogrammetry and Remote Sensing 61 (2006) 47–59

PLANE BASED CALIBRATION

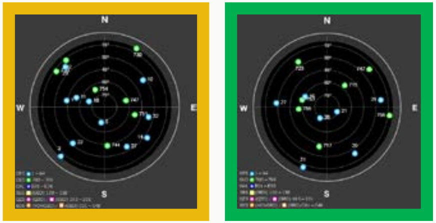
RESULTS

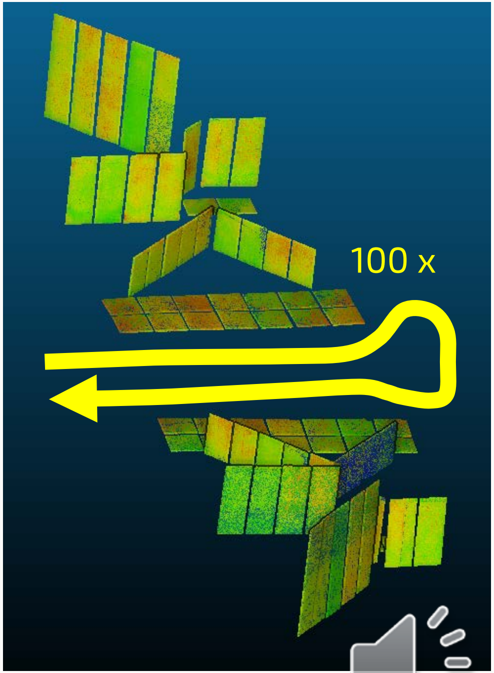
- Single Calibration:
  as shown in figure

- 100 single calibration at different days
  - 31.07.19, 15:40 – 15:55 (# 14)
  - 05.08.19, 11:05 – 11:25 (# 22)
  - 05.08.19, 12:30 – 12.50 (# 31)
  - 05.08.19, 13:45 – 14:10 (# 32)

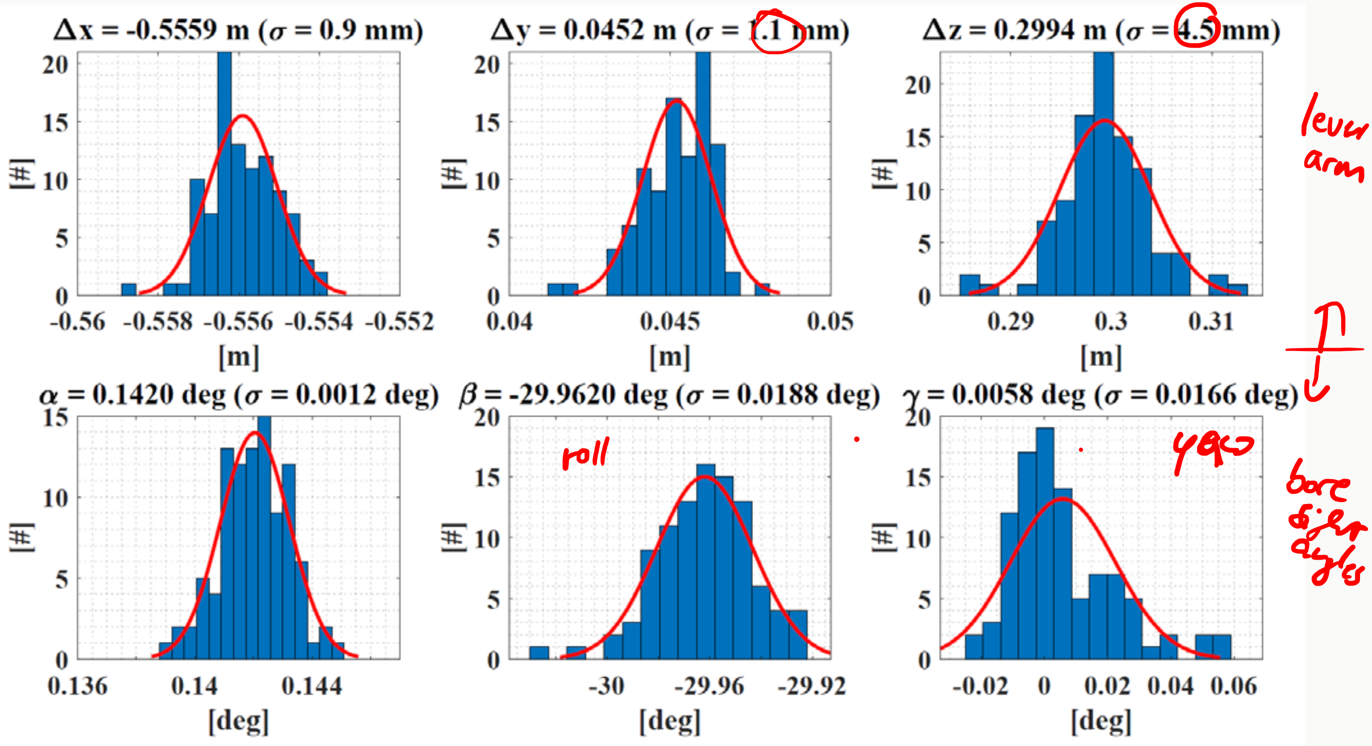
➔ reduction of systematic offsets due to GNSS conditions

- 4 reintializations of the IMU





PLANE BASED CALIBRATION - RESULTS

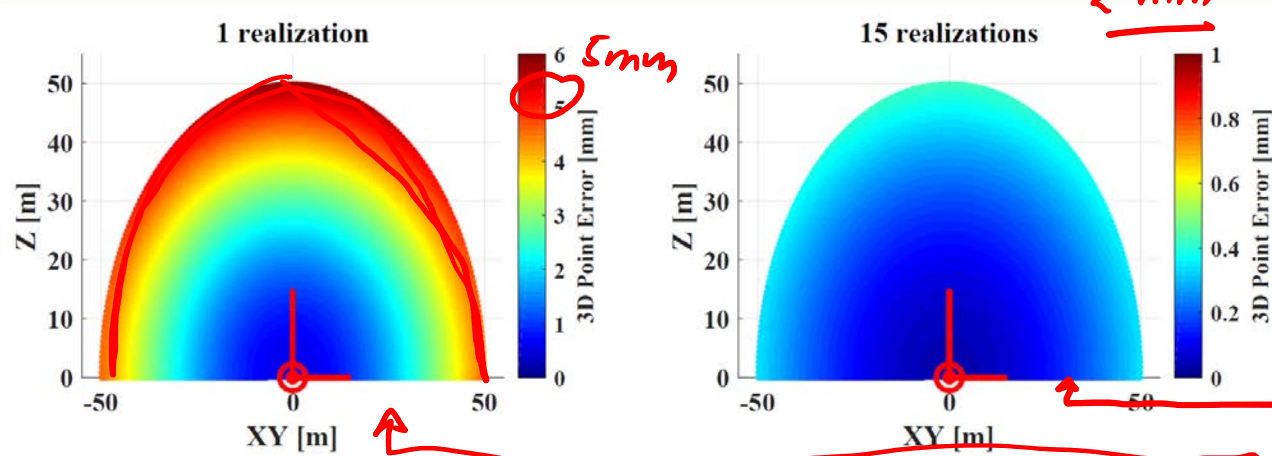


From: Heinz, E.; Holst, C.; Kuhlmann, H. Klingbeil, L. **(2020).** *Design and Evaluation of a Permanently Installed Plane-Based Calibration Field for Mobile Laser Scanning Systems*, Remote Sensing 2020, 12, 555, https://doi.org/10.3390/rs12030555.

IMPACT OF CALIBRATION ERRORS

Additional ... due to calibration

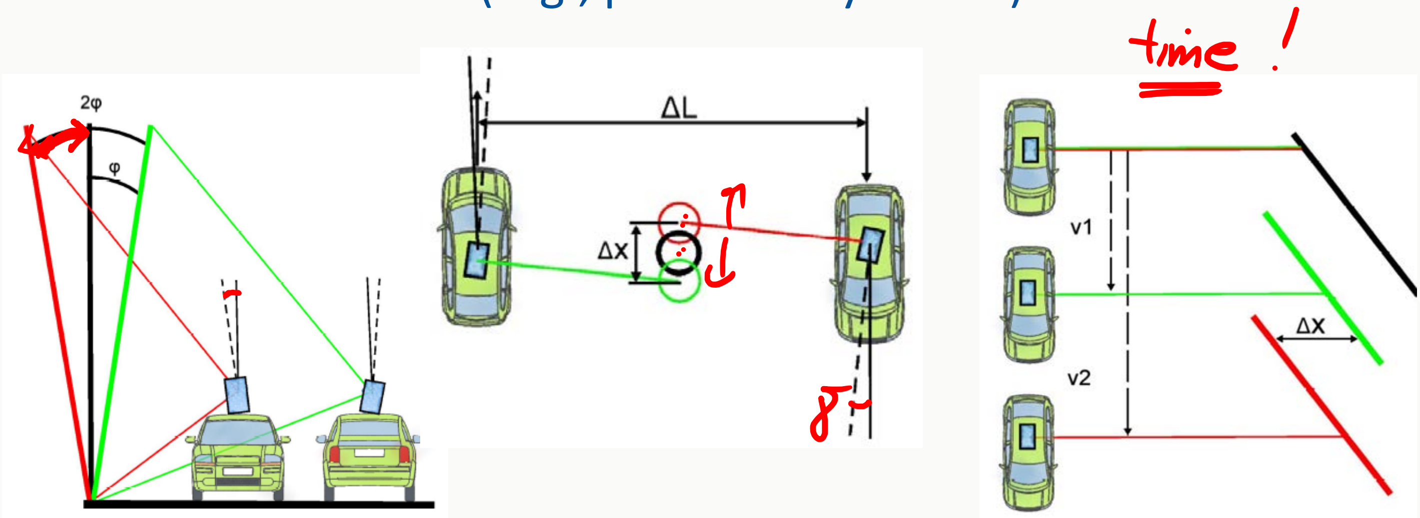
3D POINT ERROR FROM SIMULATED CALIBRATION ERRORS



Parameter	$\sigma_{\Delta x}$	$\sigma_{\Delta y}$	$\sigma_{\Delta z}$	σ_{α}	σ_{β}	σ_{γ}
Target Accuracy	1.0 mm	1.0 mm	1.5 mm	0.0050°	0.0050°	0.0050°
1 Realization	0.9 mm	1.1 mm	4.5 mm	0.0012°	0.0188°	0.0166°
15 Realizations	0.2 mm	0.3 mm	1.2 mm	0.0003°	0.0049°	0.0043°
98 Realizations	0.1 mm	0.1 mm	0.5 mm	0.0001°	0.0019°	0.0017°

IMPACT OF CALIBRATION ERRORS

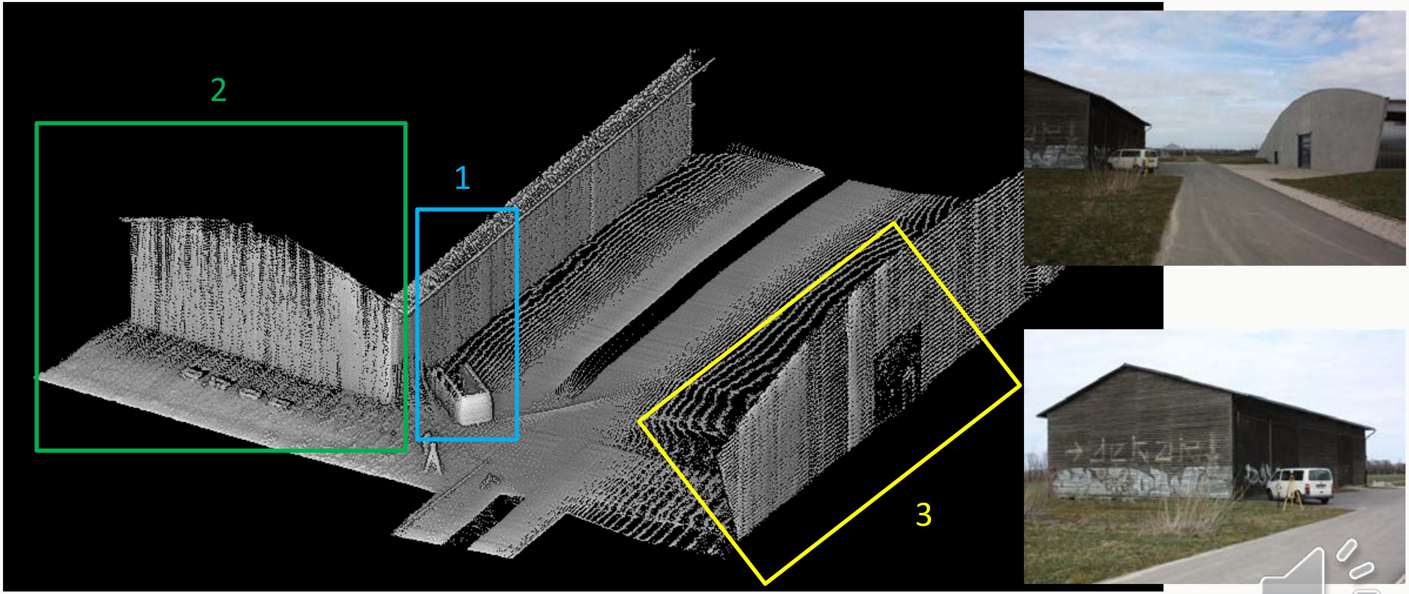
Special driving maneuvers past building facades or artifical reference structures (e. g., planes or cylinders)



From: Keller, F.; Sternberg, H. Multi-Sensor Platform for Indoor Mobile Mapping: System Calibration and Using a Total Station for Indoor Applications. *Remote Sens.* **2013**, *5*, 5805-5824.

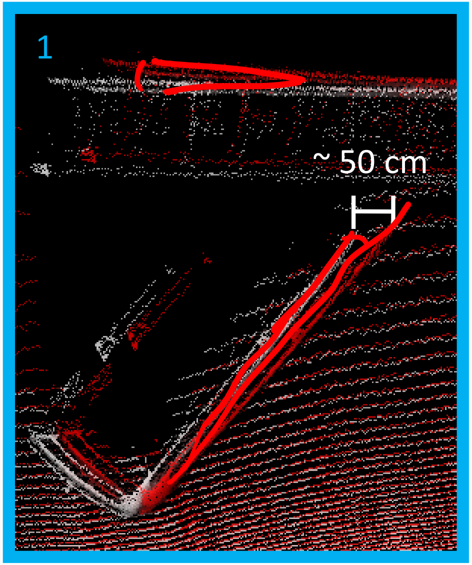
IMPACT OF CALIBRATION ERRORS

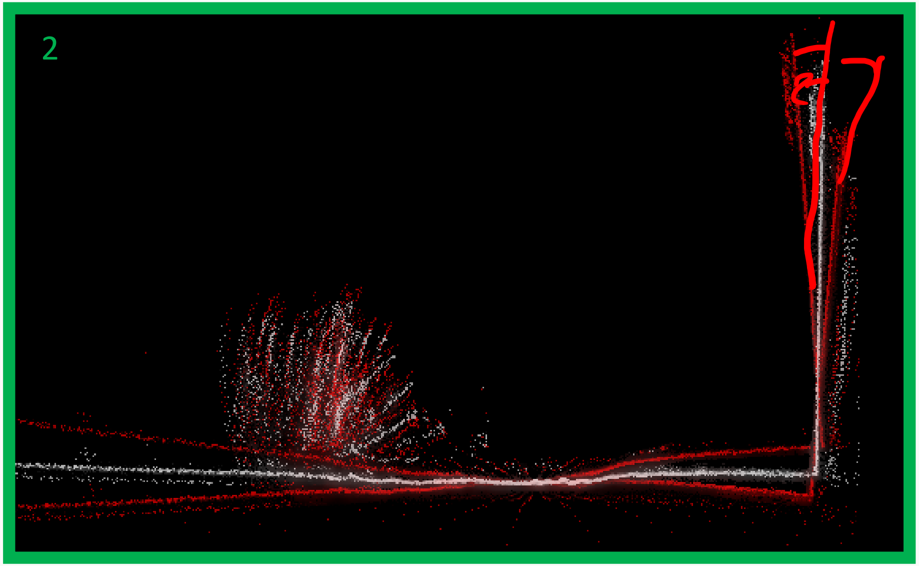
Impact of errors in the boresight angles: $\Delta\alpha,\ \Delta\beta,\ \Delta\gamma$



IMPACT OF CALIBRATION ERRORS

white : reference / truth





$\Delta\gamma = 5°$ s = 5,7 m
→ Δp = 50 cm

$\Delta\beta = 5°$ → Tilting of the facade when scanning in two different directions)

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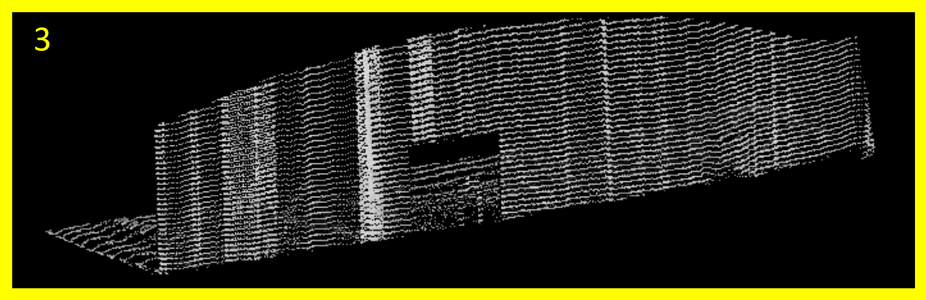
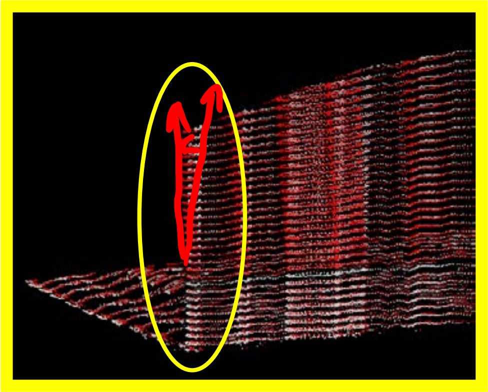
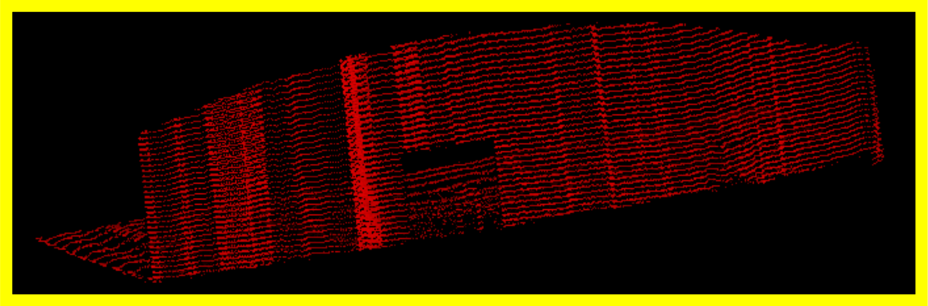
IMPACT OF CALIBRATION ERRORS



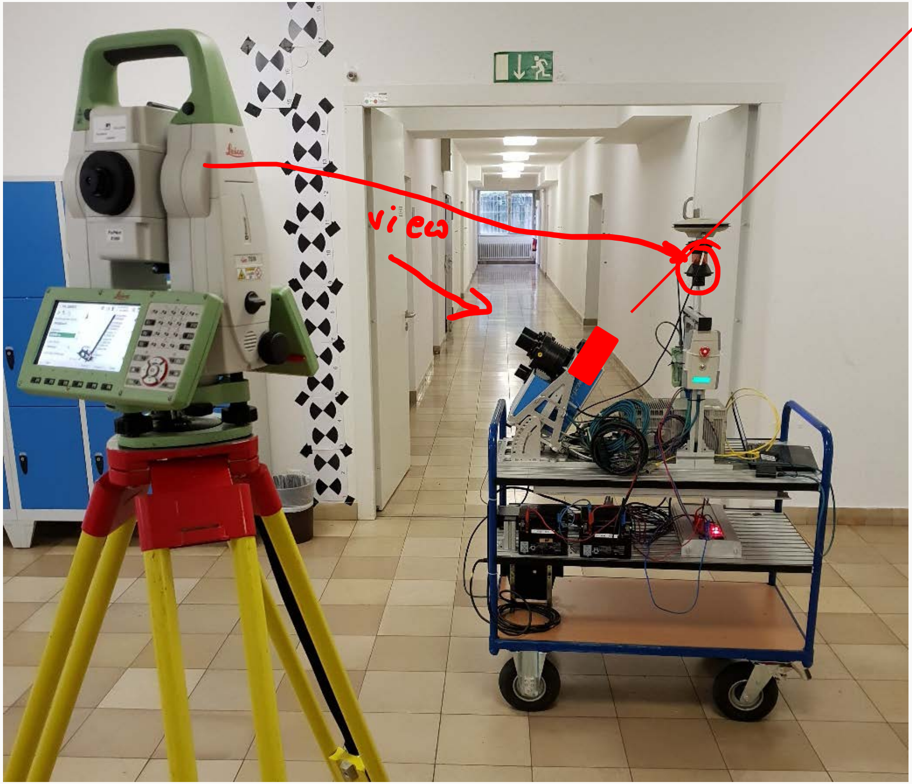


$\Delta\alpha = 5°$ → Shearing of facade

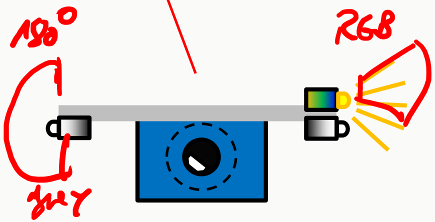


CAMERA TO LASER CALIBRATION

CAMERA TO LASER CALIBRATION

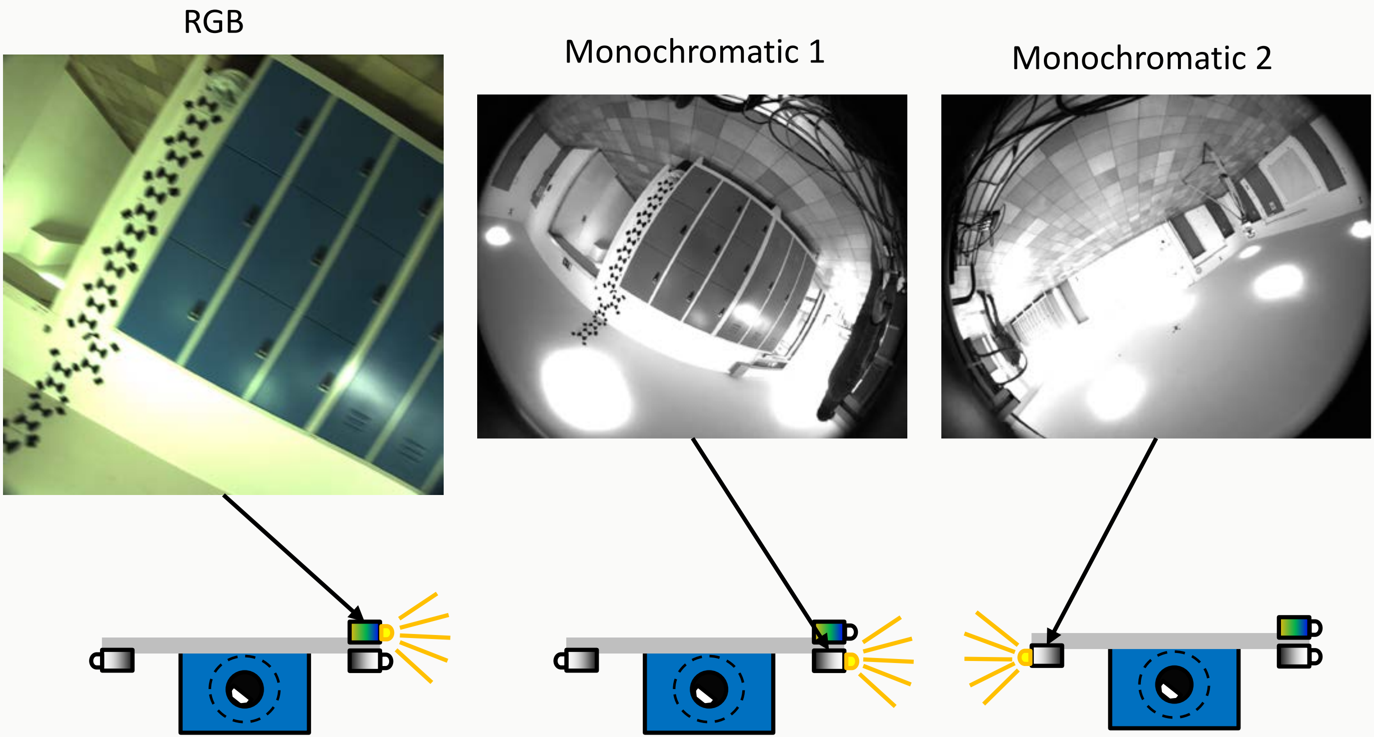


cameras



front view

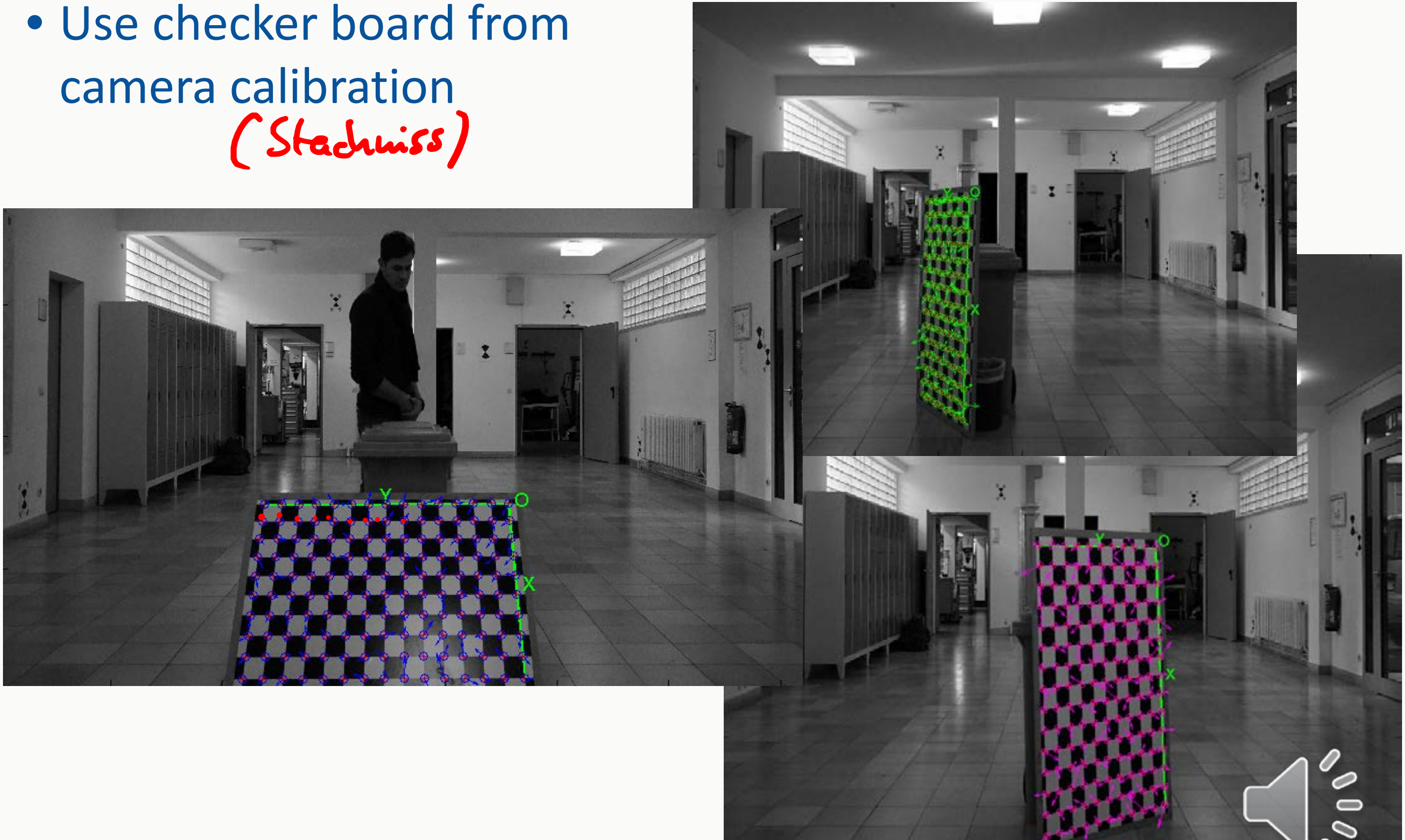
CAMERA TO LASER CALIBRATION



CAMERA TO LASER CALIBRATION

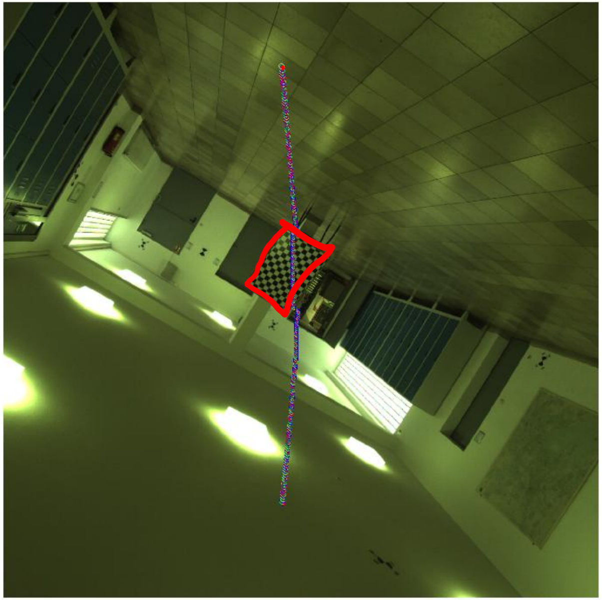
- Use checker board from camera calibration

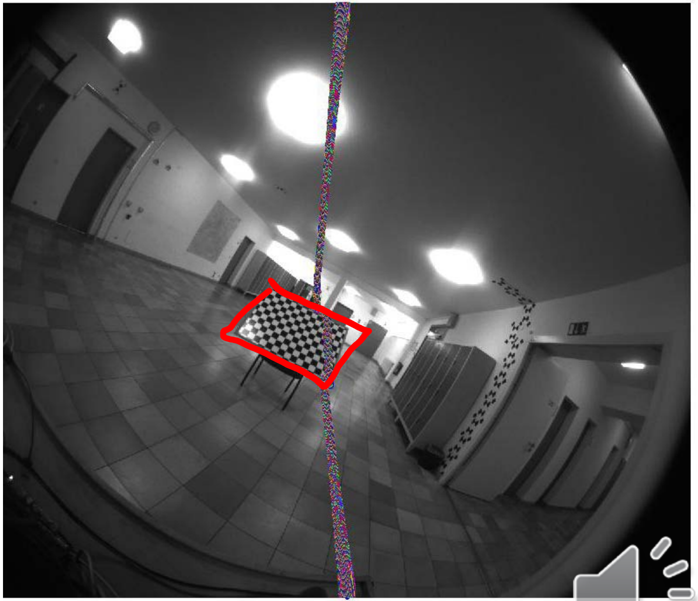
(Stachniss)



CAMERA TO LASER CALIBRATION

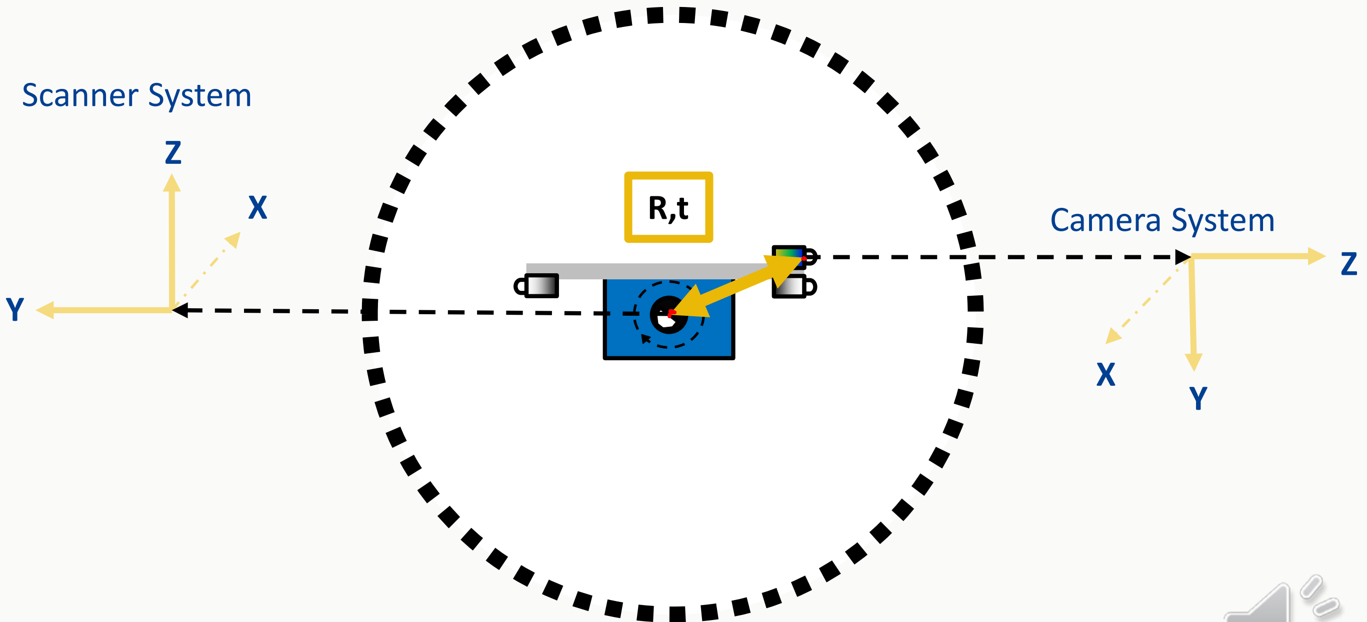
- Find correspondences between laser and profiles and images





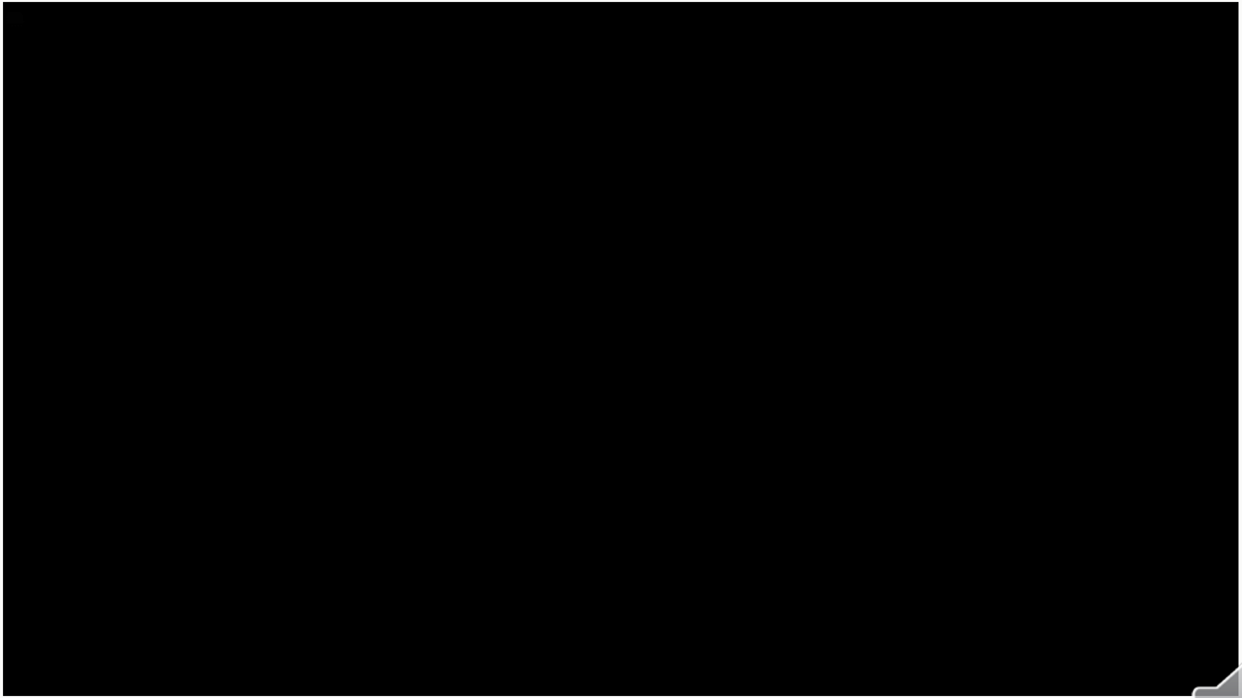
CAMERA TO LASER CALIBRATION

- Compute translation and rotation between both systems by using known point relationships



CAMERA TO LASER CALIBRATION

- Application example: colorize laser point clouds



WHAT YOU HAVE LEARNED TODAY

- What is calibration and why it is necessesary?
- What are examples for calibration parameters?
- What are possible methods for system calibration?
- How is one possible precedure for plane based calibration for mobile laser scanning systems?
- What is the impact of calibration errors in mobile laser scanning systems?

THANKS