Chapters 1 – 3: Overview

- Photogrammetric mapping: introduction, applications, and tools
- GNSS/INS-assisted geo-referencing of photogrammetric and LiDAR mapping systems
- LiDAR mapping: principles, applications, mathematical model, and error sources and their impact.

- This chapter will be focusing on the Quality Assurance (QA) and Quality Control (QC) of the LiDAR Mapping process:
  - QA: system calibration
  - QC: LiDAR data validation

Chapter 4

QUALITY ASSURANCE AND QUALITY CONTROL OF LIDAR MAPPING

Overview

- Motivation
- Quality Assurance (QA) and Quality Control (QC)
  - Introduction
  - Prerequisites
- QA/QC of Photogrammetric Mapping
- QA/QC of LiDAR Mapping:
  - LiDAR system calibration
  - Geometric validation of LiDAR data
- Concluding Remarks

Motivation

- There has been a significant advancement in the remote sensing and mapping technology.
  - **Digital cameras** provide an alternative to conventional large format analogue cameras for rapid data collection.
  - **Direct georeferencing** is providing the means for an almost control-free mapping environment.
  - **LiDAR** provides a dense point cloud representing the object space surface, and thus offers a fast and accurate way of obtaining a Digital Surface Model (DSM).
- Effective utilization of these advances mandates the development of reliable, practical, and standardized procedures for the Quality Assurance (QA) and Quality Control (QC) of the mapping process.

Quality Assurance & Quality Control

- Quality Assurance (pre-mission):
  - Management activities to ensure that a process, item, or service **will be** of the quality needed by the user
  - It deals with creating management controls that cover planning, implementation, and review of data collection.
  - Key activity in QA is the calibration procedure.
- Quality Control (post-mission):
  - Provide routines and consistent checks to ensure **available** data integrity, correctness, and completeness
  - Check whether the desired quality has been achieved

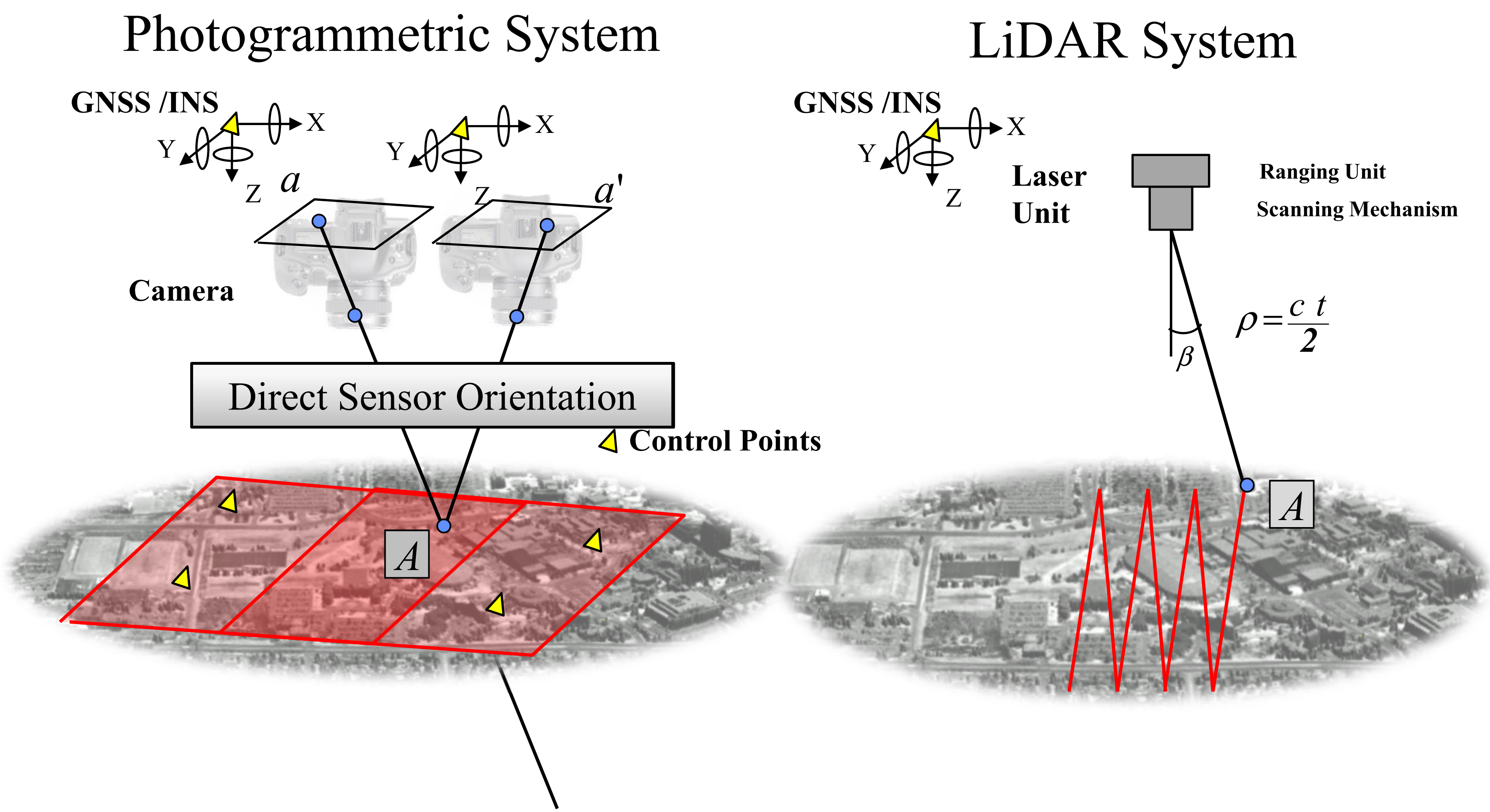
Quality Assurance & Quality Control

- To develop effective QA/QC procedures, we need to understand the mechanism of the mapping process including:
  - Data acquisition systems,
  - Error sources (random and systematic),
  - How to mitigate the impact of these error sources,
  - Nature of available data,
  - Data processing algorithms, and
  - Nature of delivered product.

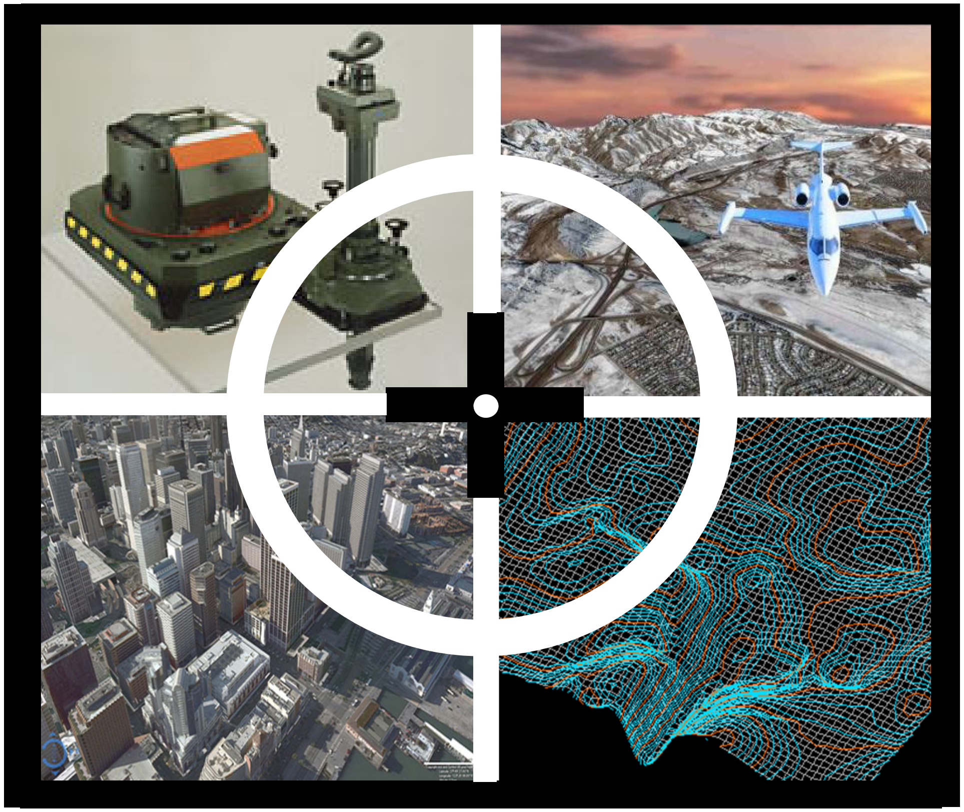
Quality Assurance & Quality Control

- The presented approach in this chapter/course has been designed to provide:
  - QA/QC for emerging mapping systems
  - QC measures for every step of the mapping process (e.g., sensor/system calibration, stability analysis, position/orientation determination, extracted features, delivered product)
  - A set of expected problems, procedures for the detection of instances of such problems, and approaches to fixing problems whenever detected
    - QC is not only concerned with accepting or rejecting a product
  - A closed loop QA/QC process
  - Minimal control requirements for the QA/QC process

Photogrammetric & LiDAR Mapping



Photogrammetric Mapping



Photogrammetric Quality Assurance

- Photogrammetric quality assurance include:
  - Percentage of overlap
  - Percentage of side lap
  - Flying height
  - Base-height ratio
  - Number and distribution of tie points
  - Number and distribution of ground control points
  - Scanning resolution (analog images)
  - Georeferencing procedure
  - Camera calibration
  - System calibration
  - Stability analysis of the system calibration parameters

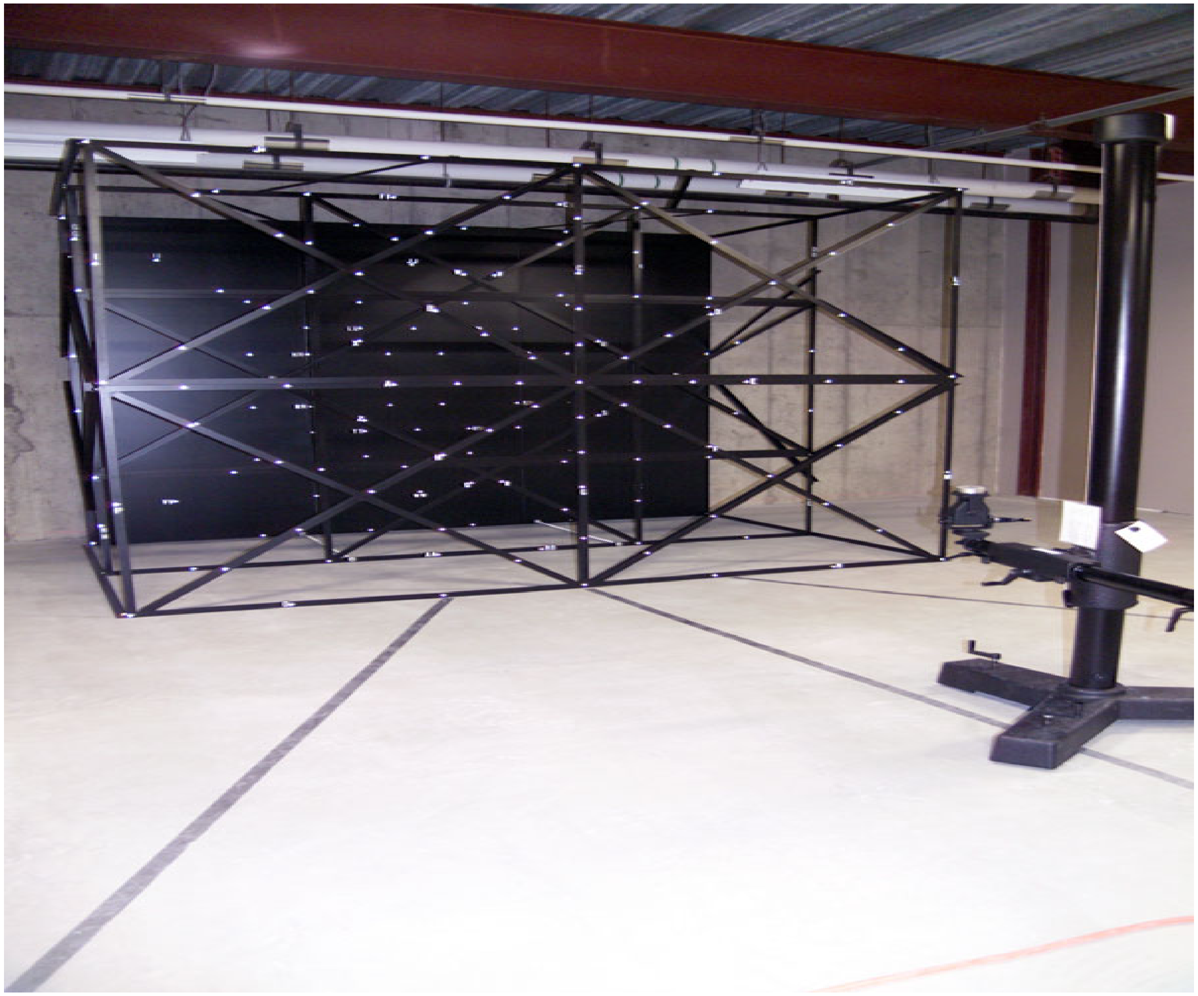
Photogrammetric Quality Assurance

- One of the key issues in quality assurance of data acquisition systems is the calibration process.
- Camera calibration:
  - Laboratory calibration,
  - Indoor calibration, and
  - In-situ calibration
- Total system calibration:
  - Camera calibration (IOPs)
  - Spatial and rotational offsets between various system components (e.g., camera, GNSS, and INS)
  - Time offsets (synchronization)
- Stability analysis:
  - Ensure that the estimated parameters do not significantly change

Photogrammetric Quality Assurance

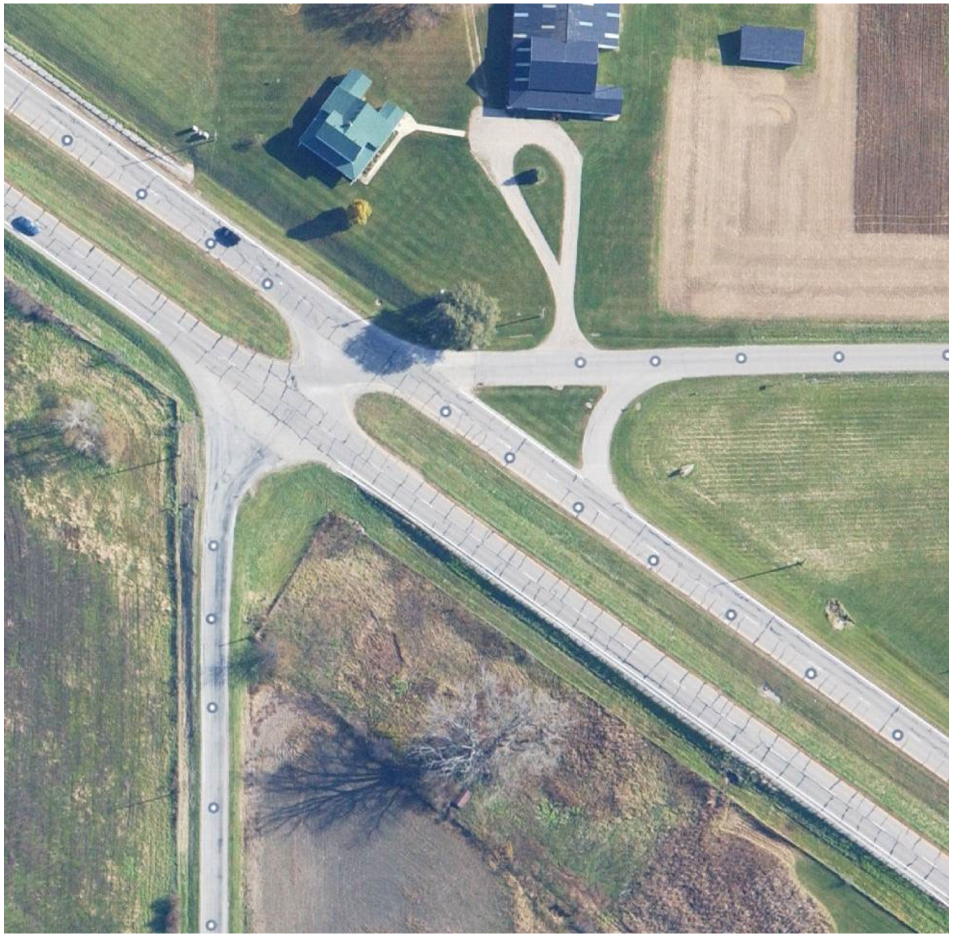
Laboratory Calibration: Multi-Collimators

Photogrammetric Quality Assurance



Indoor Camera Calibration

Photogrammetric Quality Assurance



In-Situ Camera Calibration

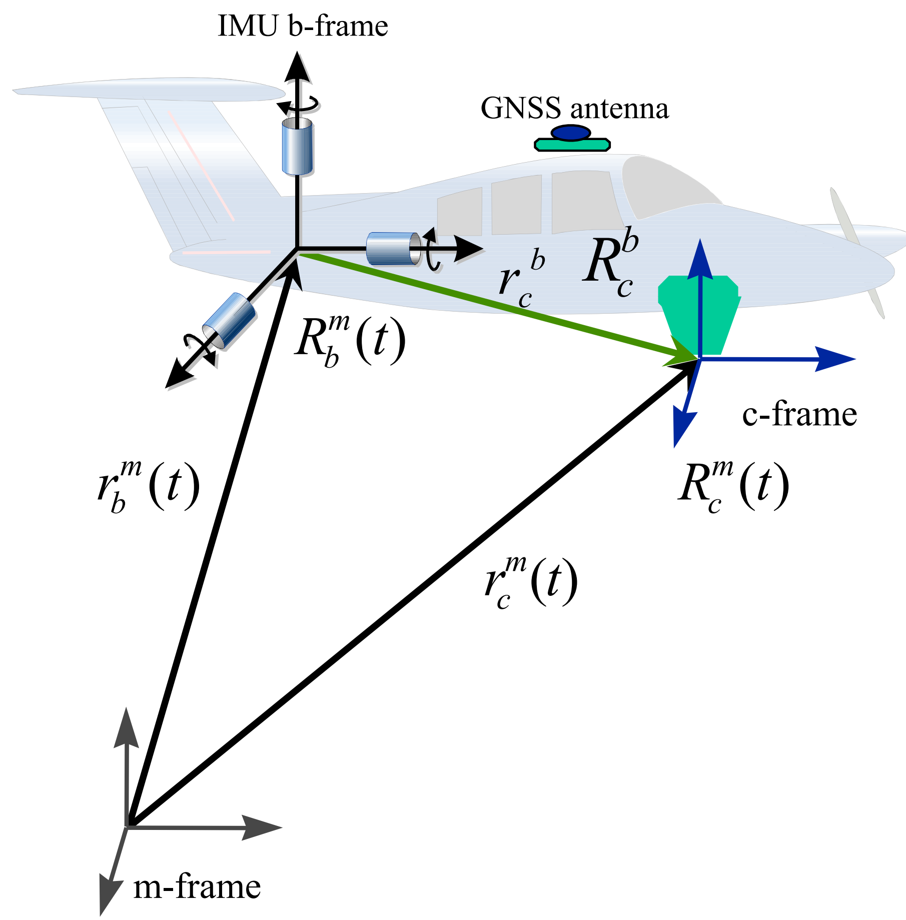
Photogrammetric Quality Assurance

$$r_c^m(t) = r_b^m(t) + R_b^m(t)\, r_c^b$$

Camera position — GNSS/INS position — GNSS/INS attitude — Calibration

$$R_c^m(t) = R_b^m(t)\, R_c^b$$

Camera attitude — GNSS/INS attitude — Calibration

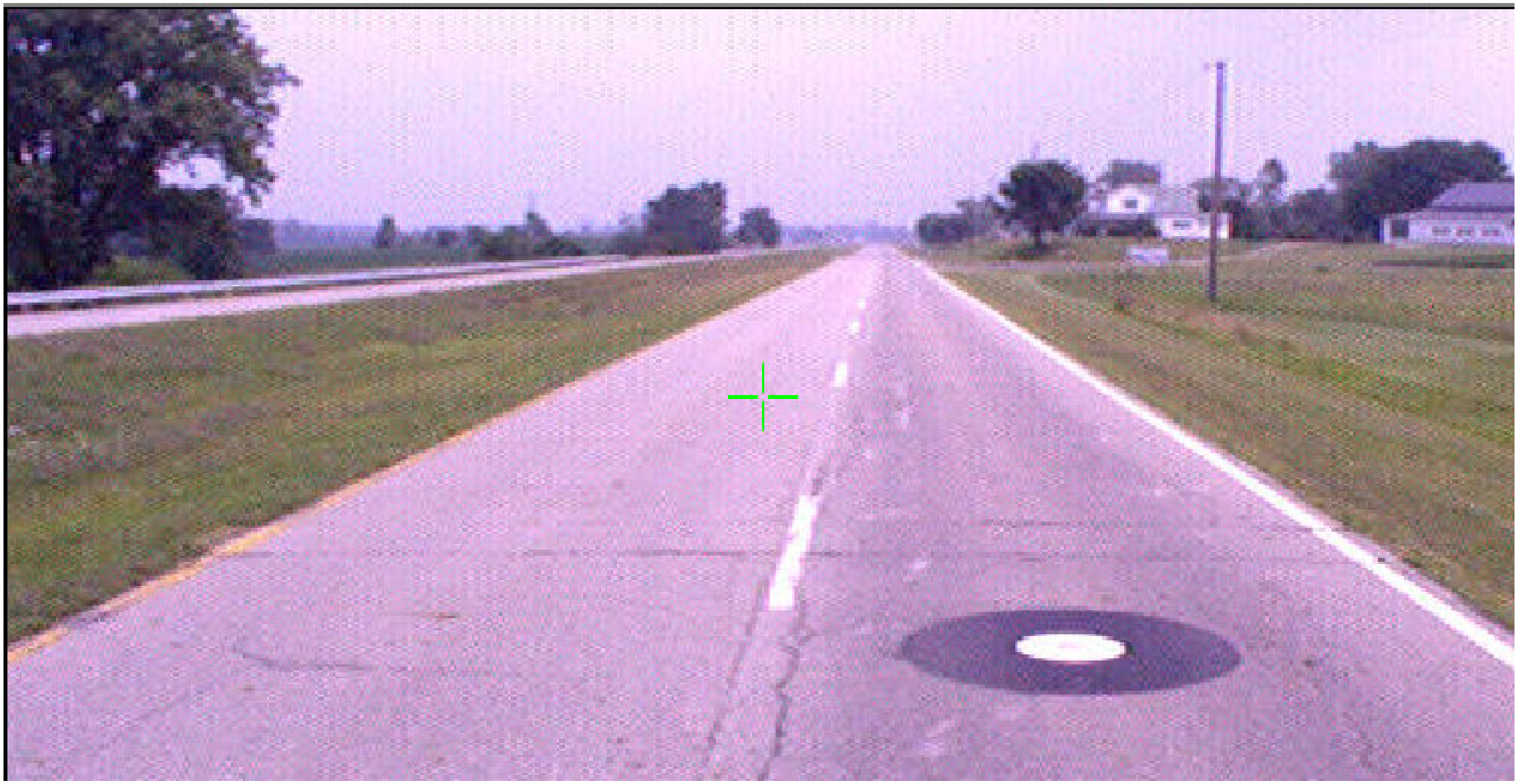


Total System Calibration

Photogrammetric Quality Control

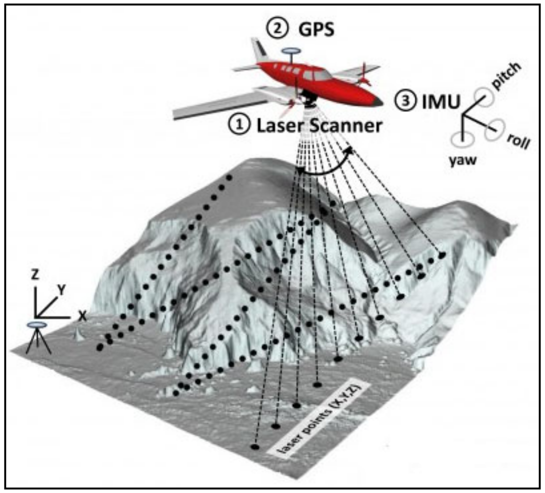
- Photogrammetric reconstruction is based on redundant measurements.
- Results from the photogrammetric triangulation gives quantitative measures of the precision of the reconstruction outcome.
  - A posteriori variance factor/variance component (overall measure of the quality of fit between the observed quantities and estimated unknowns as defined by the used model)
  - Variance-covariance matrix for the derived object coordinates
  - These values can be compared with expected nominal values.
- Independent measure for accuracy verification can be established using check point analysis.
  - Photogrammetric coordinates are compared with independently measured coordinates (e.g., GNSS survey) → RMSE analysis.

Photogrammetric Quality Control



Check Point Analysis

LiDAR Mapping



Operational LiDAR Systems (Terrestrial)

Pulse Based

Hybrid Type

Trimble, http://www.trimble.com/trimblegx.shtml, (accessed March 16, 2010)

Phase Based

Panoramic Type

Leica Geosystems, http://hds.leica-geosystems.com/en/index.htm, (accessed October 7, 2009)

Triangulation Based

Camera Type

Konica Minolta, http://www.konicaminolta.com/instruments/products/3d/index.html, (accessed October 7, 2009)

Accuracy

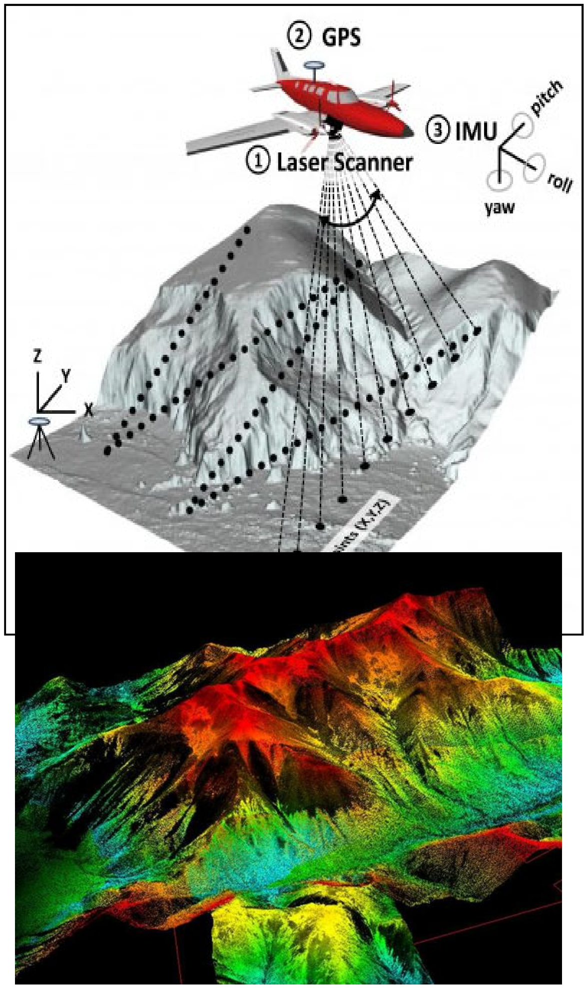
1mm → 0.01mm

Range

100m ← 10m ← 1m

LiDAR Mapping

Airborne Laser Scanning



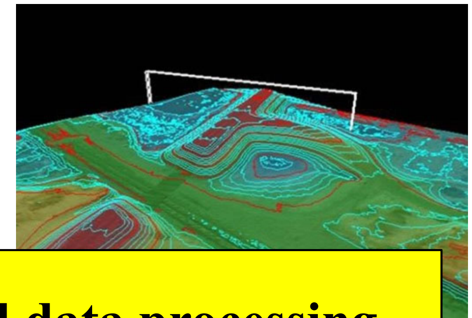
Static Terrestrial Laser Scanning

Kinematic Terrestrial Laser Scanning

LiDAR Mapping

Heritage Documentation

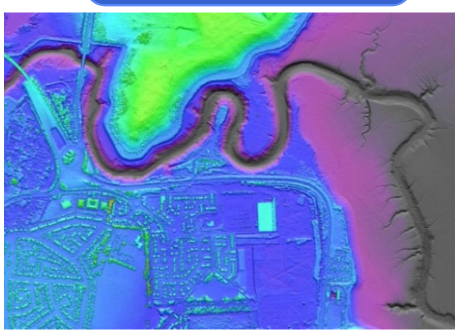
Transportation Planning



LiDAR Data

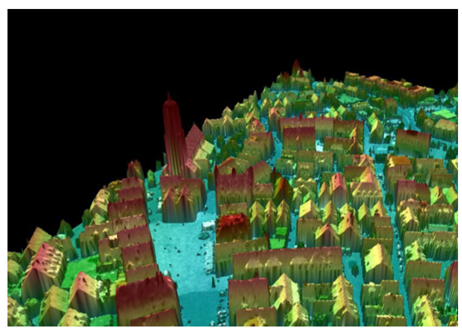
Collected point clouds should undergo QC and data processing techniques to extract useful information for these applications.

Flood Plain Mapping



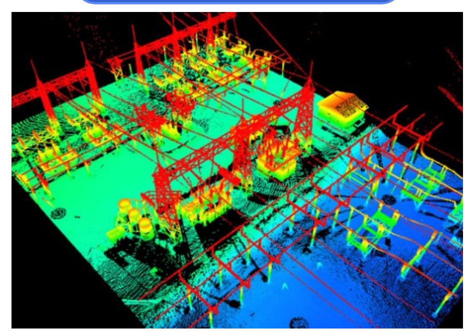
Source: www.maritimejournal.com

3D City Modeling



Source: www.trimble.com

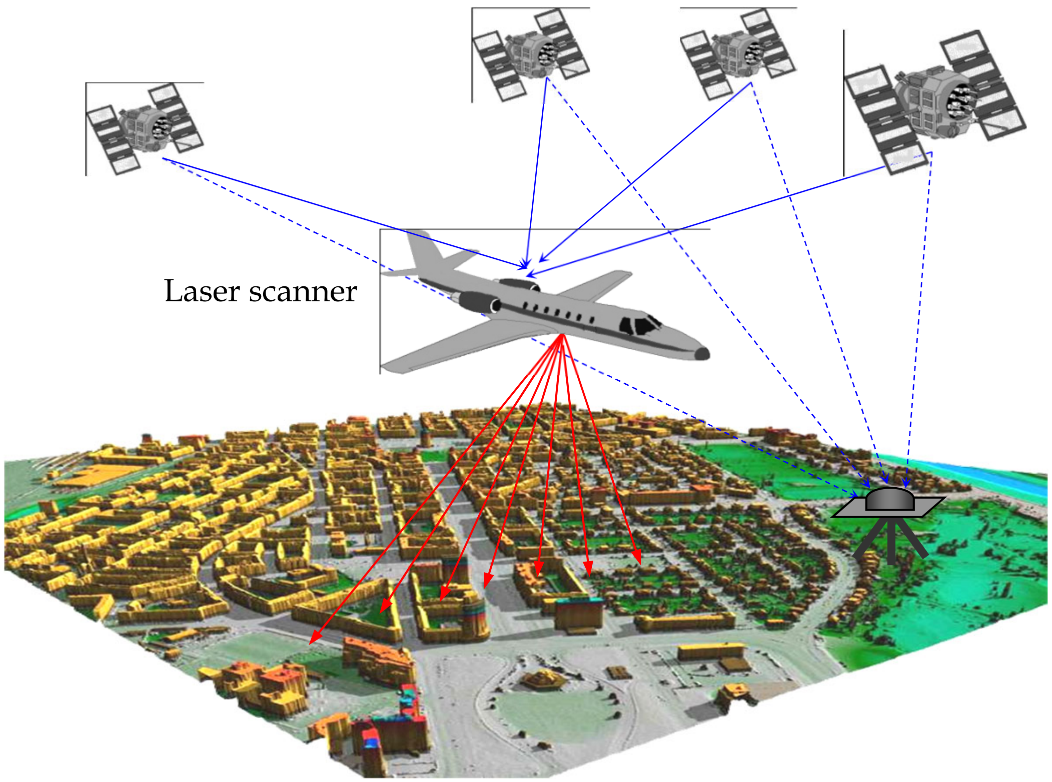
Power Line Mapping



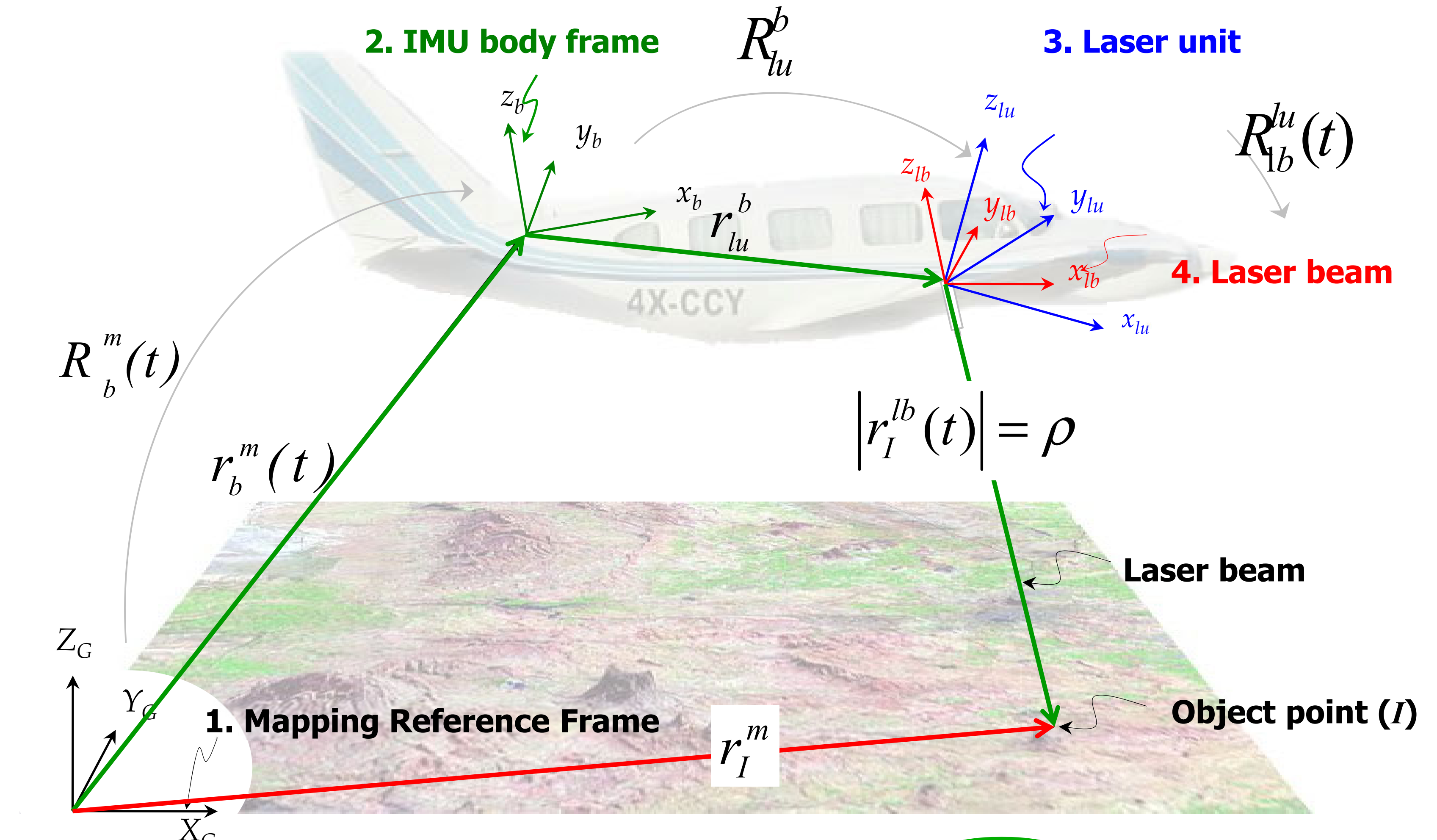
Source: www.merrick.com

LiDAR Quality Assurance

- QA activities/measures include:
  - Optimum mission time
  - Distance to GNSS base station
  - Flying height
  - Pulse repetition rate
  - Beam divergence angle
  - Scan angle
  - Percentage of overlap
  - System calibration
  - Stability analysis

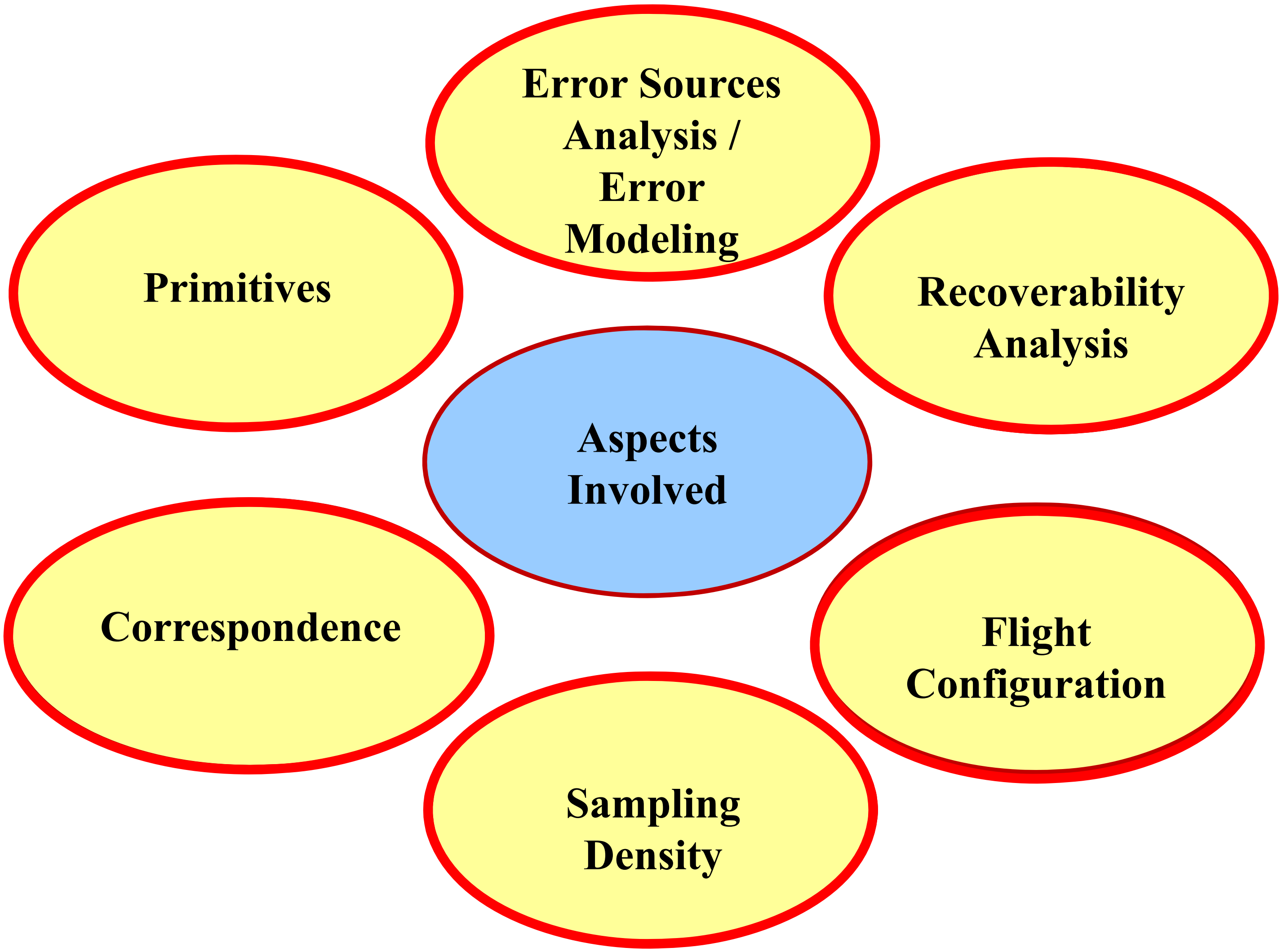


LiDAR QA: System Calibration



$$r_I^m = r_b^m(t) + R_b^m(t)\, r^b_{lu(\Delta X, \Delta Y, \Delta Z)} + R_b^m(t)\, R^b_{lu(\Delta\omega, \Delta\varphi, \Delta\kappa)}\, R^{lu}_{lb(S_\alpha \alpha, S_\beta \beta)}\, r^{lb}_{I(\rho, \Delta\rho)}$$

LiDAR QA: System Calibration



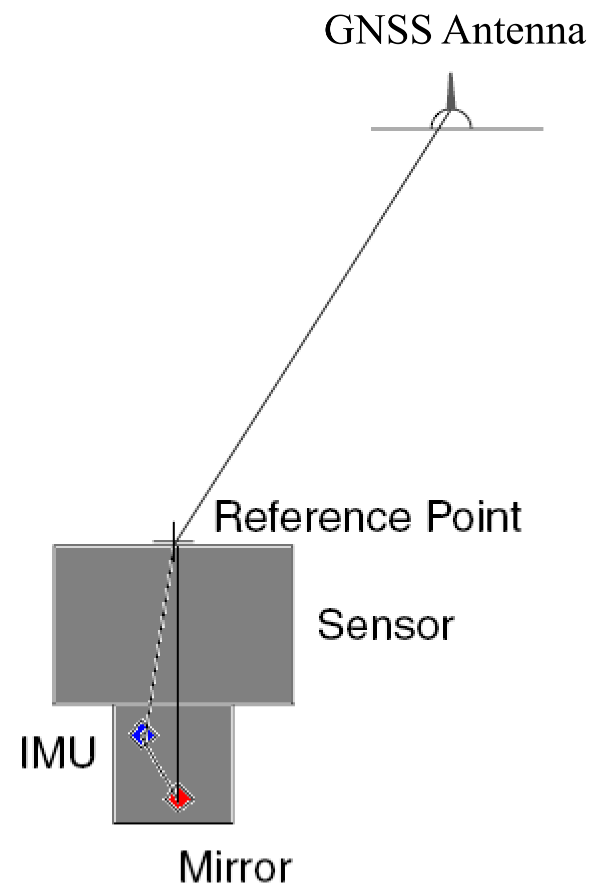
LiDAR QA: System Calibration

- The calibration of a LiDAR system aims at the estimation of systematic errors, which describe the deviation from the assumed theoretical model.
  - One can assume that the derived point cloud after system calibration are only contaminated by random errors.
- Usually accomplished in several steps:
  - Laboratory calibration,
  - Platform calibration, and
  - In-flight calibration

LiDAR QA: System Calibration

- Laboratory Calibration (conducted by the system manufacturer)
  - Calibration of individual system components,
  - Mirror to IMU misalignment,
  - Mirror to IMU lever arm, and
  - Mirror to reference point

- Platform Calibration
  - Reference point to GNSS antenna



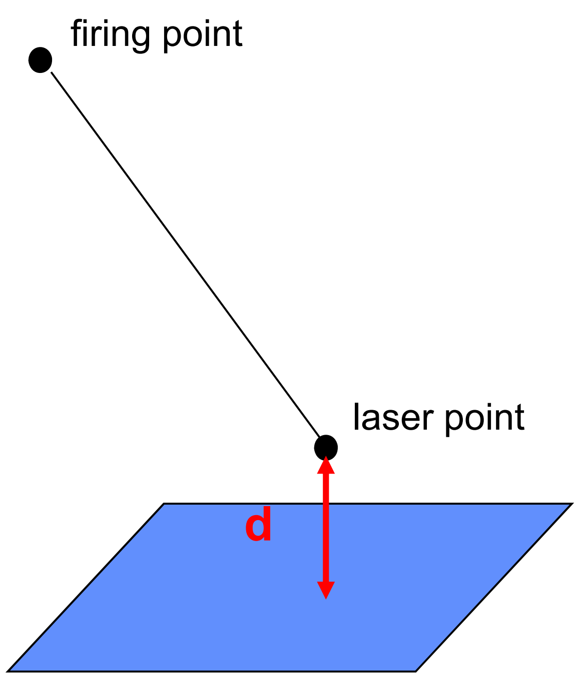
Usually refined during the in-flight calibration

LiDAR QA: System Calibration

- In-Flight Calibration:
  - Utilizes a calibration test field composed of control surfaces for the estimation of biases and systematic errors in the LiDAR system parameters.
  - The observed discrepancies between the LiDAR and control surfaces are used to determine the biases and systematic errors in the system parameters (e.g., boresight roll and pitch angles and scale parameters).

LiDAR QA: System Calibration

- **<u>Target Function:</u>** minimize the normal distance between the laser point footprint and a known (control) surface.
- Use the LiDAR equation to estimate the error parameters that minimize the cost of the target function.
- Caution: flight and control surface configurations should be carefully established.

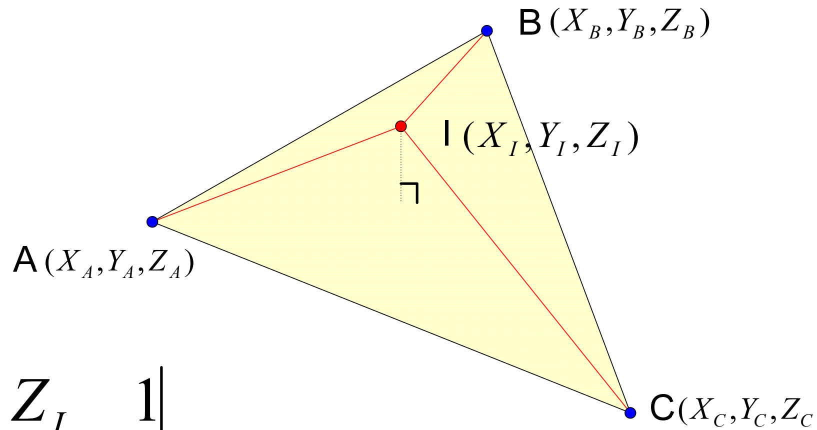


Only possible if we are dealing with a transparent system

LiDAR QA: System Calibration

$$\text{Volume} = \frac{\text{Determinant (D)}}{6} = 0$$

$$\text{Normal Distance} = \frac{\text{Volume}}{\text{Area}}$$



$$D = \begin{vmatrix} X_I & Y_I & Z_I & 1 \\ X_A & Y_A & Z_A & 1 \\ X_B & Y_B & Z_B & 1 \\ X_C & Y_C & Z_C & 1 \end{vmatrix} = 0$$

- (X_I, Y_I, Z_I) coordinates of laser beam footprint
- (X_A, Y_A, Z_A), (X_B, Y_B, Z_B), and (X_C, Y_C, Z_C) ground coordinates of the control patch

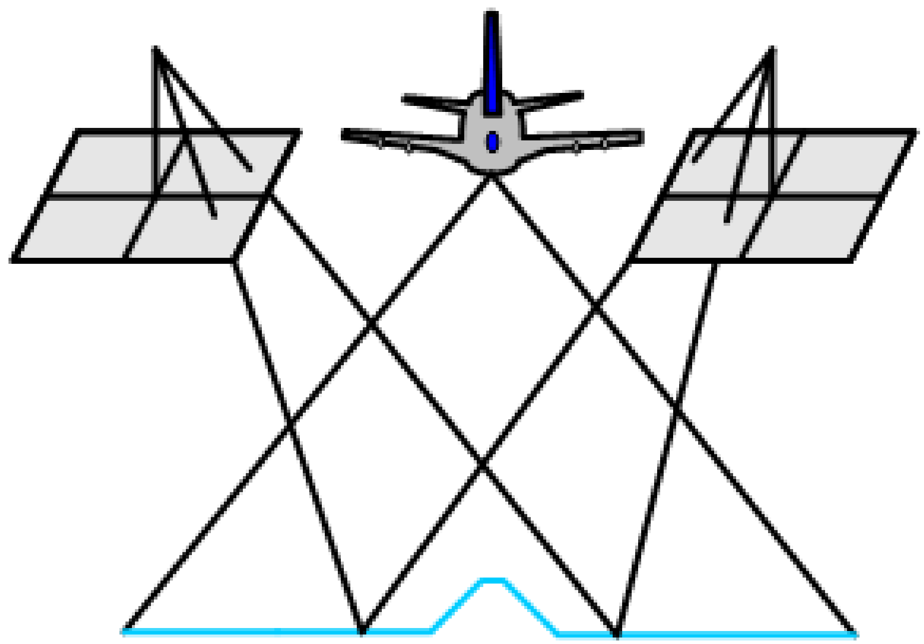
LiDAR QA: System Calibration

$$r_I^m = r_b^m(t) + R_b^m(t)\, r_{lu}^b + R_b^m(t)\, R_{lu}^b\, R_{lb}^{lu}(t)\, r_I^{lb}(t)$$

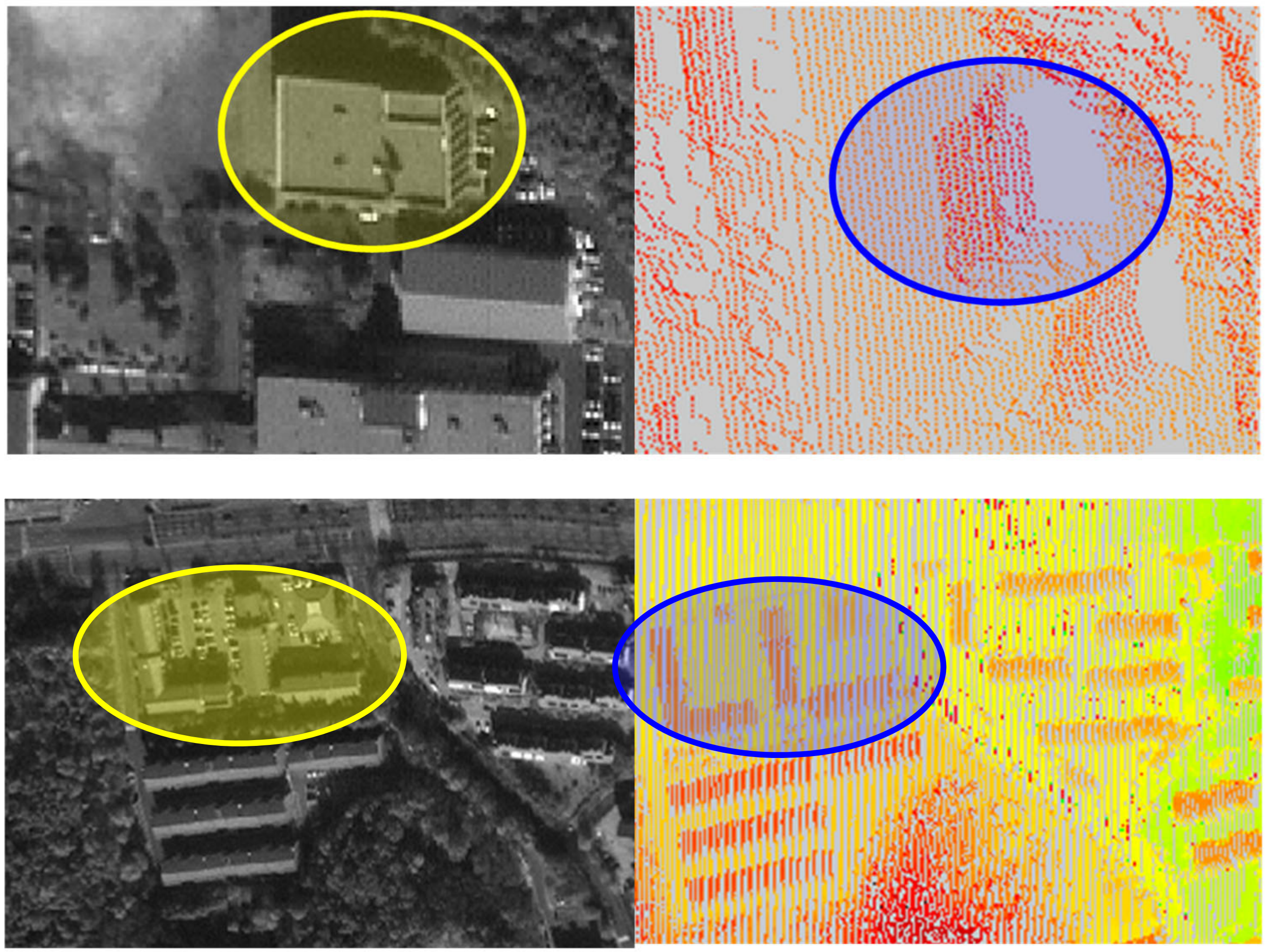
- Target function: determine the system parameters that minimize the determinant values for the given control patches.
- Challenges:
  - How can we acquire control surfaces?
  - LiDAR raw measurements $\{r_b^m(t), R_b^m(t), R_{lb}^{lu}(t), r_I^{lb}(t)\}$ are needed (not always available).

LiDAR QA: System Calibration

- The ground control surface can be generated from a well-calibrated and well-georeferenced photogrammetric system.



LiDAR QA: System Calibration

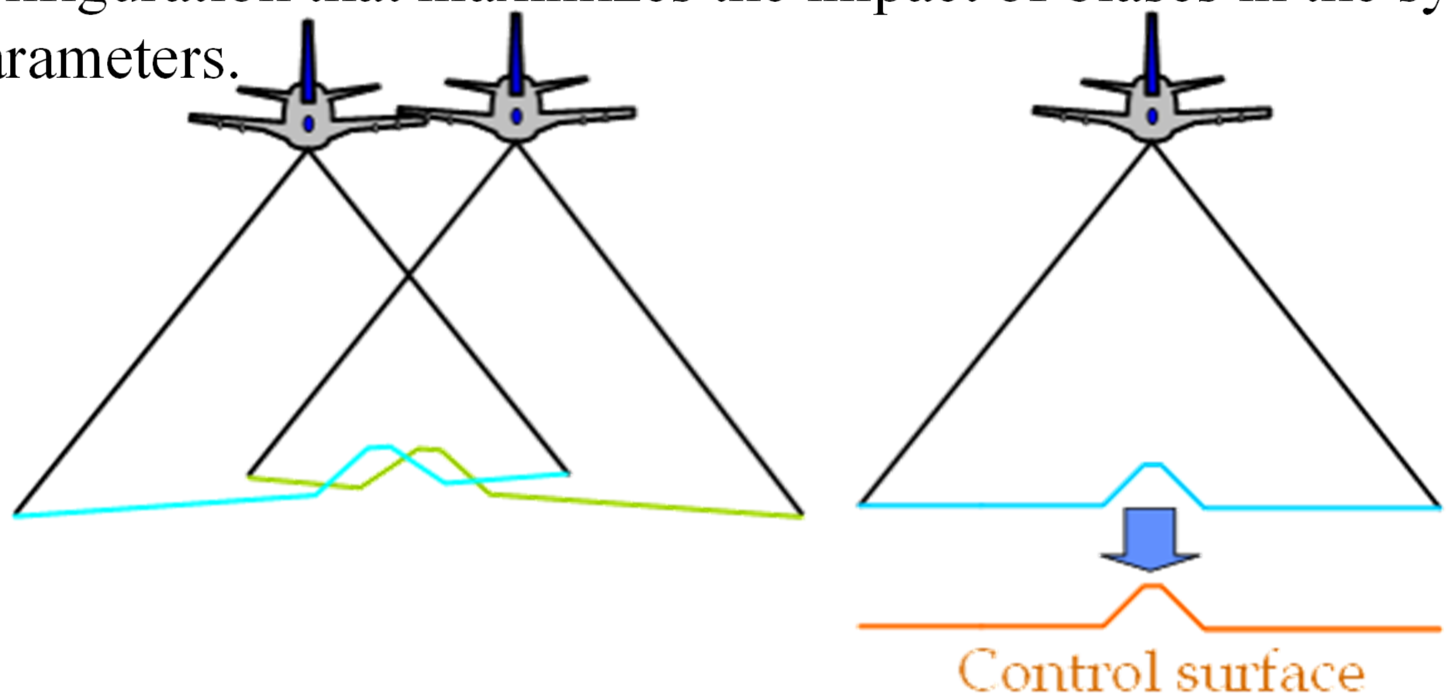


LiDAR QA: System Calibration

- Status of current calibration methods:
  - There is lack of a commonly accepted calibration methodology.
  - System raw measurements are required.
  - Estimated parameters are limited.
  - Manual and empirical approaches are utilized.
  - Calibration sites with control targets are required.
    - For example, buildings and runways
  - Calibration is not possible for end-users using point cloud coordinates in overlapping strips.

LiDAR QA: System Calibration

- Conceptual Basis: Estimate the system parameters that minimize discrepancies between derived surfaces from multiple flight lines while reducing ground control requirements
  - This process requires establishing the optimal flight configuration that maximizes the impact of biases in the system parameters.

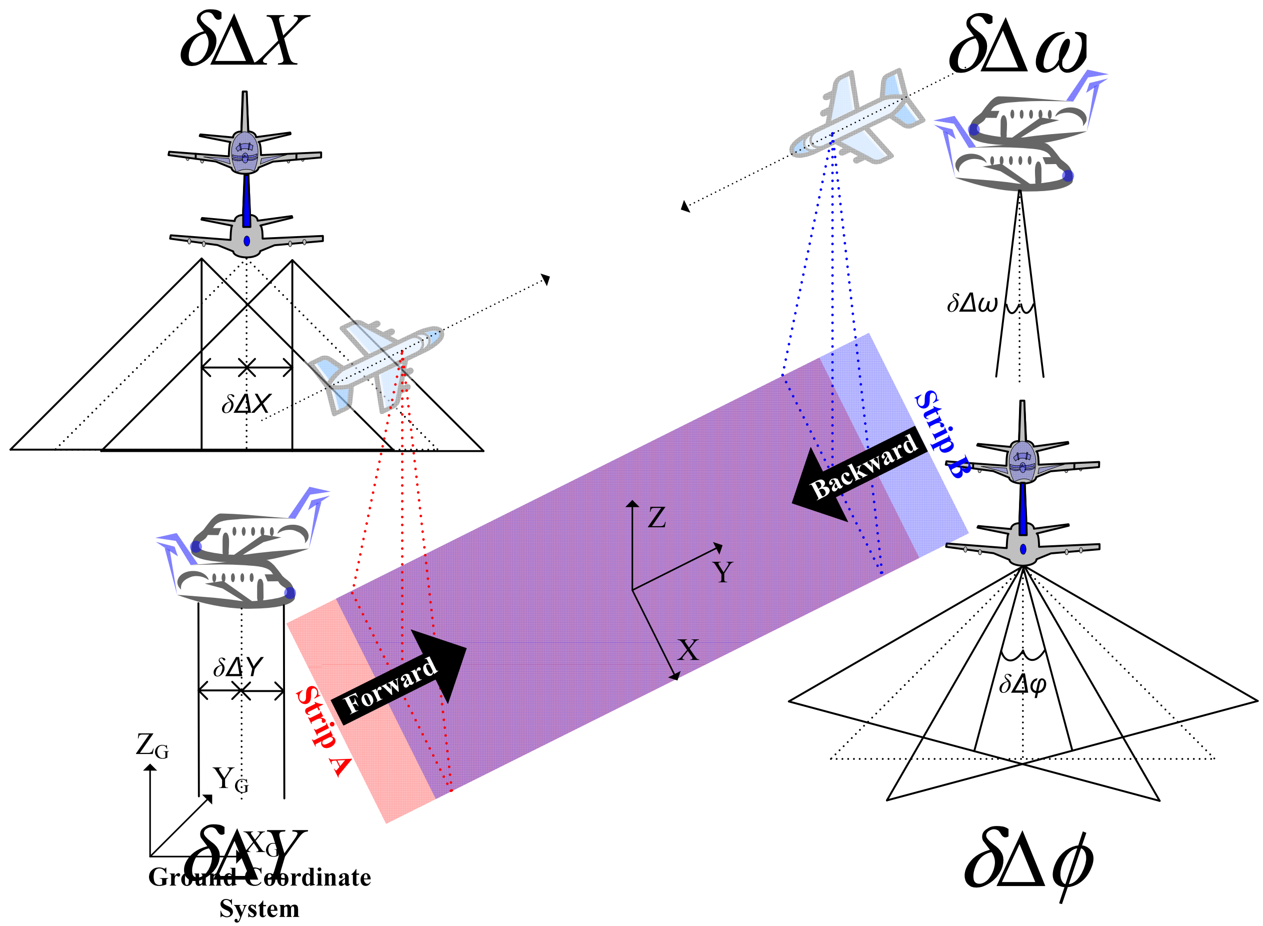


LiDAR QA: System Calibration

Optimum Flight Configuration

Opposite directions with 100% overlap ratio

Biases in system parameters
Lever-arm $\delta\Delta X$
Lever-arm $\delta\Delta Y$
Lever-arm $\delta\Delta Z$
Boresight $\delta\Delta\omega$
Boresight $\delta\Delta\varphi$
Boresight $\delta\Delta\kappa$
Range bias $\delta\Delta\rho$
Scale bias of S.A. δS

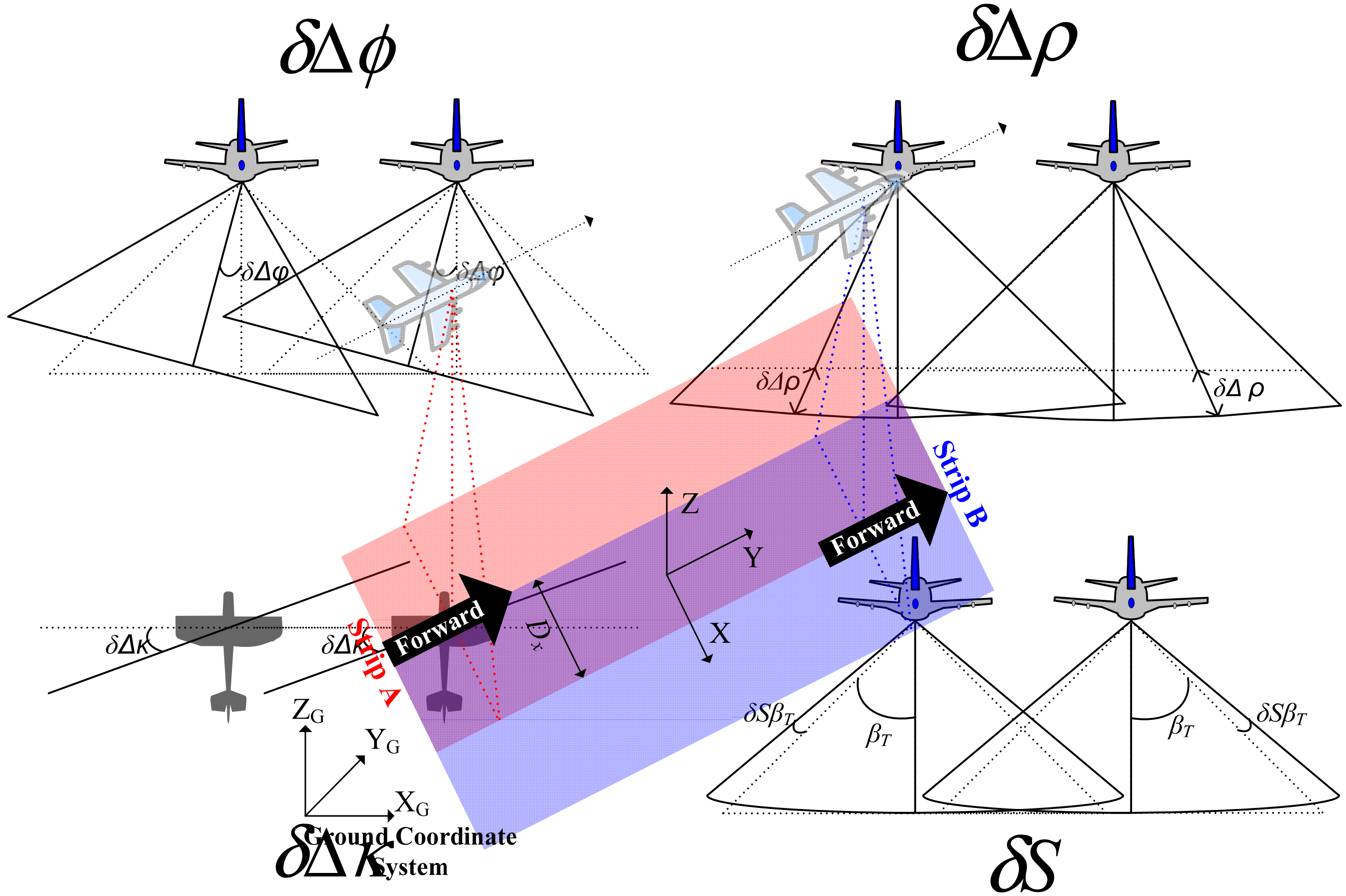


LiDAR QA: System Calibration

Optimum Flight Configuration

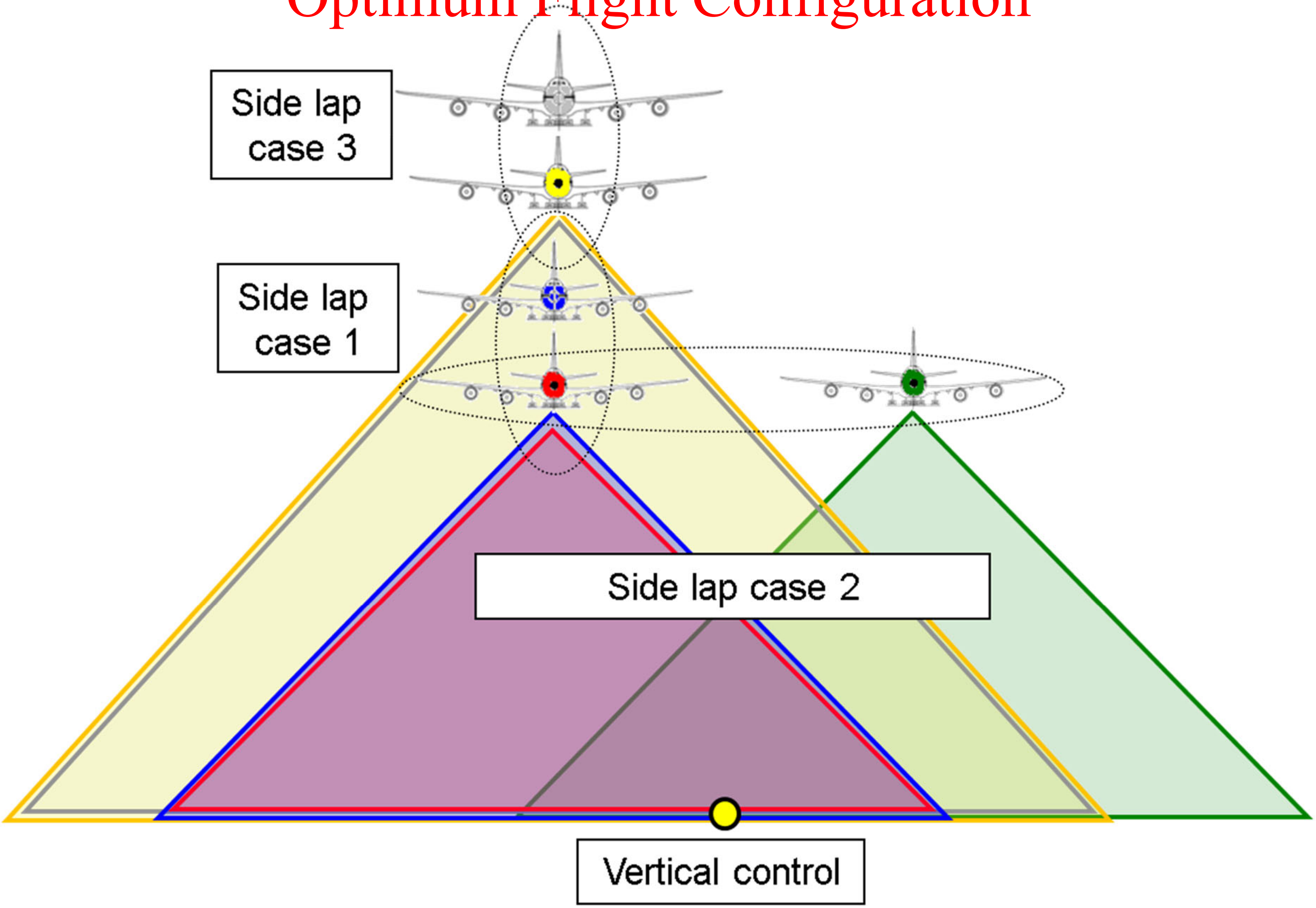
Same direction with some sidelap

Biases in system parameters
Lever-arm $\delta\Delta X$
Lever-arm $\delta\Delta Y$
Lever-arm $\delta\Delta Z$
Boresight $\delta\Delta\omega$
Boresight $\delta\Delta\varphi$
Boresight $\delta\Delta\kappa$
Range bias $\delta\Delta\rho$
Scale bias of S.A. δS



LiDAR QA: System Calibration

Optimum Flight Configuration



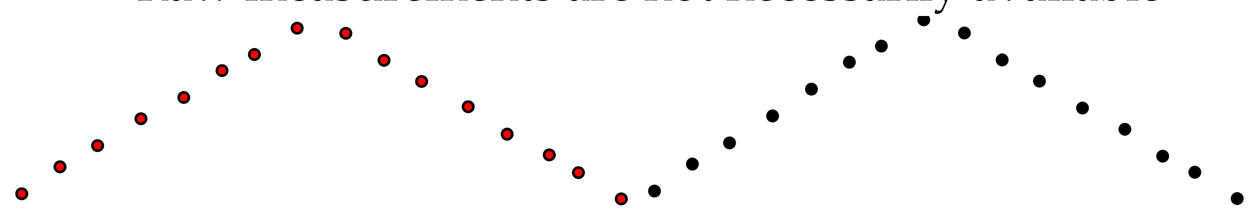
LiDAR QA: System Calibration

- Several LiDAR system calibration techniques can be introduced according to the nature of available data.
  - **Simplified Calibration:** With some constraints on the flight configuration and ground coverage, we can conduct the calibration using only the point cloud coordinates.
  - **Quasi-Rigorous Calibration:** Using the trajectory data and time-tagged point cloud coordinates, we can estimate the system parameters with fewer constraints on the flight configuration.
  - **Rigorous Calibration:** With the availability of raw measurements, the calibration can be conducted without any assumptions regarding the flight configuration and ground coverage.

LiDAR QA: System Calibration

Simplified Calibration

- LiDAR Data in Overlapping Parallel Strips
  - ✓ Point cloud coordinates
  - ✓ Raw measurements are not necessarily available



Overlapping strips

Discrepancies

3D Transformation

Rotation

Shifts

→ **Calibration Parameters**

LiDAR QA: System Calibration

Simplified Calibration

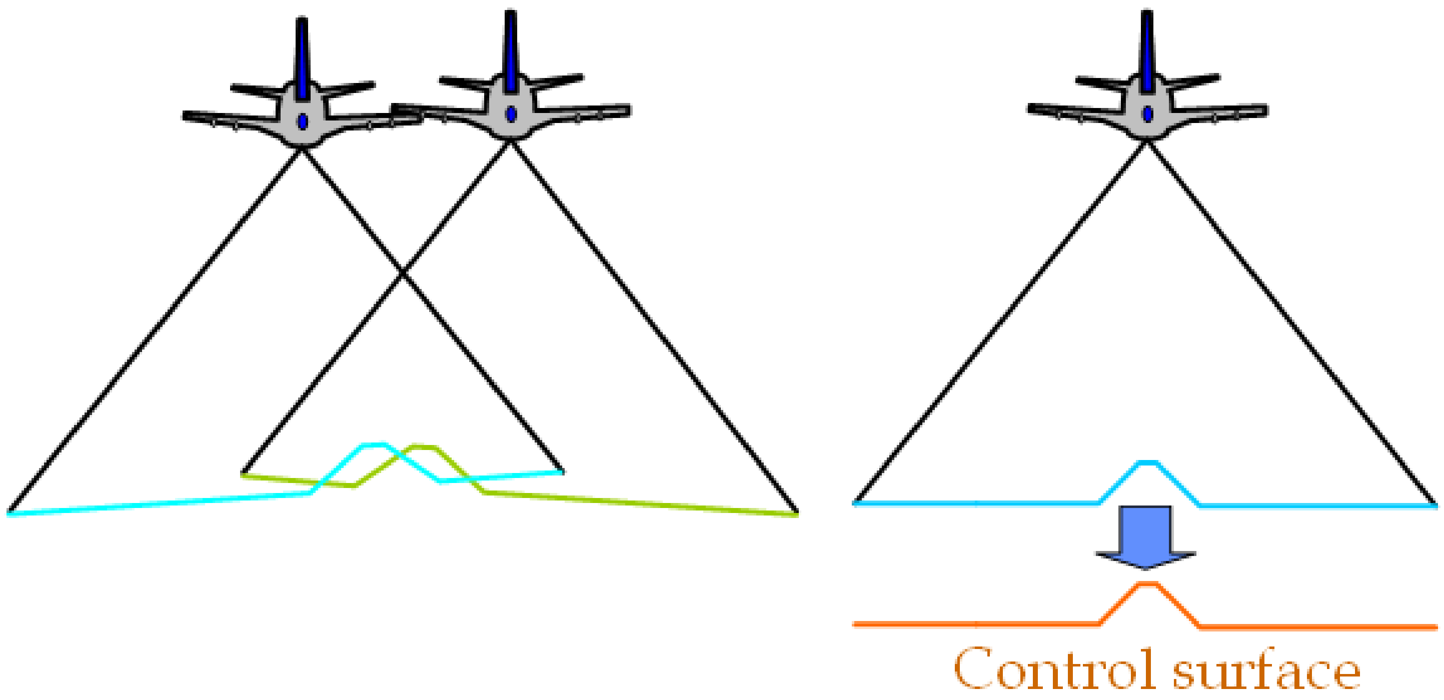
- LiDAR Data in Overlapping Parallel Strips
  - ✓ Point cloud coordinates
  - ✓ Raw measurements are not necessarily available

- Assumptions:
  - o Linear scanner,
  - o Vertical scanner,
  - o Parallel flight lines,
  - o Terrain-height variations are minimal compared to the flying height, and
  - o Small biases in the boresight angles
- Can handle any type of terrain coverage
- Cannot handle control points

LiDAR QA: System Calibration

Quasi-Rigorous Calibration

- LiDAR Data in Overlapping Strips
  - ✓ Point cloud coordinates with the time tag
  - ✓ Time-tagged trajectory



LiDAR QA: System Calibration

Quasi-Rigorous Calibration

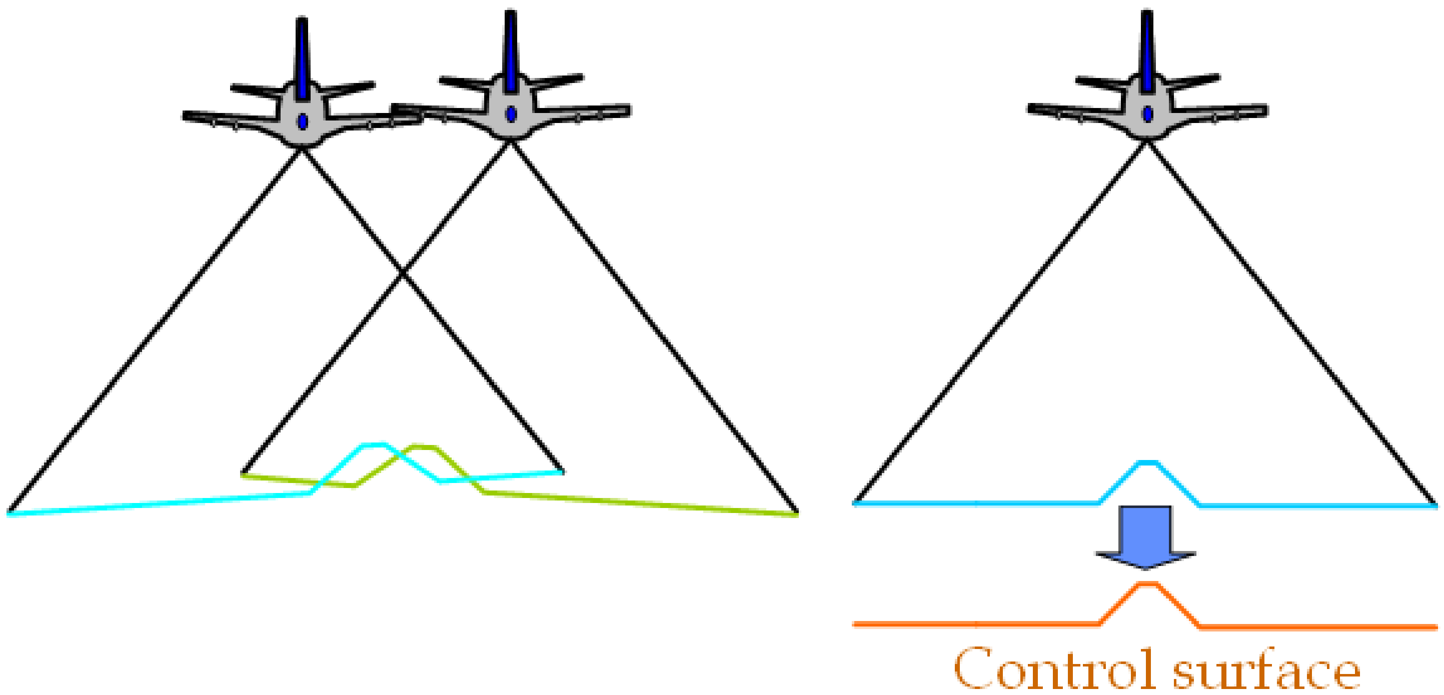
- LiDAR Data in Overlapping Strips
  - ✓ Point cloud coordinates with the time tag
  - ✓ Time-tagged trajectory

- Assumptions:
  - Vertical scanner,
  - Small biases in the boresight angles
- Can handle parallel & cross strips
- Can handle any type of terrain coverage
- Can handle control points

LiDAR QA: System Calibration

Rigorous Calibration

- LiDAR Data in Overlapping Strips
  - ✓ Point cloud coordinates together with the system raw measurements (position and the attitude of each pulse as well as the measured scan angles and ranges)



LiDAR QA: System Calibration

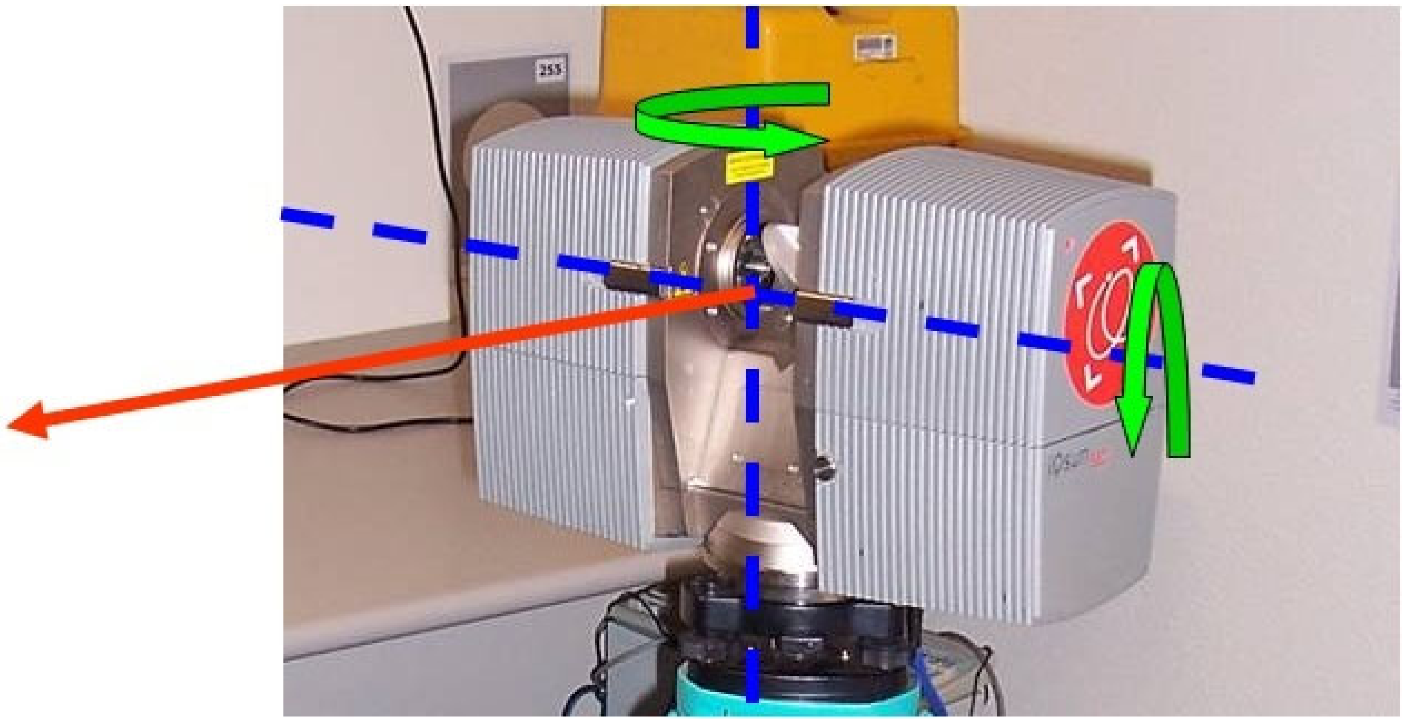
Rigorous Calibration

- LiDAR Data in Overlapping Strips
  - ✓ Point cloud coordinates together with the system raw measurements (position and the attitude of each pulse as well as the measured scan angles and ranges)

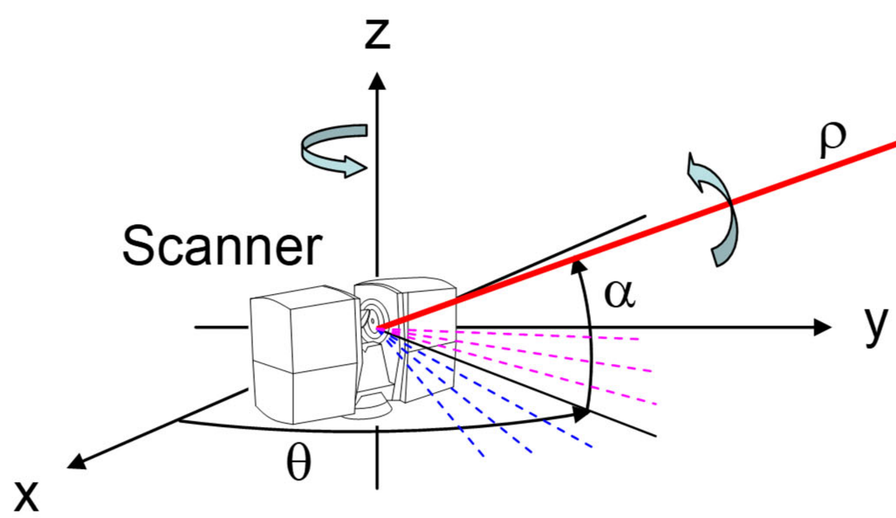
- Assumptions:
  - None
- Can handle parallel & cross strips
- Can handle any type of terrain coverage
- Can handle control points

Static System Calibration

- Sensor modelling is a pre-requisite to the system calibration process.



Static System Calibration

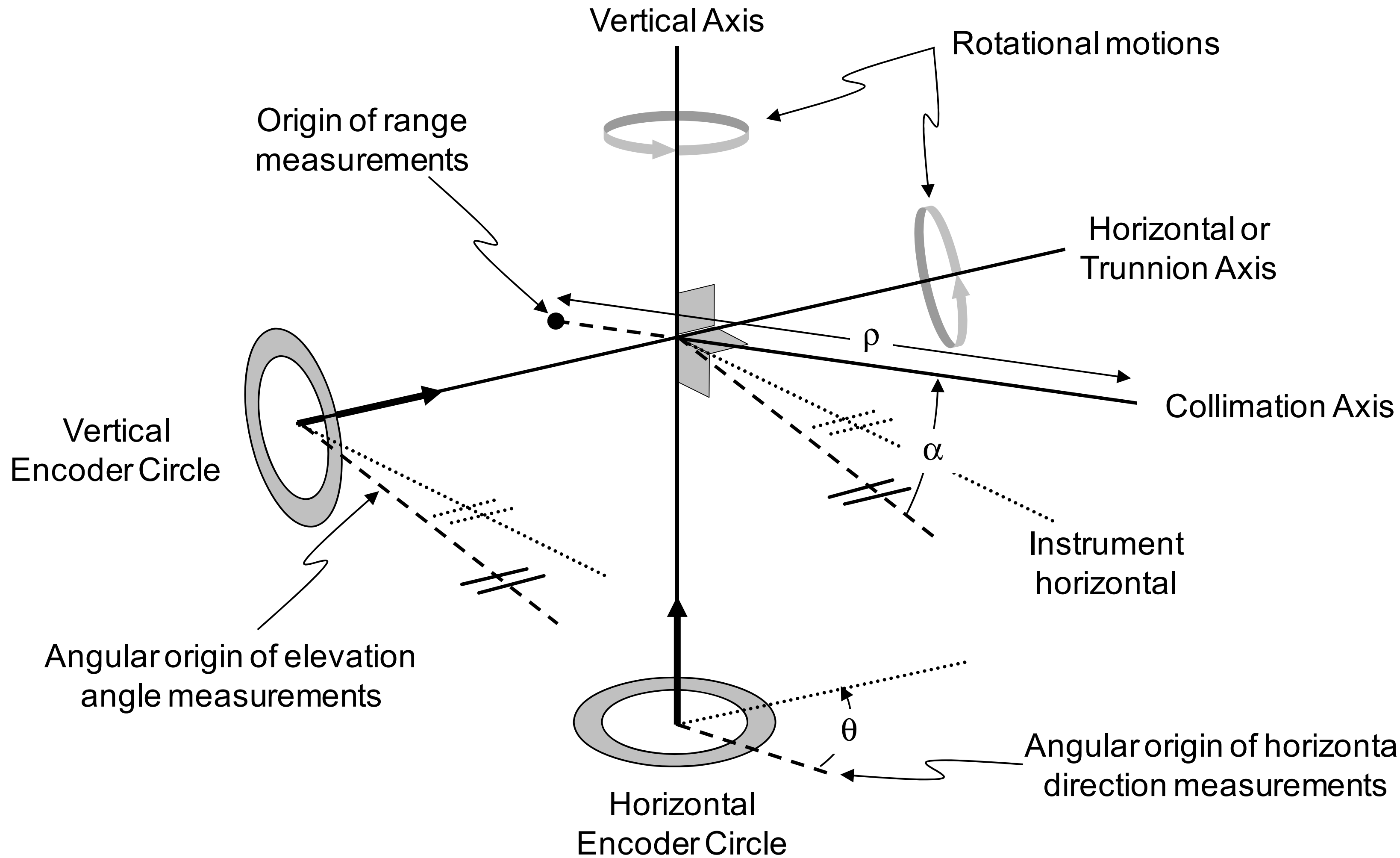


Point cloud

- Observations:
  - Horizontal circle reading (θ)
  - Vertical circle reading (α)
  - Range (ρ)

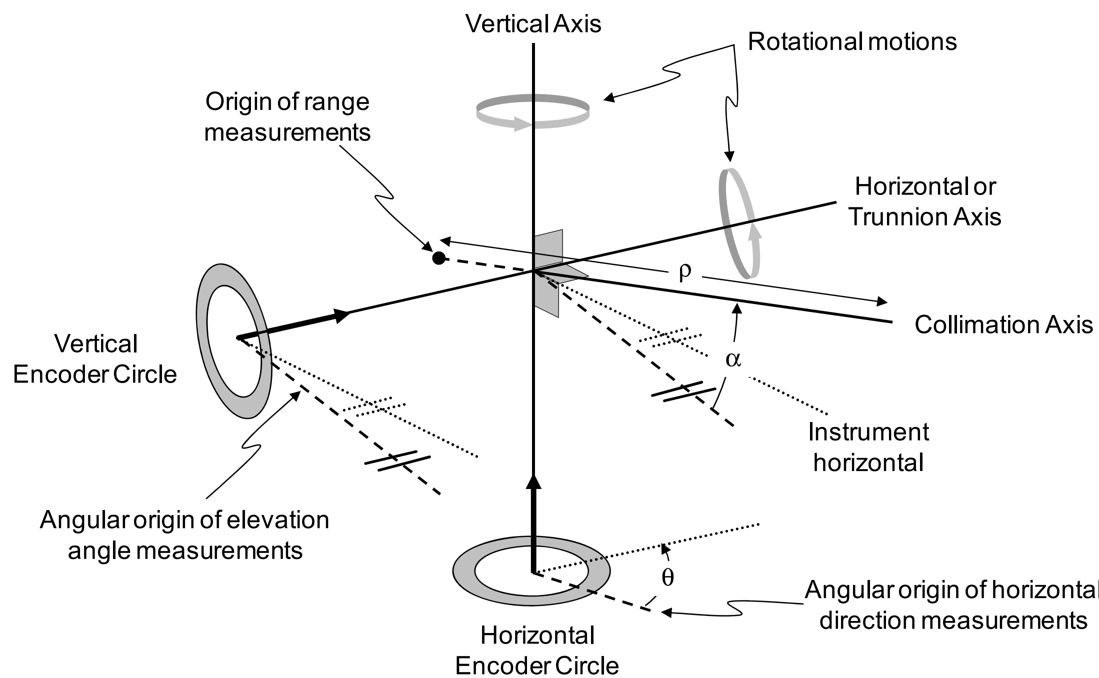
Static System Calibration

Ideal scanner model



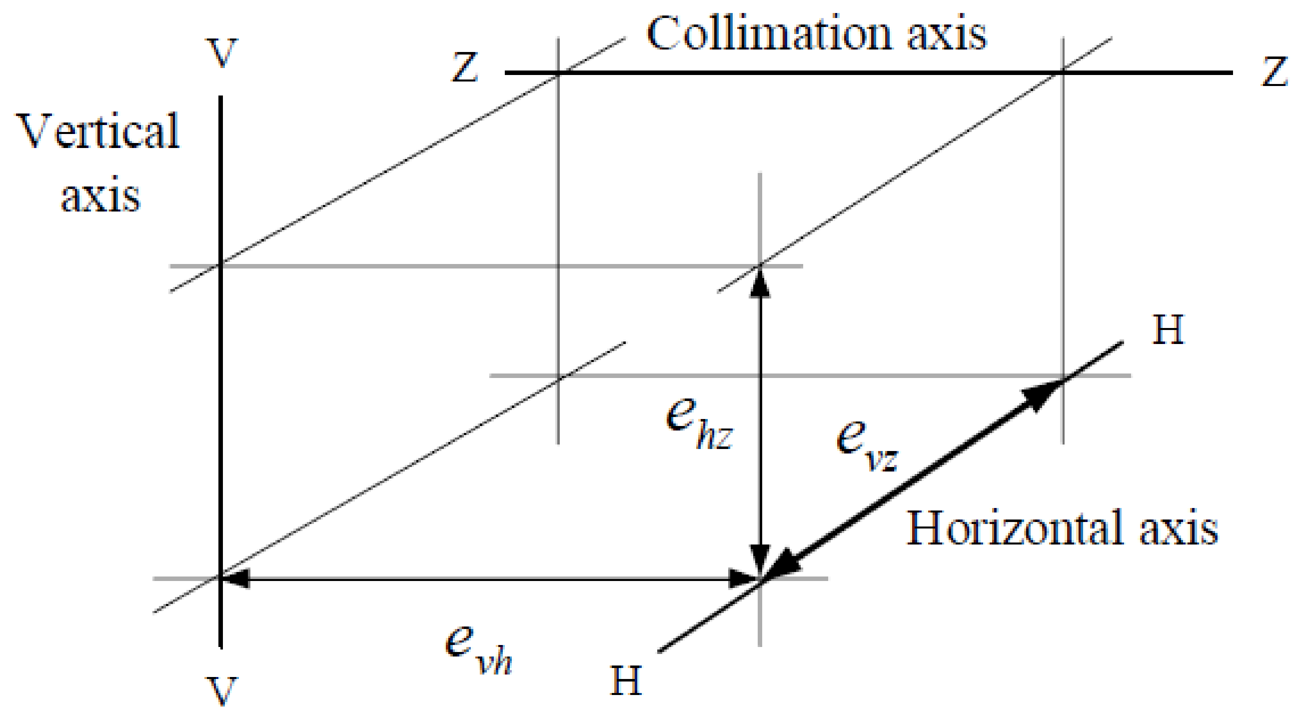
Static System Calibration

- Assumptions for the **Ideal Scanner Model**:
  - Trunnion, vertical, and collimation axes intersect at a single point (laser beam firing point).
  - Trunnion, vertical, and collimation axes are orthogonal to each other.



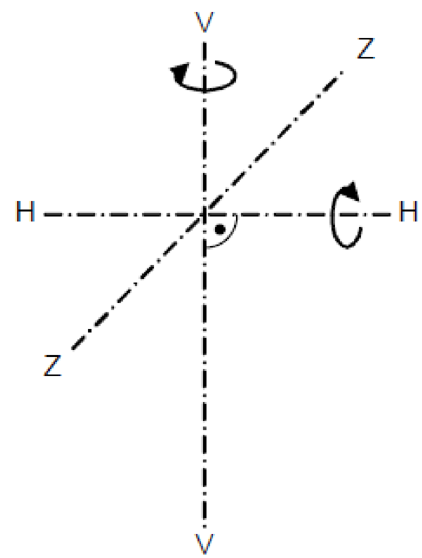
Static System Calibration

- Deviations from the Ideal Scanner Model (1):
  - ***Trunnion-Vertical axes eccentricity*** *(e_{vh})*
  - ***Vertical-Collimation axes eccentricity*** *(e_{vz})*
  - ***Trunnion-Collimation axes eccentricity*** *(e_{hz})*



Static System Calibration

- Deviations from the Ideal Scanner Model (2):
  - ***Range error:*** Additive and scale errors
  - ***Trunnion axis error:*** *Non-orthogonality of the trunnion and vertical axes*
  - ***Horizontal collimator error:*** *Non-orthogonality of the trunnion and collimator axes*
  - ***Vertical index error:*** *Constant error in the vertical angle reading*



Static System Calibration

- Functional Model for System Calibration

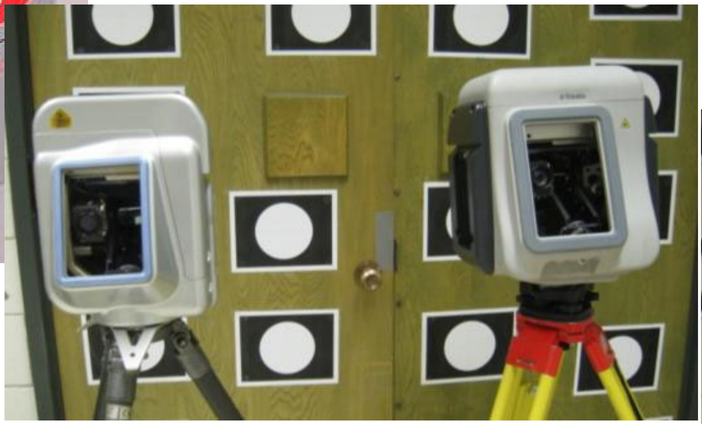
- $r_I^{lu} = R_{lb}^{lu}(\alpha + \Delta\alpha, \theta + \Delta\theta) \begin{bmatrix} 0 \\ 0 \\ -(S_\rho \rho + \Delta\rho) \end{bmatrix}$

- $\Delta\alpha \; and \; \Delta\theta = f(eccentricities, trunion \; axis \; error, horizontal \; collimation \; error, and \; vertical \; index \; error)$

- The systematic errors can be estimated using either:
  - Control targets
  - Planar features

Static System Calibration

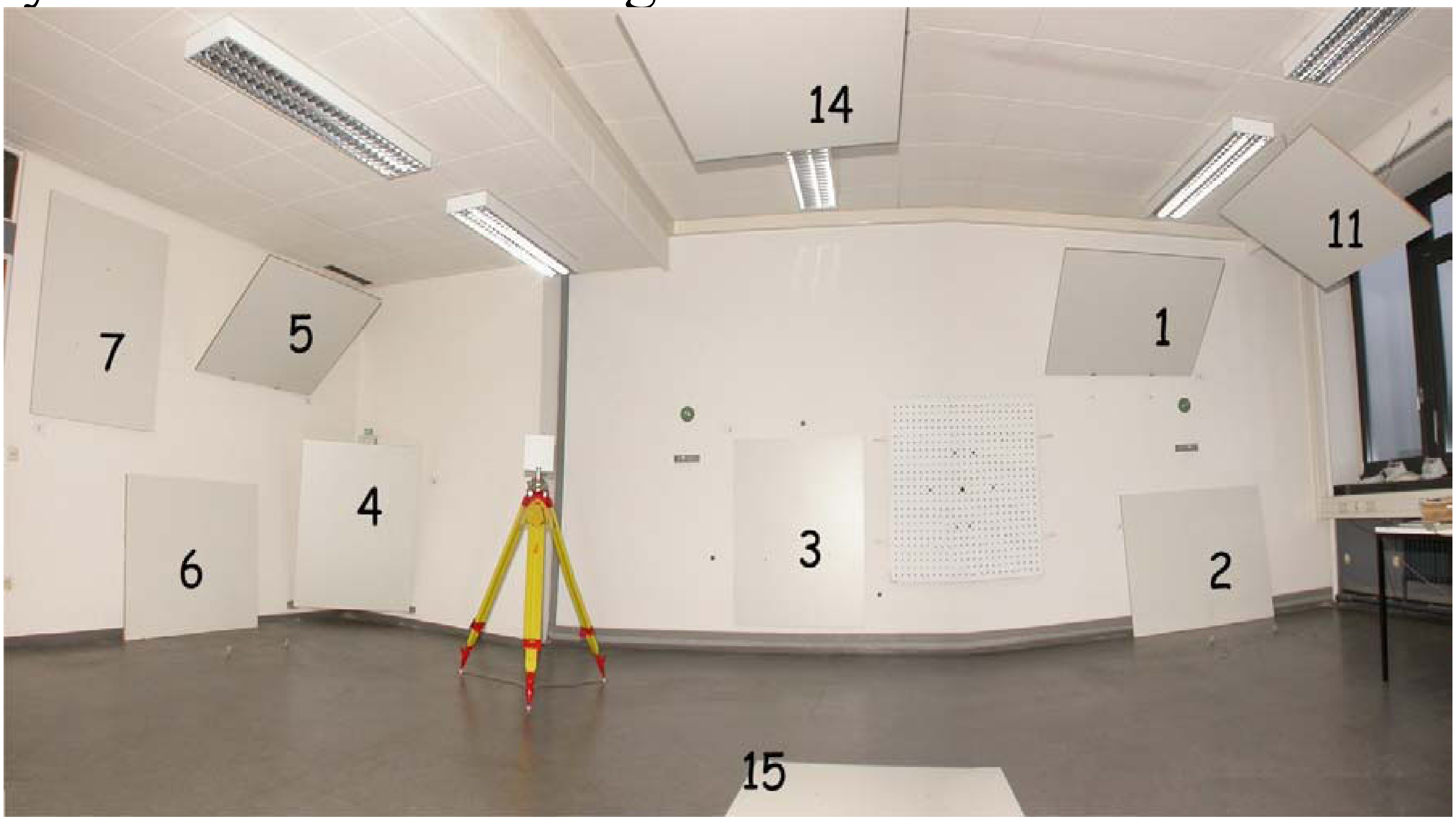
- System Calibration using Control Points/Targets



- **Objective:** Minimize the differences between the TLS derived coordinates and independently measured coordinates of the targets

Static System Calibration

- System Calibration using Planar Features



- **Objective:** Minimize the differences between the TLS derived coordinates and a planar surface

LiDAR Quality Control

- Quality control is a post-mission procedure to ensure/verify the quality of collected data.
- Quality control procedures can be divided into two main categories:
  - **External/absolute QC measures:** the LiDAR point cloud is compared with an independently collected surface.
    - Check point analysis
  - **Internal/relative QC measures:** the LiDAR point cloud from different flight lines is compared with each other to ensure data coherence, integrity, and correctness.

LiDAR Quality Control

- Accuracy of the system components

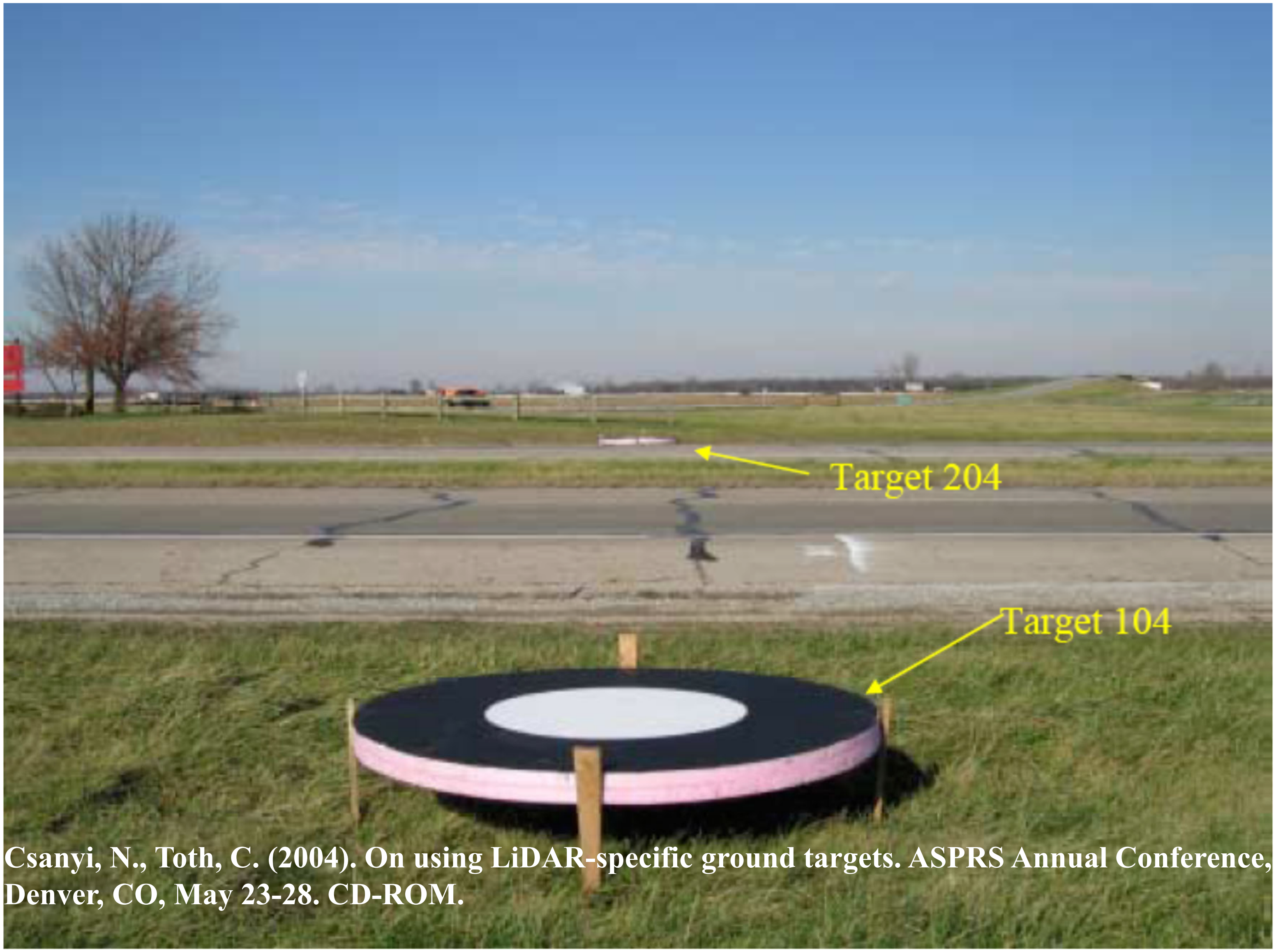
System Model	GPS (m) Post-Processed	IMU (deg) Post-Processed			Scan Angle (deg)	Laser Range (cm)
		Roll	Pitch	Heading		
ALTM 2050	0.05 – 0.3	0.008	0.008	0.015	0.009	~ 2
ALTM 3100	0.05 – 0.3	0.005	0.005	0.008	0.009	~ 2

- System Manufacturer Specification (Optech: ALTM 2050 and ALTM 3100)
  - Horizontal accuracy : 1/2000 x altitude
  - Vertical accuracy : <15 cm at 1200 m
    : <25 cm at 2000 m

Quality Control using LiDAR Targets

- External/absolute quality control measures (EQC):
  - Similar to photogrammetric quality control, the derived LiDAR coordinates can be compared with independently surveyed targets.
    - Check point analysis
  - Problem: How can we correlate the non-selective LiDAR footprints to the utilized check points?
  - Solution: Use specially designed targets.
    - The target design depends on the involved LiDAR system and collected data.
  - Caution: the data collection should be carried out under normal operational circumstances.
    - Same flying height, point density, etc.

EQC: LiDAR Control Targets

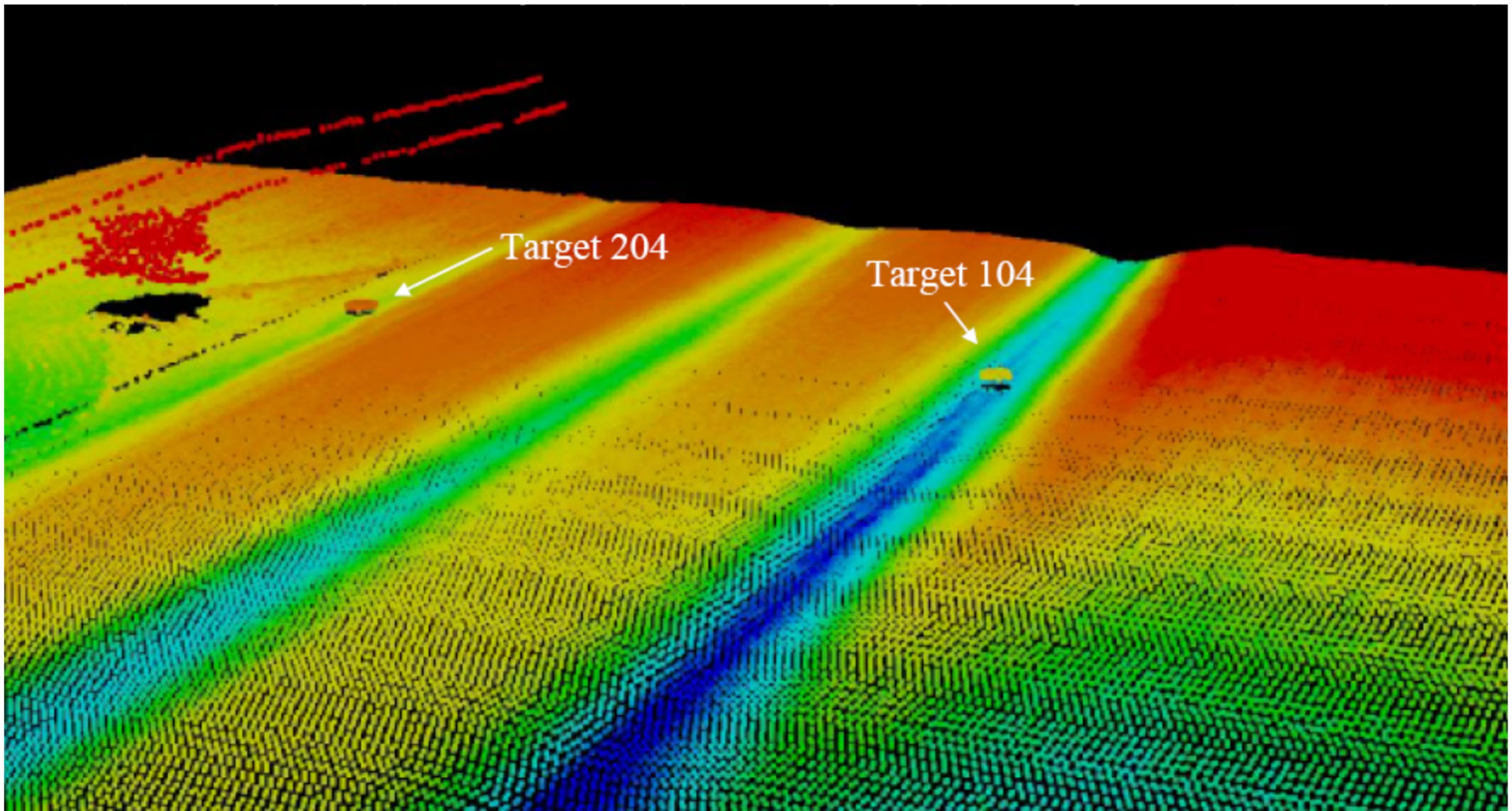


Csanyi, N., Toth, C. (2004). On using LiDAR-specific ground targets. ASPRS Annual Conference, Denver, CO, May 23-28. CD-ROM.

EQC: LiDAR Control Targets

Csanyi, N., Toth, C. (2004). On using LiDAR-specific ground targets. ASPRS Annual Conference, Denver, CO, May 23-28. CD-ROM.

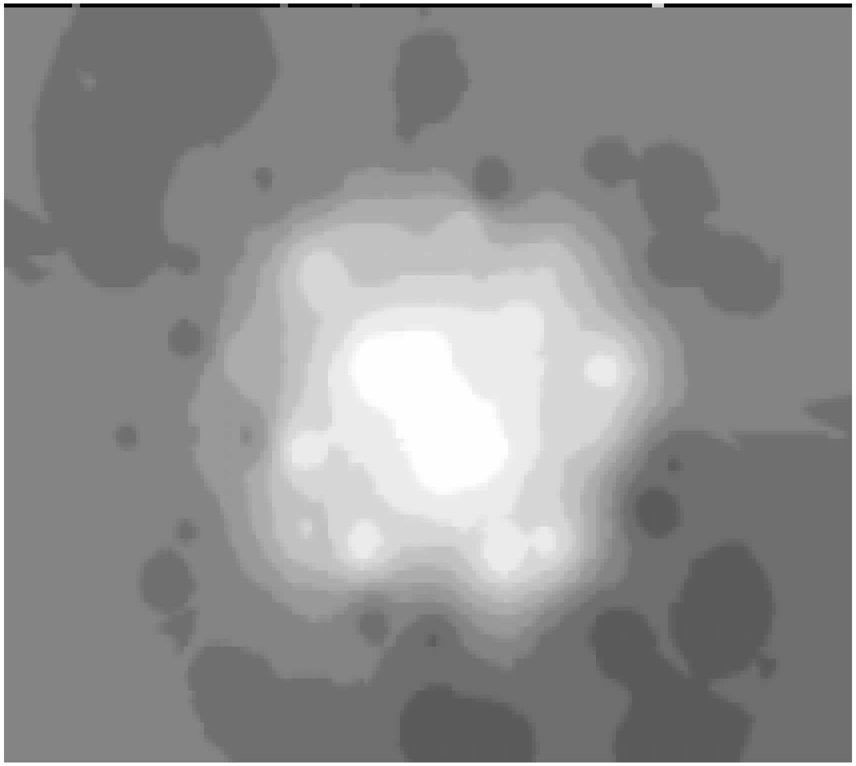
EQC: LiDAR Control Targets



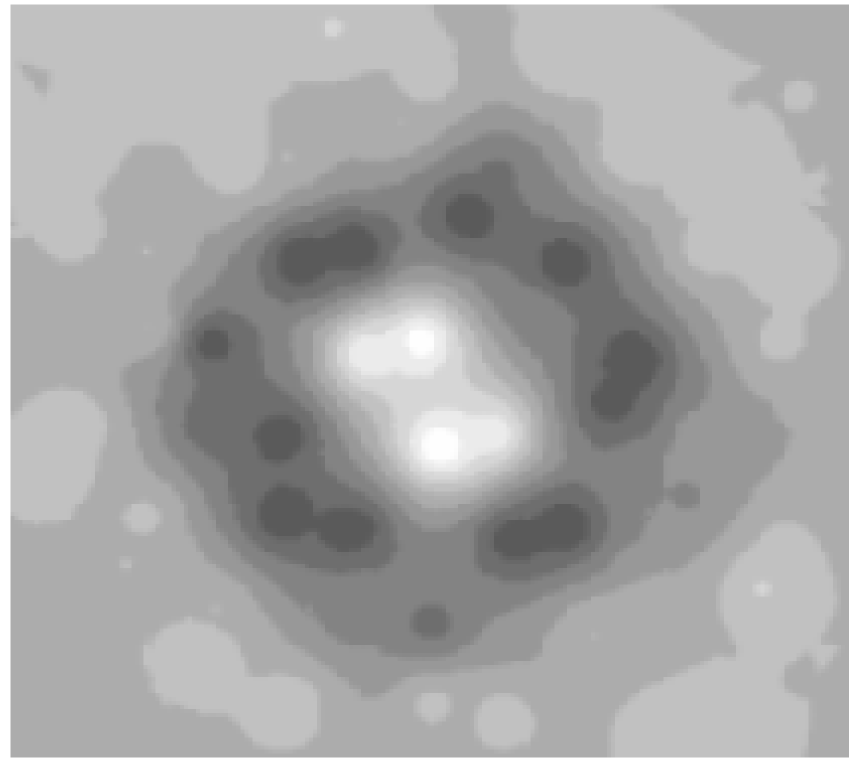
Csanyi, N., Toth, C. (2004). On using LiDAR-specific ground targets. ASPRS Annual Conference, Denver, CO, May 23-28. CD-ROM.

EQC: LiDAR Control Targets

Csanyi, N., Toth, C. (2004). On using LiDAR-specific ground targets. ASPRS Annual Conference, Denver, CO, May 23-28. CD-ROM.



Range Data



Intensity Data

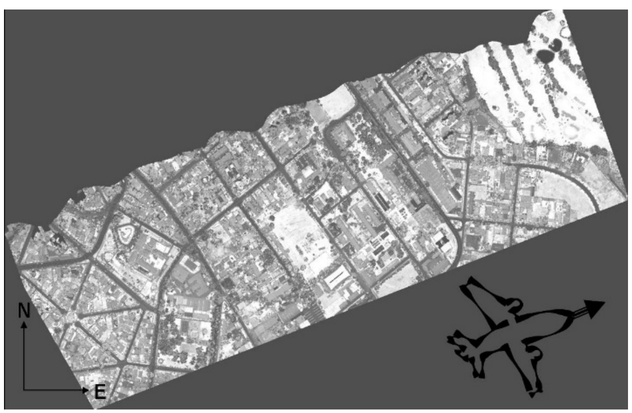
- One should implement a segmentation procedure to derive the LiDAR coordinates of the target.

IQC: LiDAR Quality Control

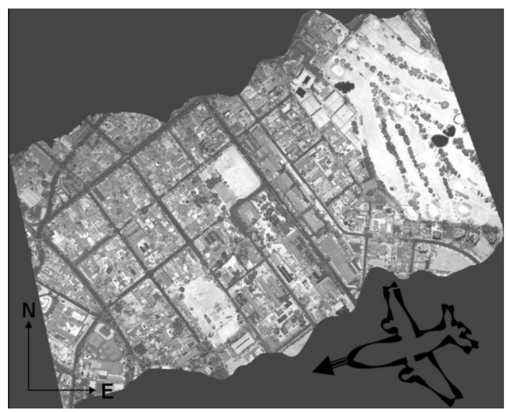
- Surface reconstruction from LiDAR does not have redundancy.
  - Therefore, we do not have explicit measures in the derived surfaces to assess the quality of LiDAR-derived surfaces.
- Users should have other measures to evaluate the internal quality of the derived LiDAR surfaces (IQC).
- Alternative methodologies are based on the:
  - Coincidence of conjugate features in overlapping strips

LiDAR Internal QC

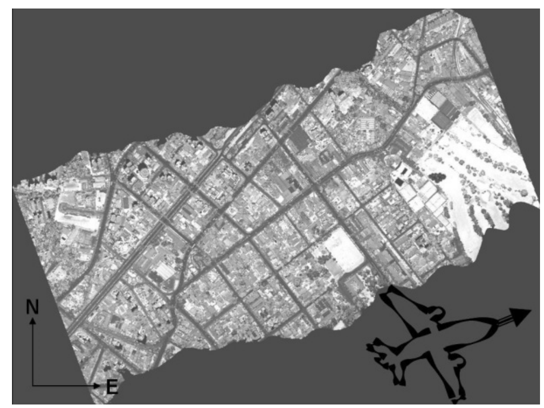
- Surface reconstruction from LiDAR does not have redundancy.
  - Therefore, we do not have explicit measures to assess the quality of LiDAR coordinates.
- <u>**Proposed Concept**</u>: Evaluate the degree of consistency among the LiDAR footprints in overlapping strips.



Strip 2



Strip 3

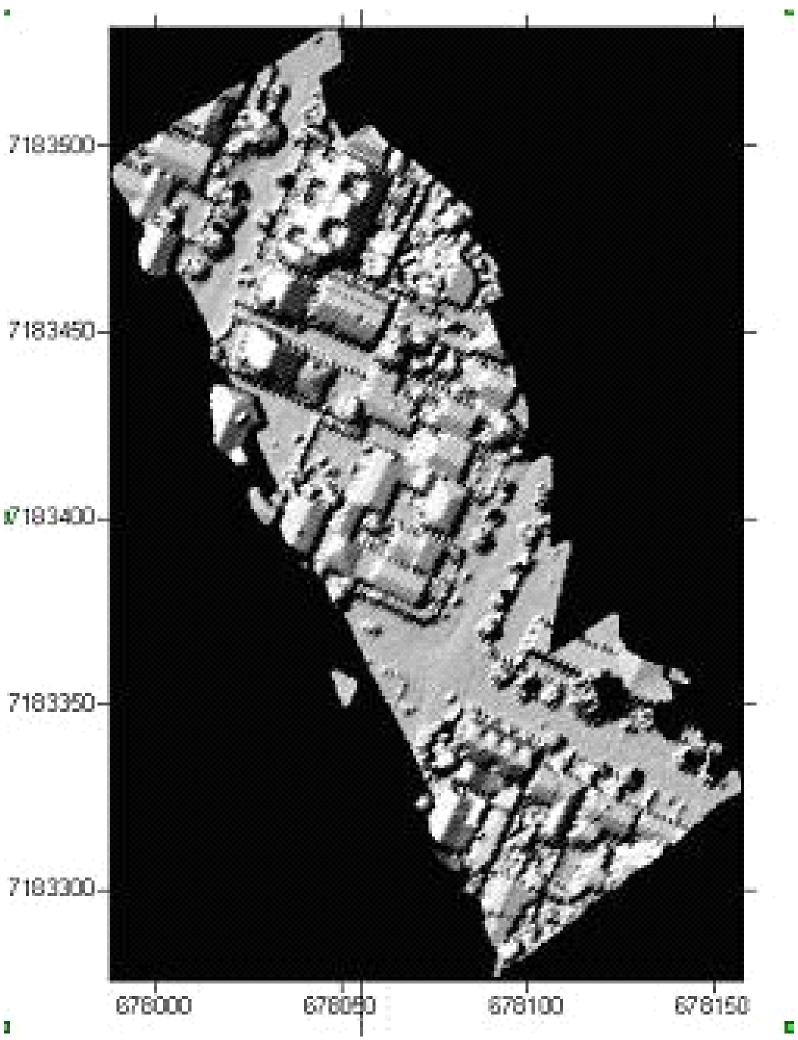


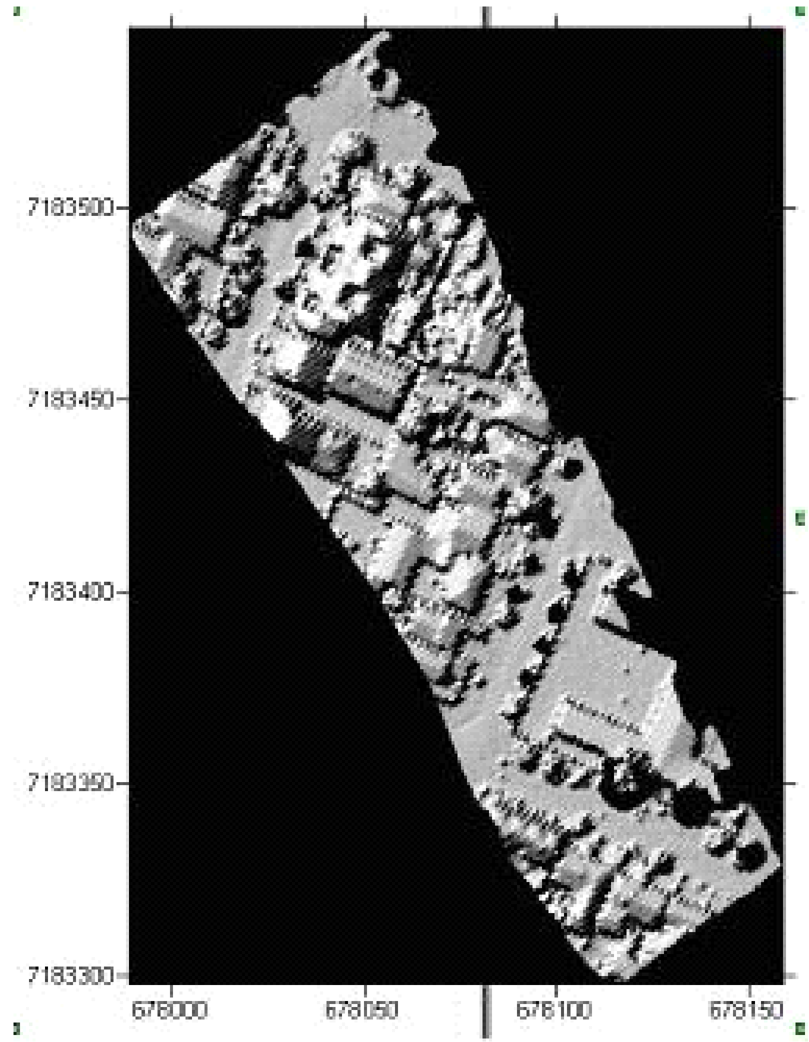
Strip 4

IQC: LiDAR Quality Control

- LiDAR strips are usually collected with some overlap coverage in the object space.
- A common procedure for quality control is to check the quality of coincidence of common features in overlapping strips.
- Three approaches are possible:
  - **First approach:** quality control using interpolated range or intensity images from overlapping strips
  - **Second approach:** quality control using extracted features from overlapping strips
  - **Third approach:** quality control using the original point cloud

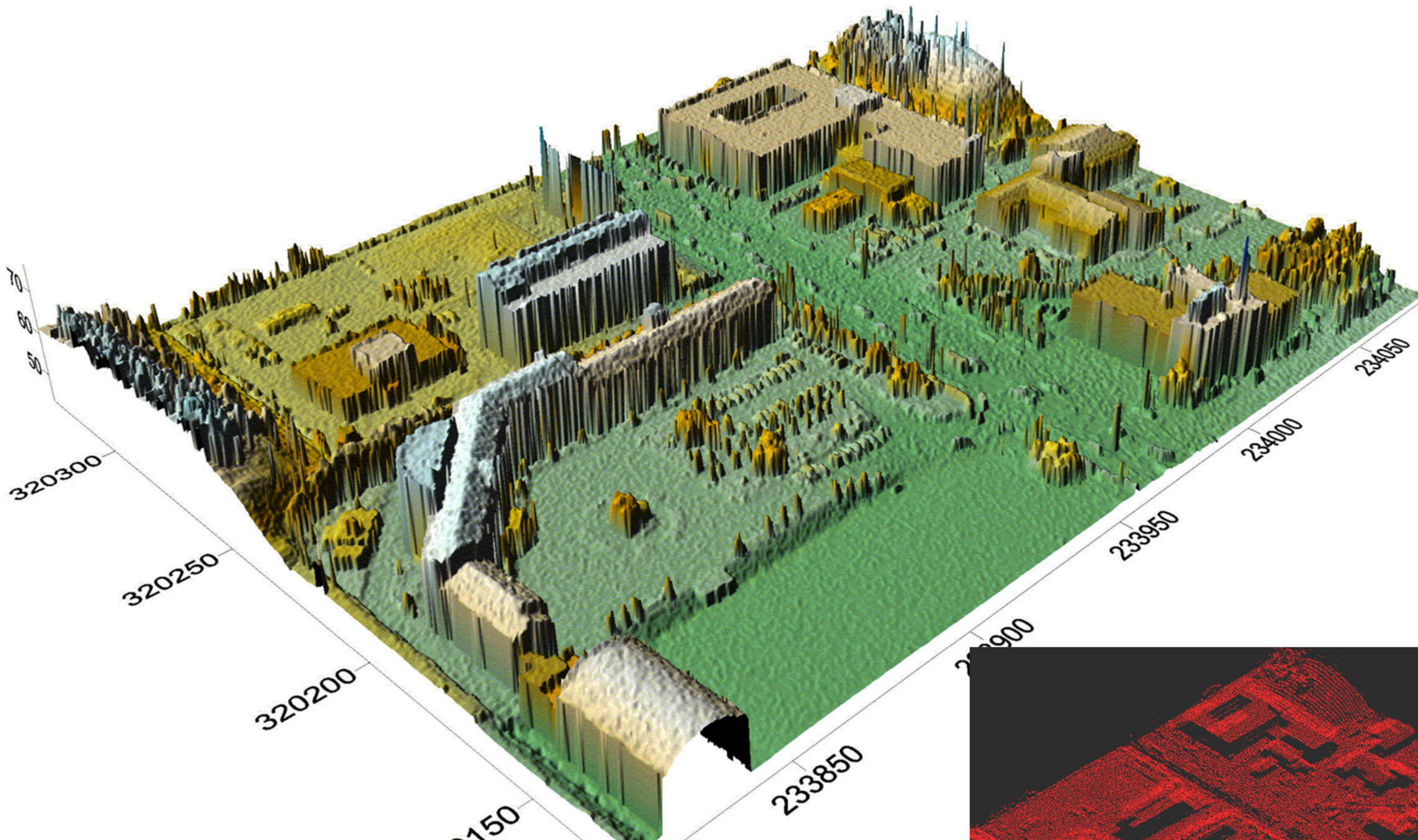
IQC: LiDAR Quality Control

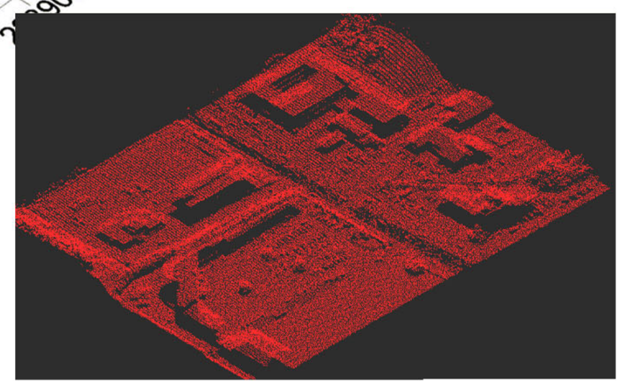




Overlapping strips with common features

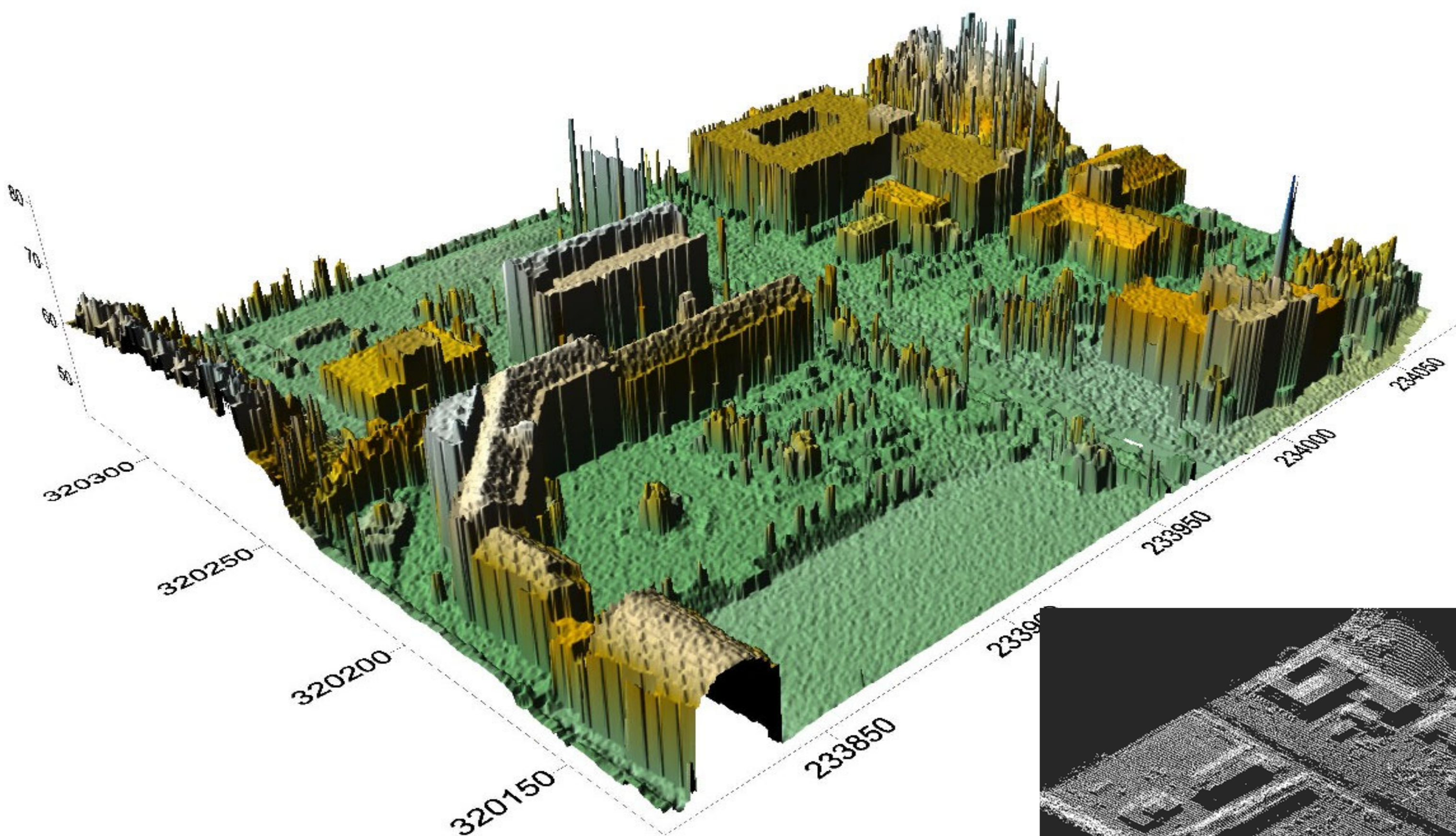
IQC: LiDAR Quality Control

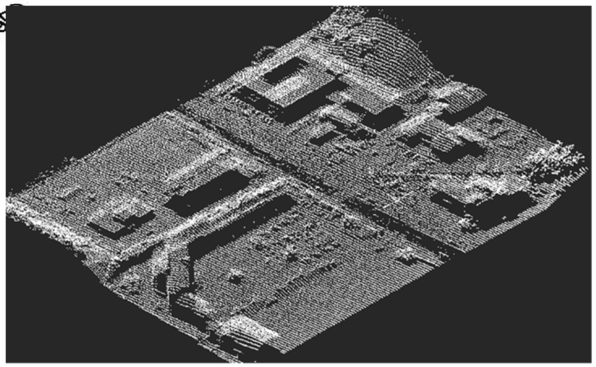




First Strip

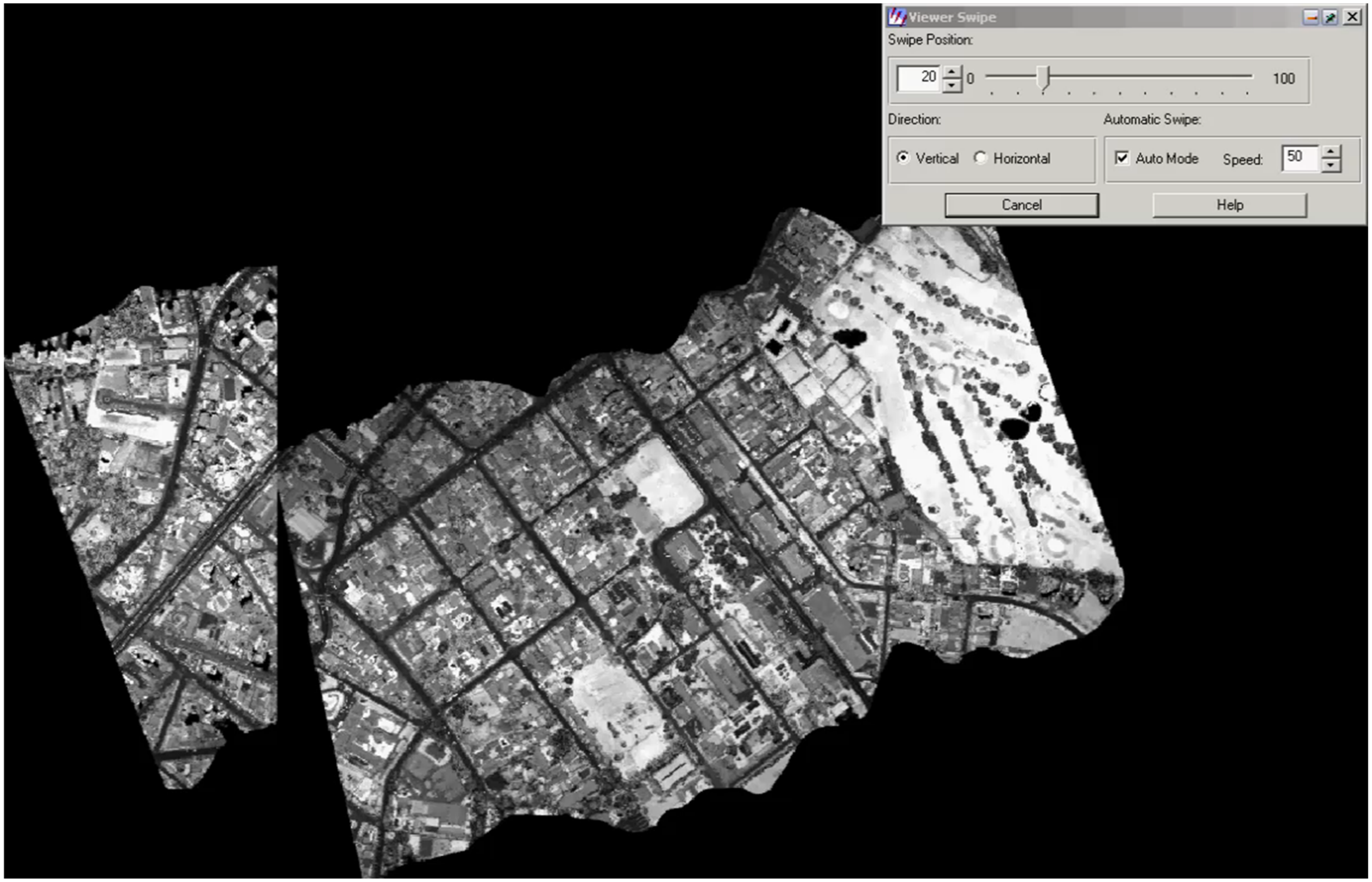
IQC: LiDAR Quality Control



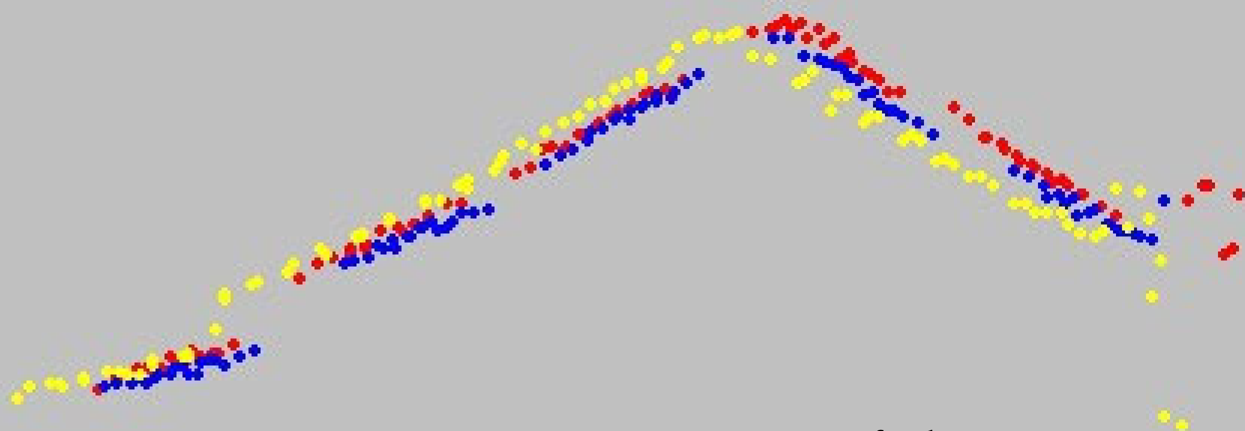


Second Strip

LiDAR Internal QC



LiDAR Internal QC



- Derive quantitative estimate of the necessary transformation parameters (shifts & rotations) for the co-alignment of the captured data from different flight lines.
  - For a well-calibrated system and with accurate navigation information, the transformation parameters should be very close to zero.

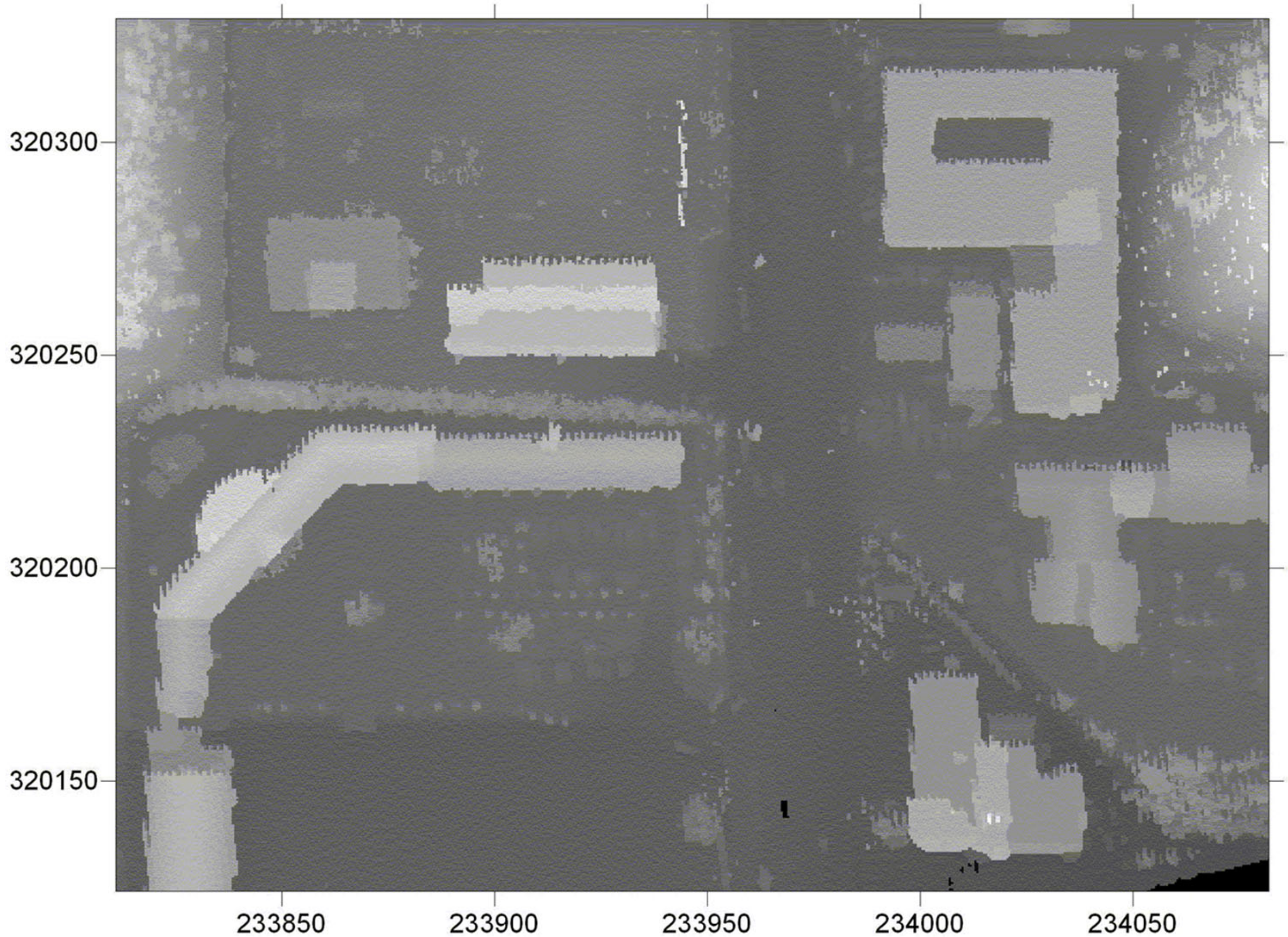
Check for the presence of biases

IQC: LiDAR Quality Control (#1)

- Using interpolated range images:
  - Interpolate LiDAR heights into a grid → Range images
  - Image differencing of overlapping range images
  - Observed deviations in the difference image can be used as a measure of the quality of the LiDAR data.
- Caution: Interpolation would lead to artifacts in the interpolated images (especially at the vicinity of discontinuities in the range data).
  - It does not give a good indication of the quality of the planimetric coordinates of the LiDAR point cloud.

IQC: LiDAR Quality Control (#1)

First Range Image



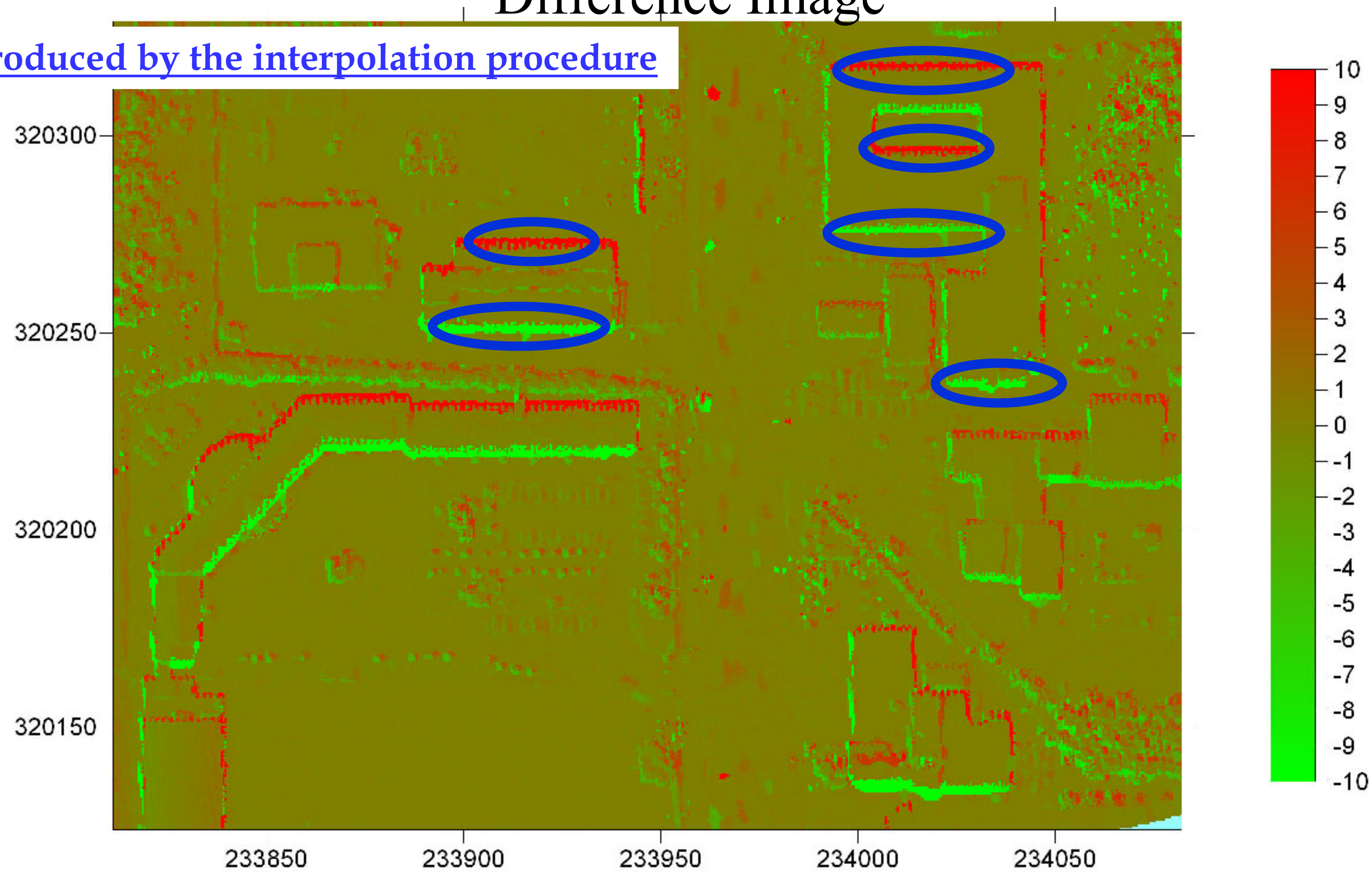
IQC: LiDAR Quality Control (#1)

Second Range Image

IQC: LiDAR Quality Control (#1)

Difference Image

Introduced by the interpolation procedure



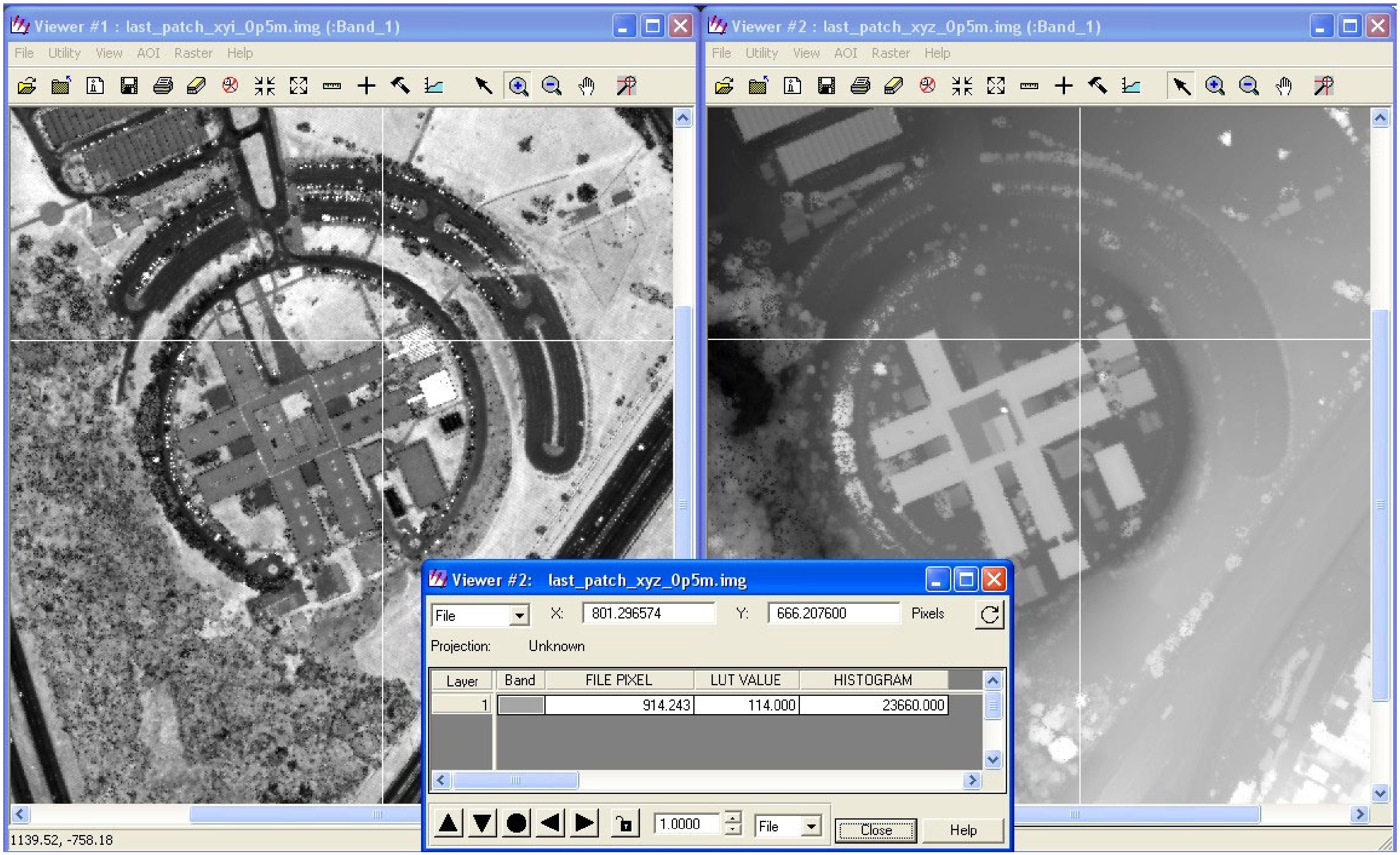
IQC: LiDAR Quality Control (#2)

- Using Interpolated intensity images:
  - Interpolate the intensity data into a grid → Intensity images
  - Identify distinct features in the intensity images
    - For these features, the X, Y, and Z coordinates can be derived.
  - Compare the derived coordinates of the same feature from overlapping strips
  - Theoretically, it leads to a quantification of the planimetric and vertical quality of the coordinates of the LiDAR point cloud.
- Caution: Interpolation would lead to artifacts in the interpolated images (especially at the vicinity of discontinuities in the intensity data).

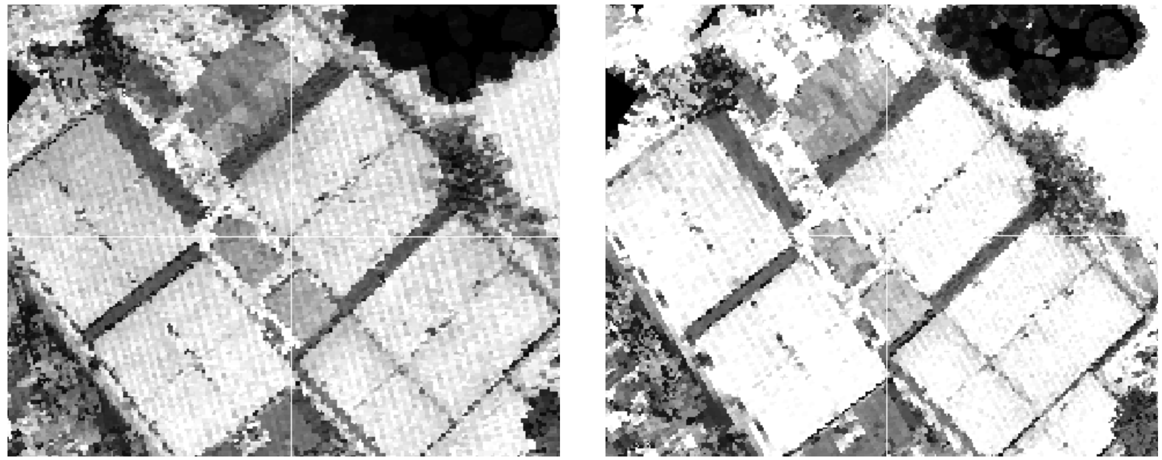
IQC: LiDAR Quality Control (#2)

Intensity Images

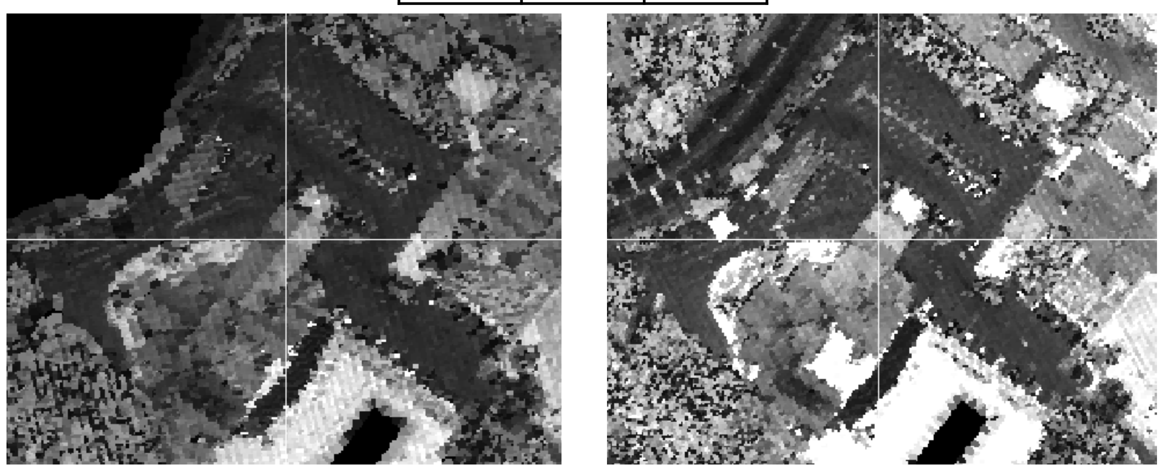
IQC: LiDAR Quality Control (#2)



IQC: LiDAR Quality Control (#2)

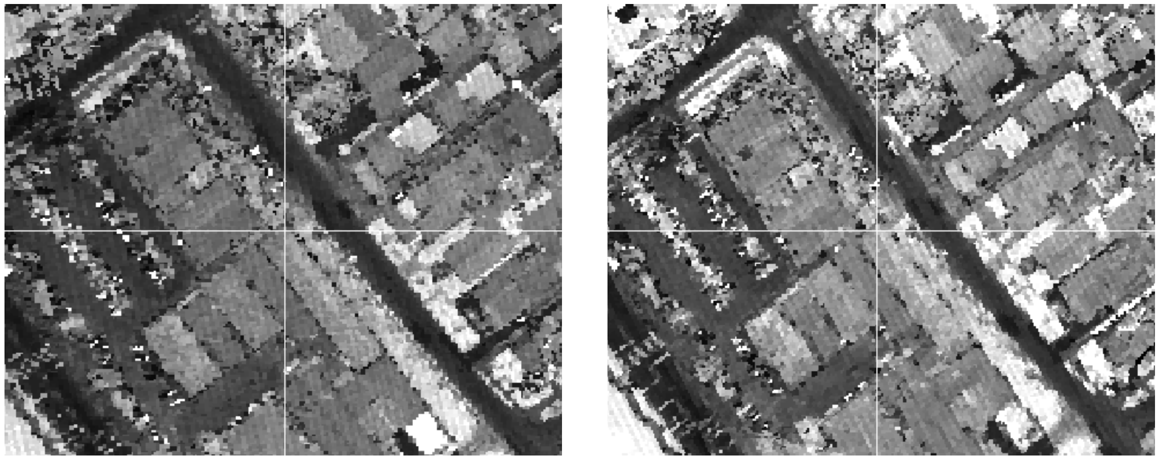


DX(m)	DY(m)	DZ(m)
-0.97	0.00	1.92

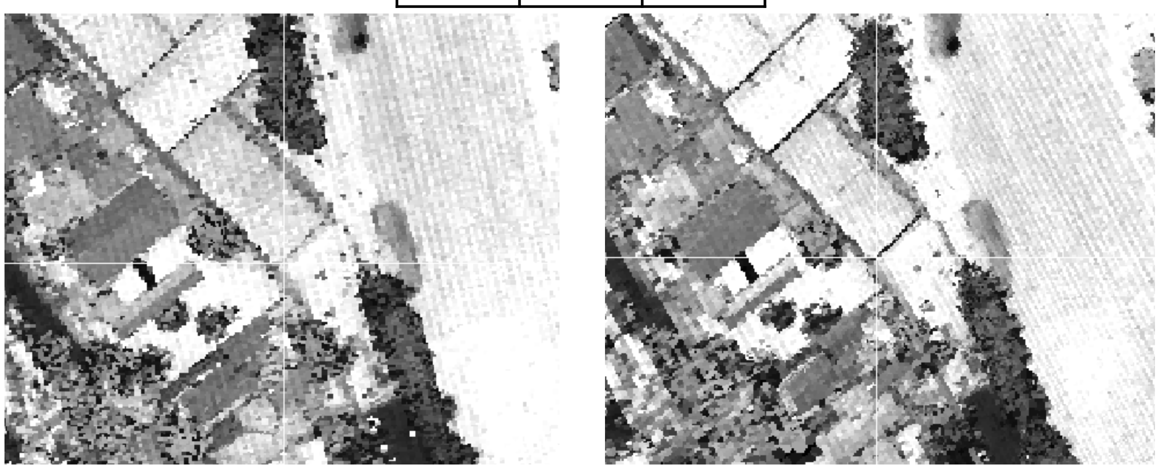


DX(m)	DY(m)	DZ(m)
-0.79	0.25	0.05

IQC: LiDAR Quality Control (#2)

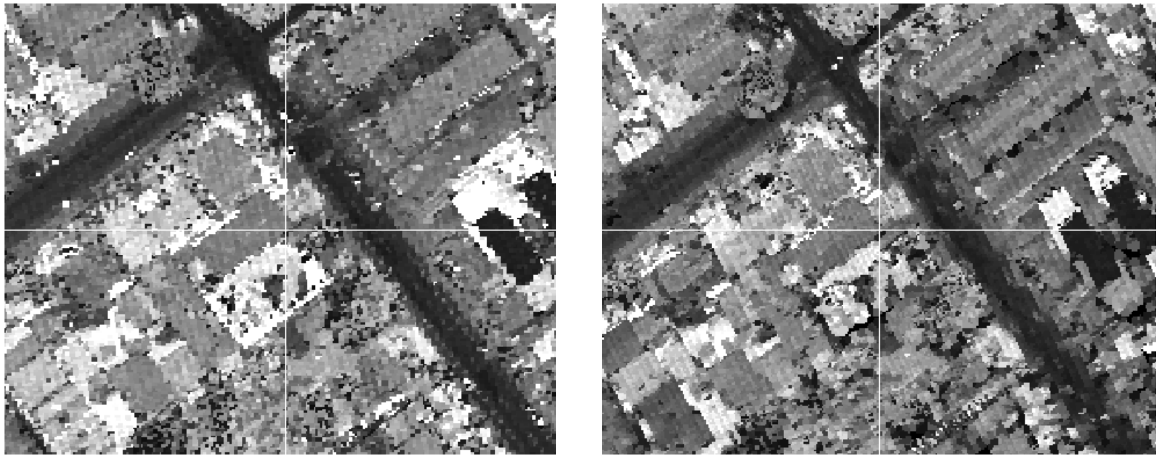


DX(m)	DY(m)	DZ(m)
0.39	0.90	-0.15

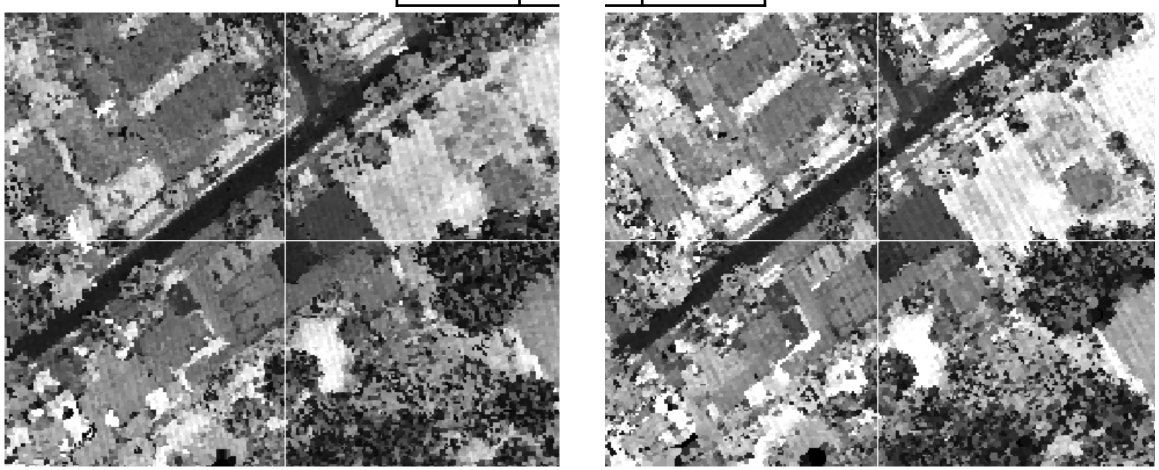


DX(m)	DY(m)	DZ(m)
0.08	-0.20	-1.35

IQC: LiDAR Quality Control (#2)



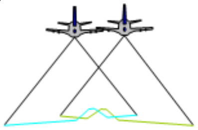
DX(m)	DY(m)	DZ(m)
-1.65	-1.11	0.63



DX(m)	DY(m)	DZ(m)
-0.78	0.08	-0.03

IQC: LiDAR Quality Control (# 1, 2)

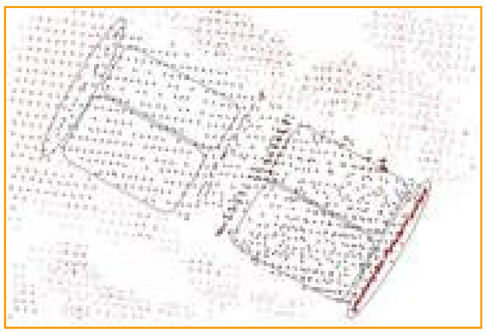
- Interpolating the LiDAR data might introduce artifacts, which will lead to unreliable quality control measures.
- Alternative procedures should be developed while relying on the original point cloud:
  - Extract features from the original LiDAR points
  - Compare conjugate features in overlapping strips
  - Deviations can be used as a quality control measure.



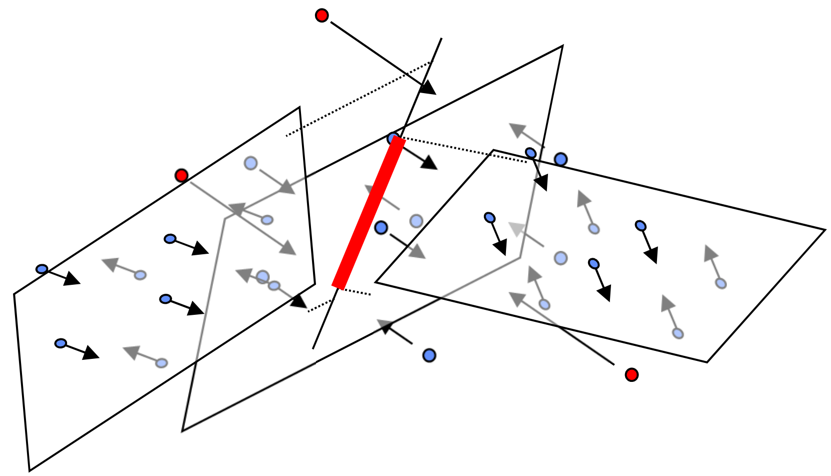
IQC: LiDAR Quality Control (#3)

- The quality of the coincidence of the extracted features from overlapping strips can be used for evaluating the internal quality of the LiDAR data.
  - Quality of coincidence can be evaluated by computing the offsets between conjugate elements in the X, Y, and Z directions, respectively.
  - Alternatively, the quality of coincidence can be evaluated by estimating the absolute orientation parameters (shifts, scale, and rotations), which are necessary for ensuring the coincidence of corresponding features.
    - The deviation from the optimal parameters (zero shifts, unit scale, and zero rotation angles) can be used as the IQC measures.

IQC: LiDAR Quality Control (#3)

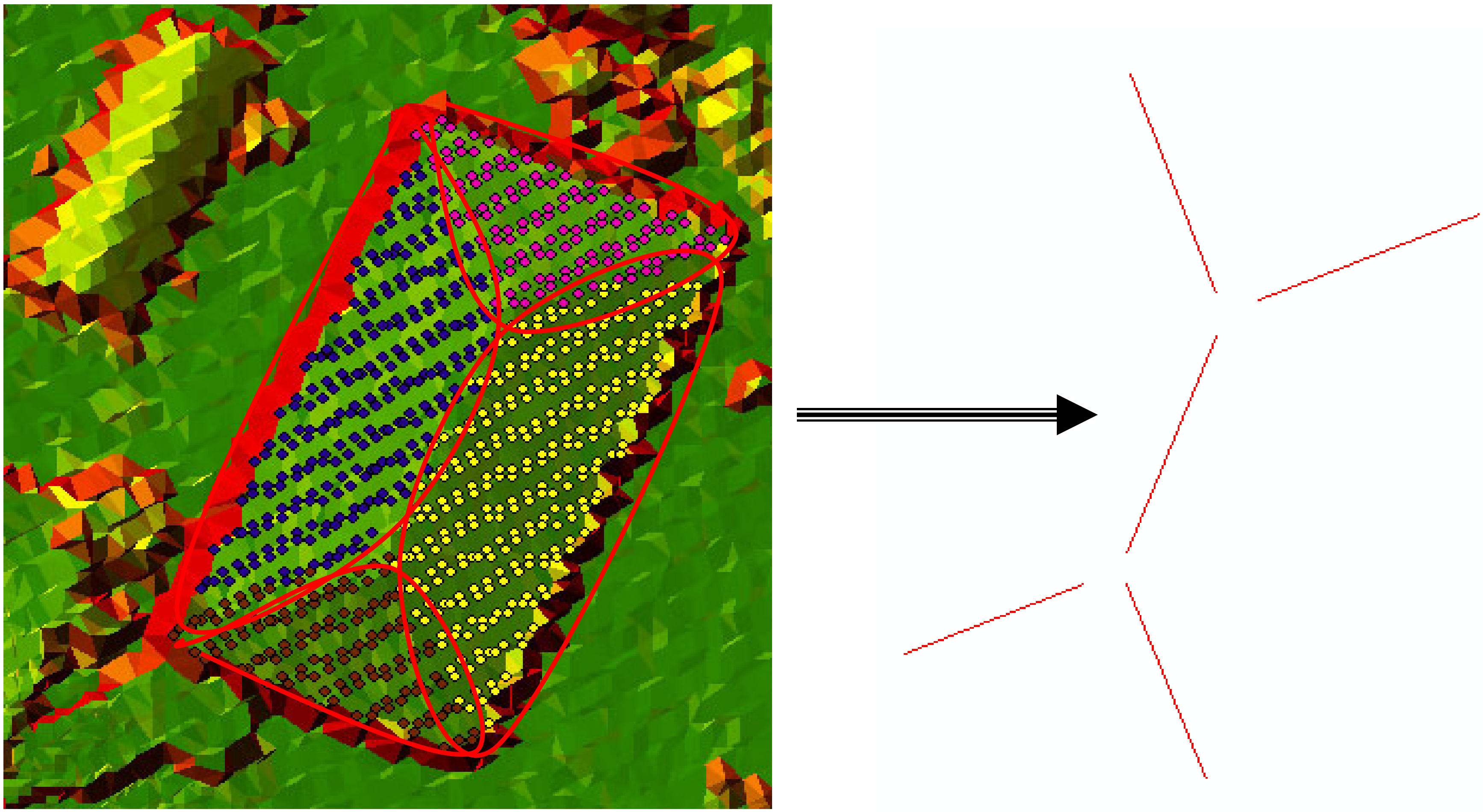


manual identification of LiDAR patches with the aid of imagery

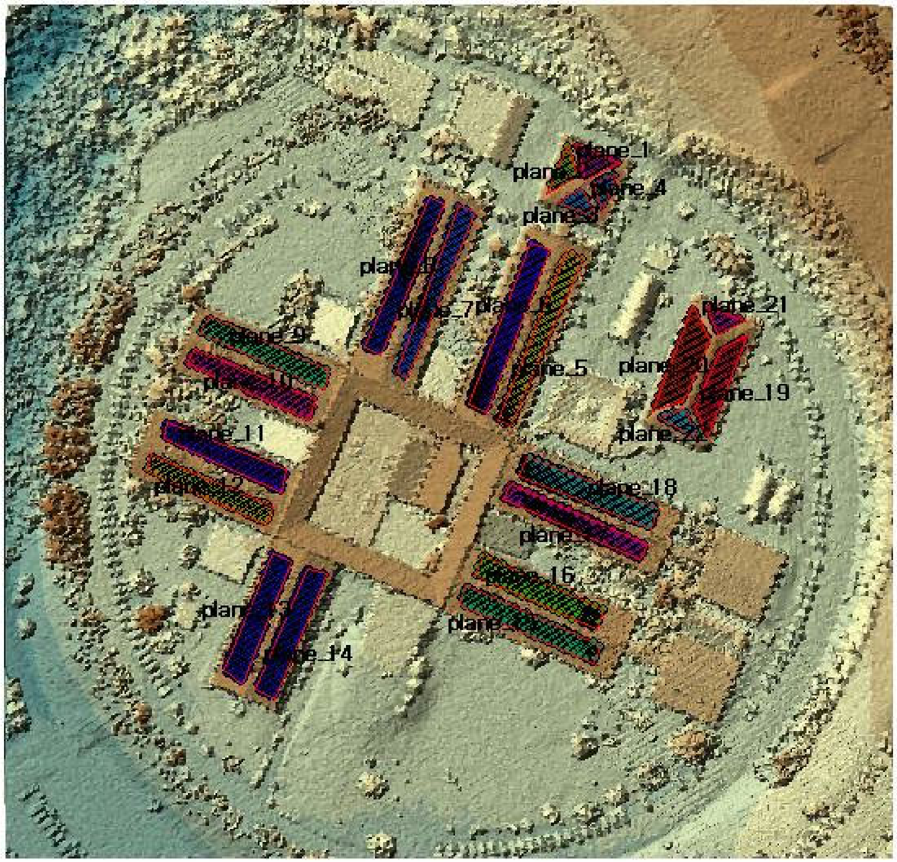


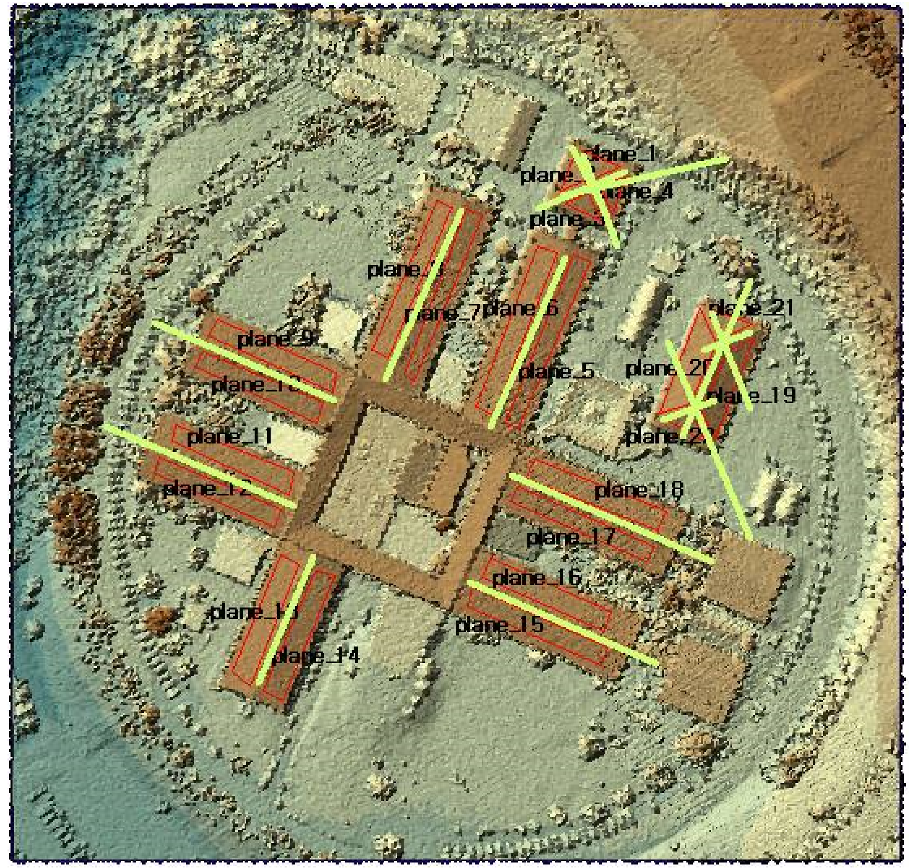
Linear Feature Extraction

IQC: LiDAR Quality Control (#3)



IQC: LiDAR Quality Control (#3)



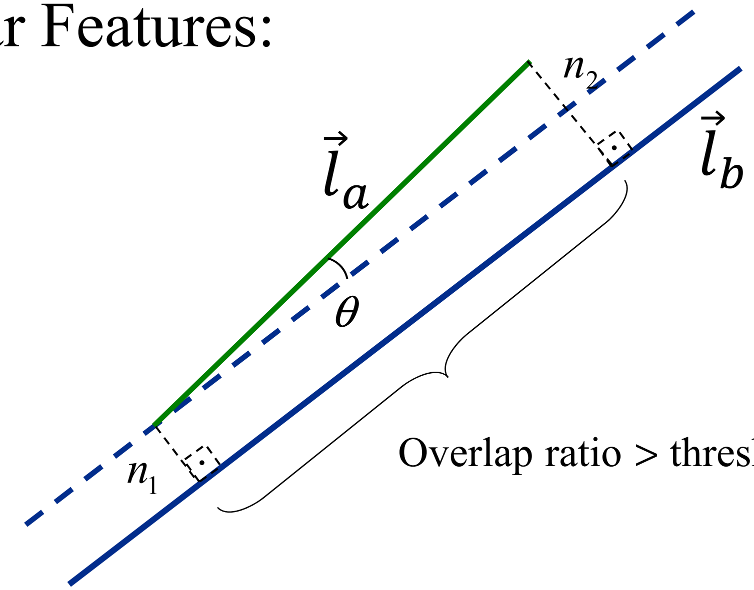


IQC: LiDAR Quality Control (#3)

Segmented Patches
Extracted Lines
Matched Lines

IQC: LiDAR Quality Control (#3)

Conjugate Linear Features:



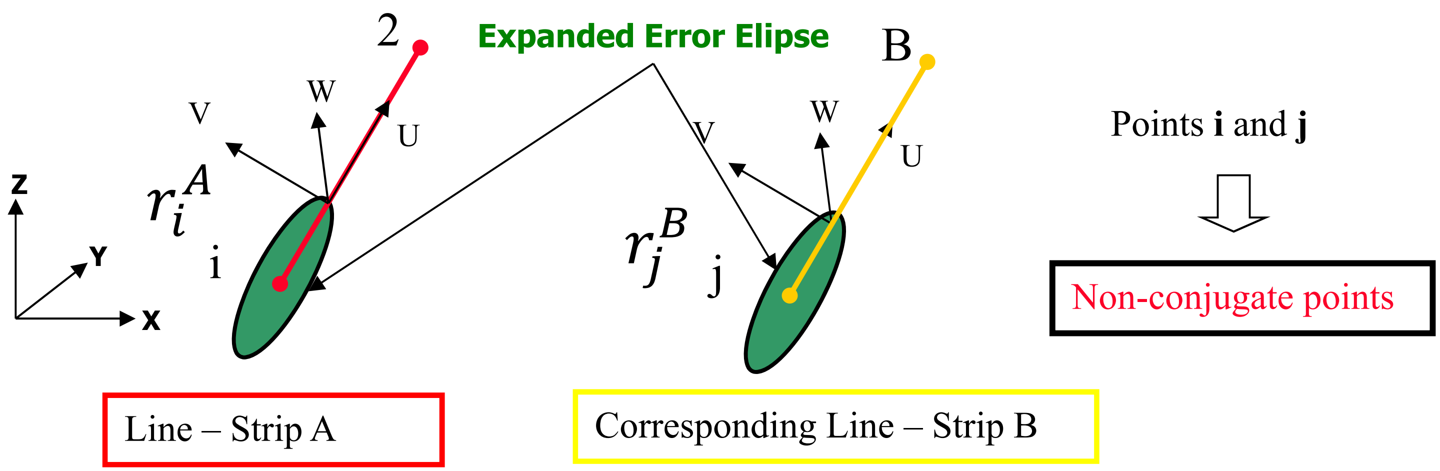
$n_1, n_2 \leq$ threshold (normal dist. verification)

$$\theta = COS^{-1}\left[\frac{\vec{l}_a \odot \vec{l}_b}{\|\vec{l}_a\|\|\vec{l}_b\|}\right] \leq \text{threshold (parallelism verification)}$$

Matching Procedure

IQC: LiDAR Quality Control (#3)

Conjugate Linear Features:



$$r_i^A(biased) = r_B^A + S\, R_B^A\, r_j^B(biased) + \bar{e}_{ij}$$

Only valid if we are dealing with conjugate points

Variance Expansion (Weight Restriction)

IQC: LiDAR Quality Control (#3)

Conjugate Linear Features:

$$r_i^A(biased) = r_B^A + S\,R_B^A\,r_j^B(biased) + \bar{e}_{ij}$$

Only if we are dealing with conjugate points

$$r_i^A(biased) + \vec{D} = r_B^A + S\,R_B^A\,r_j^B(biased) + \bar{e}_{ij}$$

If we are dealing with non-conjugate points

- $\vec{D}$ represents the difference vector between non-conjugate points along conjugate linear features (pseudo-conjugate points).
- $\vec{D}$ is aligned along the linear feature.

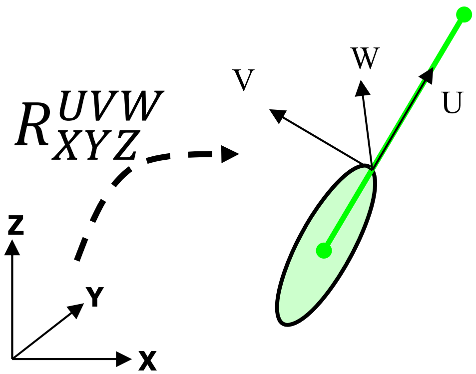
Least Squares Adjustment Target Function:

$$\sum \bar{e}_{ij}^T P'_{XYZ} \bar{e}_{ij} = \min(r_B^A, S, R_B^A, \vec{D})$$

IQC: LiDAR Quality Control (#3)

Conjugate Linear Features:

Weight Restriction



$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = R^{UVW}_{XYZ} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad \Sigma_{XYZ} = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{YX} & \sigma_Y^2 & \sigma_{YZ} \\ \sigma_{ZX} & \sigma_{ZY} & \sigma_Z^2 \end{bmatrix}$$

- UVW is defined with the U-axis aligned along the line.

$$P_{XYZ} = \Sigma_{XYZ}^{-1} \Rightarrow P_{UVW} = R^{UVW}_{XYZ}\, P_{XYZ} R^{XYZ}_{UVW}$$

Weight Restriction

$$\Rightarrow P'_{UVW} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & P_V & P_{VW} \\ 0 & P_{WW} & P_W \end{bmatrix} \Rightarrow P'_{XYZ} = R^{XYZ}_{UVW} P'_{UVW} R^{UVW}_{XYZ}$$

IQC: LiDAR Quality Control (#3)

Least Squares Adjustment Target Function:

$$\sum \bar{e}_{ij}^T P'_{XYZ} \bar{e}_{ij} = min(r_B^A, S, R_B^A, \vec{D})$$

$$\bar{e}_{ij} = r_i^A(biased) - \; r_B^A - S\, R_B^a\, r_j^B(biased) + \vec{D}$$

$$P'_{XYZ}\vec{D} = R_{UVW}^{XYZ} P'_{UVW} R_{XYZ}^{UVW} \begin{bmatrix} D_X \\ D_Y \\ D_Z \end{bmatrix} = R_{UVW}^{XYZ} P'_{UVW} \begin{bmatrix} D_U \\ D_V \\ D_W \end{bmatrix}$$

$$P'_{XYZ}\vec{D} = R_{UVW}^{XYZ} \begin{bmatrix} 0 & 0 & 0 \\ 0 & P_V & P_{VW} \\ 0 & P_{WW} & P_W \end{bmatrix} \begin{bmatrix} D_U \\ 0 \\ 0 \end{bmatrix} = 0$$

- $[D_U \quad D_V \quad D_W]^T$ represents the difference vector relative to the line coordinate system.
- Since $[D_U \quad D_V \quad D_W]^T$ represents the difference vector relative to the line coordinate system, then D_V and D_W = 0

IQC: LiDAR Quality Control (#3)

Least Squares Adjustment Target Function:

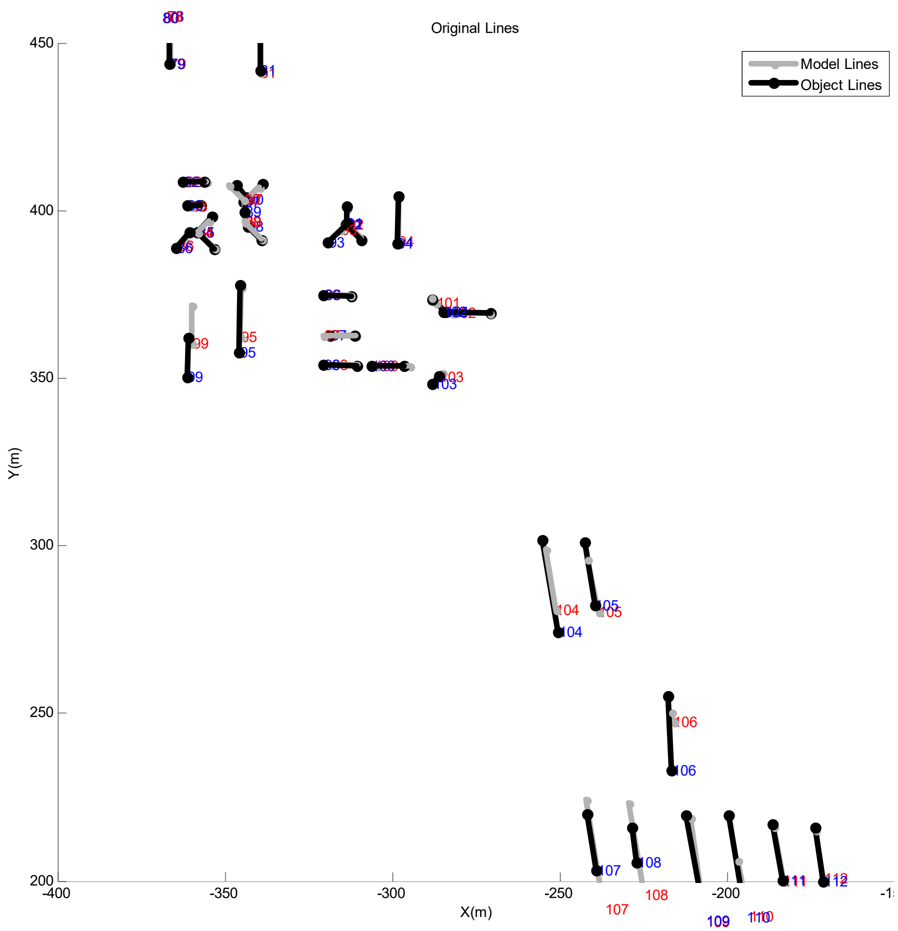
$$\sum \bar{e}_{ij}^{T} P'_{XYZ} \bar{e}_{ij} = min(r_B^A, S, R_B^A, \vec{D})$$

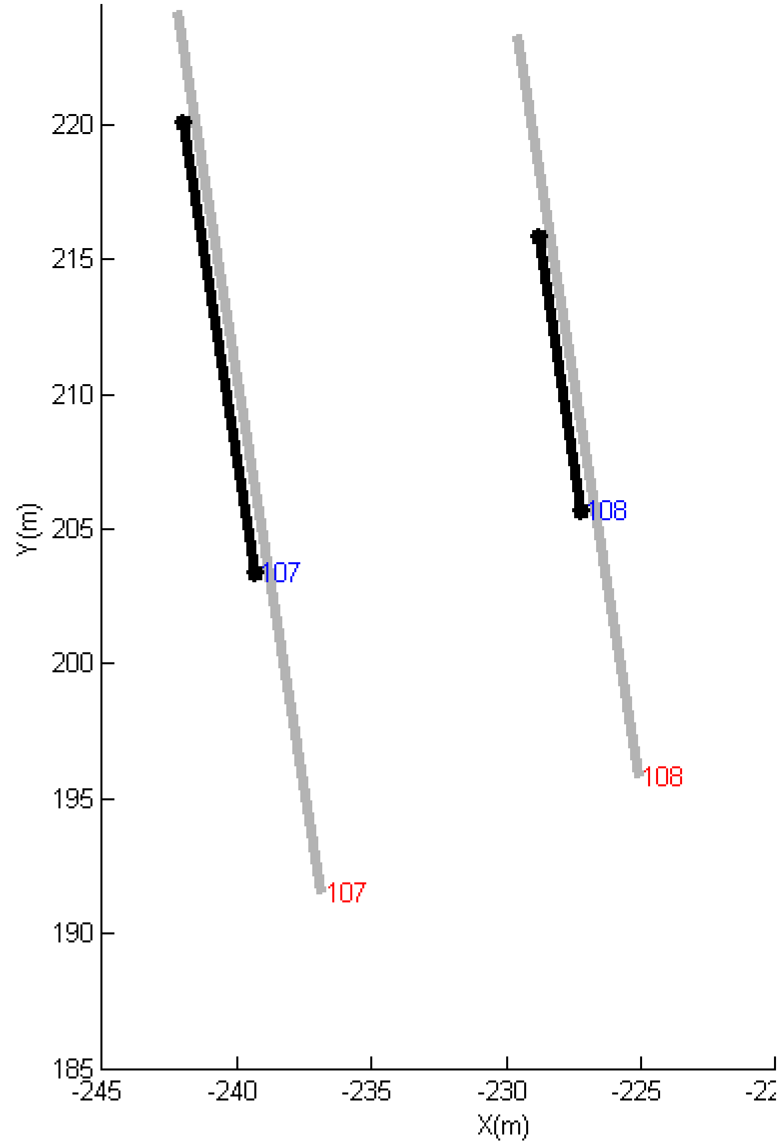
$$\bar{e}_{ij} = r_i^A(biased) - r_B^A - S\, R_B^a\, r_j^B(biased) + \vec{D}$$

$$\boldsymbol{\sum \bar{e}_{ij}^{T} P'_{XYZ} \bar{e}_{ij} = min(r_B^A, S, R_B^A)}$$

- Thus, utilizing the modified weight matrix would eliminate the discrepancy vector $\vec{D}$, which arises from the utilization of non-conjugate points along conjugate linear features – pseudo conjugate points, from the LSA target function.

IQC: LiDAR Quality Control (#3)





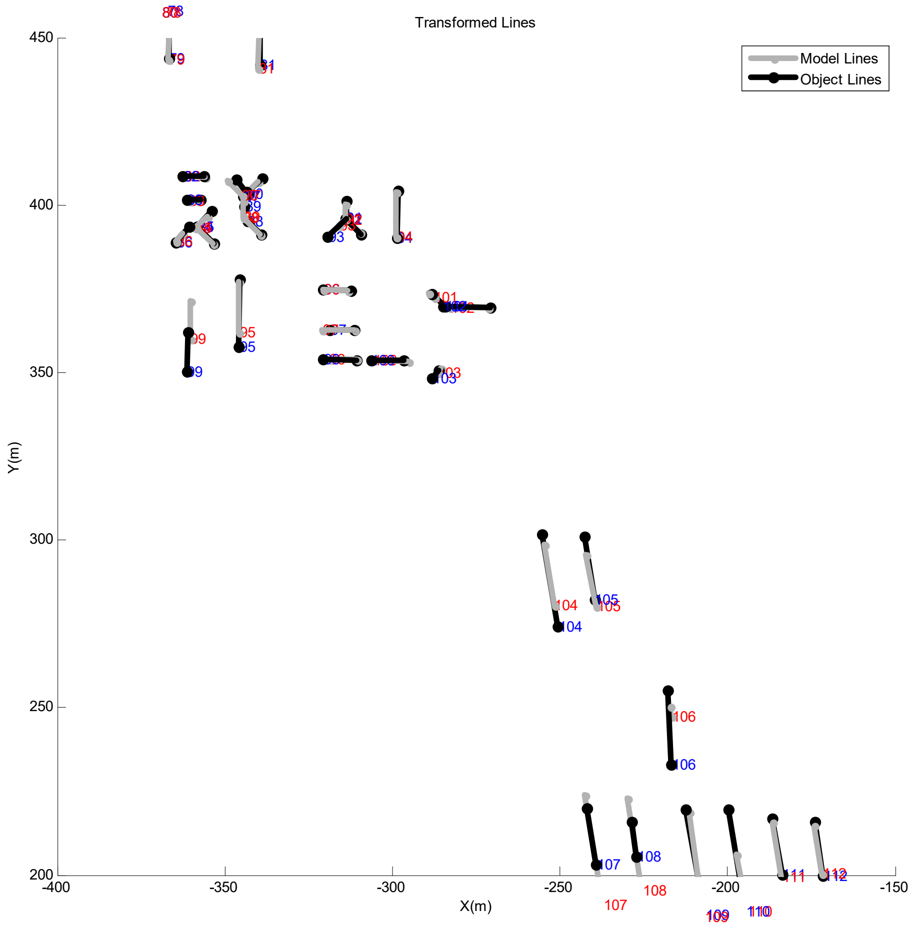
IQC: LiDAR Quality Control (#3)

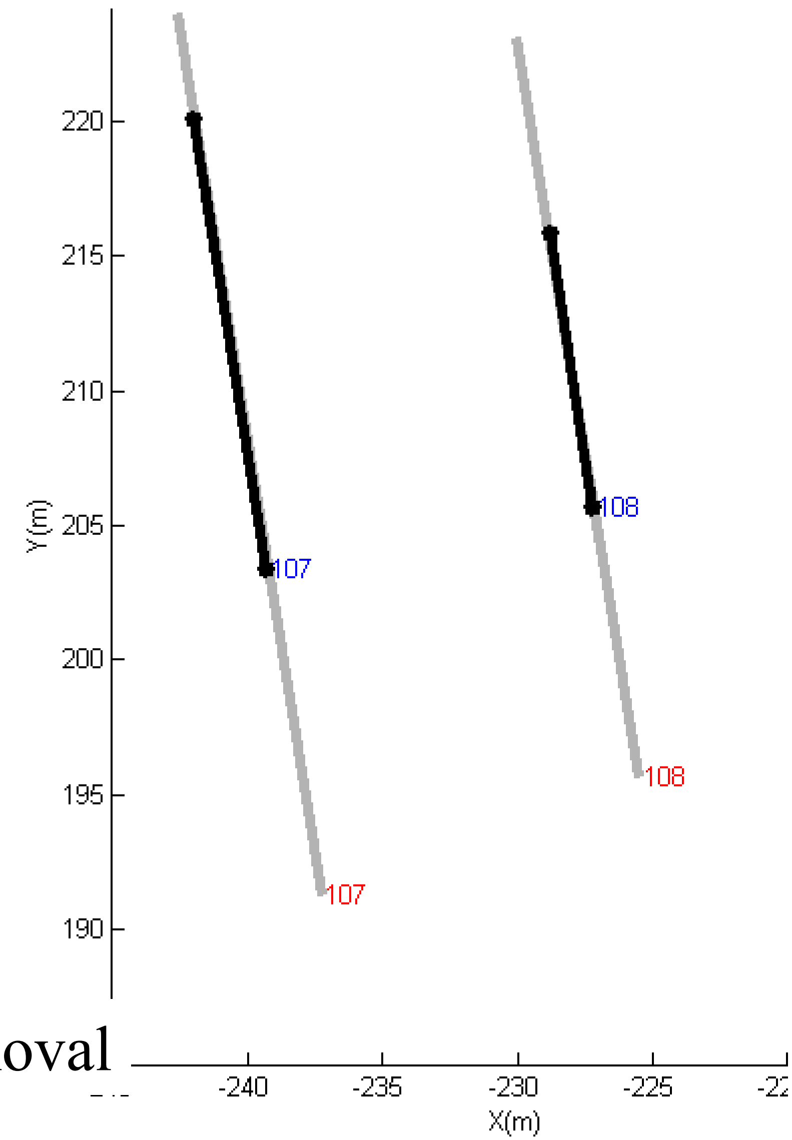
	X_T (m)	Y_T (m)	Z_T (m)	S	ω (°)	ϕ (°)	κ (°)
Optimal Para.*	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Estimated	-0.418	-0.209	-0.019	1.000	-0.010	0.017	0.003

* Assuming the LiDAR data has no biases

Biases are detected

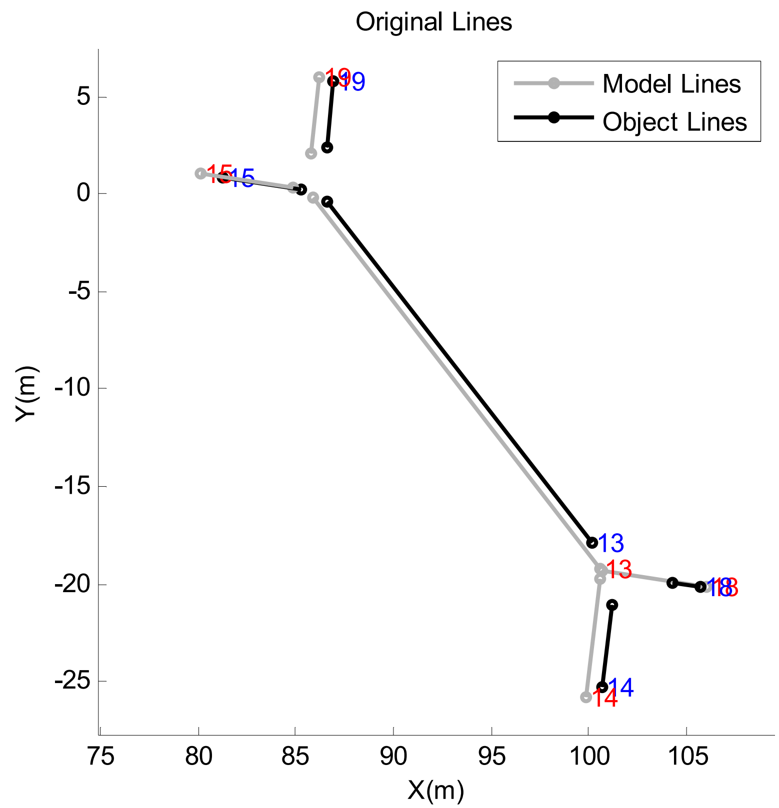
IQC: LiDAR Quality Control (#3)



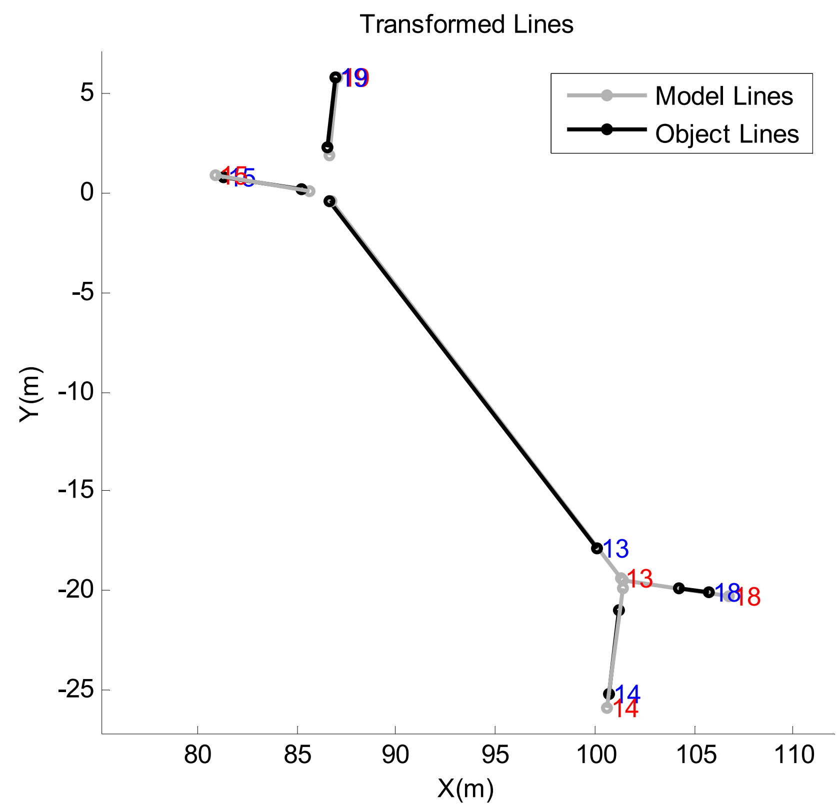


After bias removal

IQC: LiDAR Quality Control (#3)

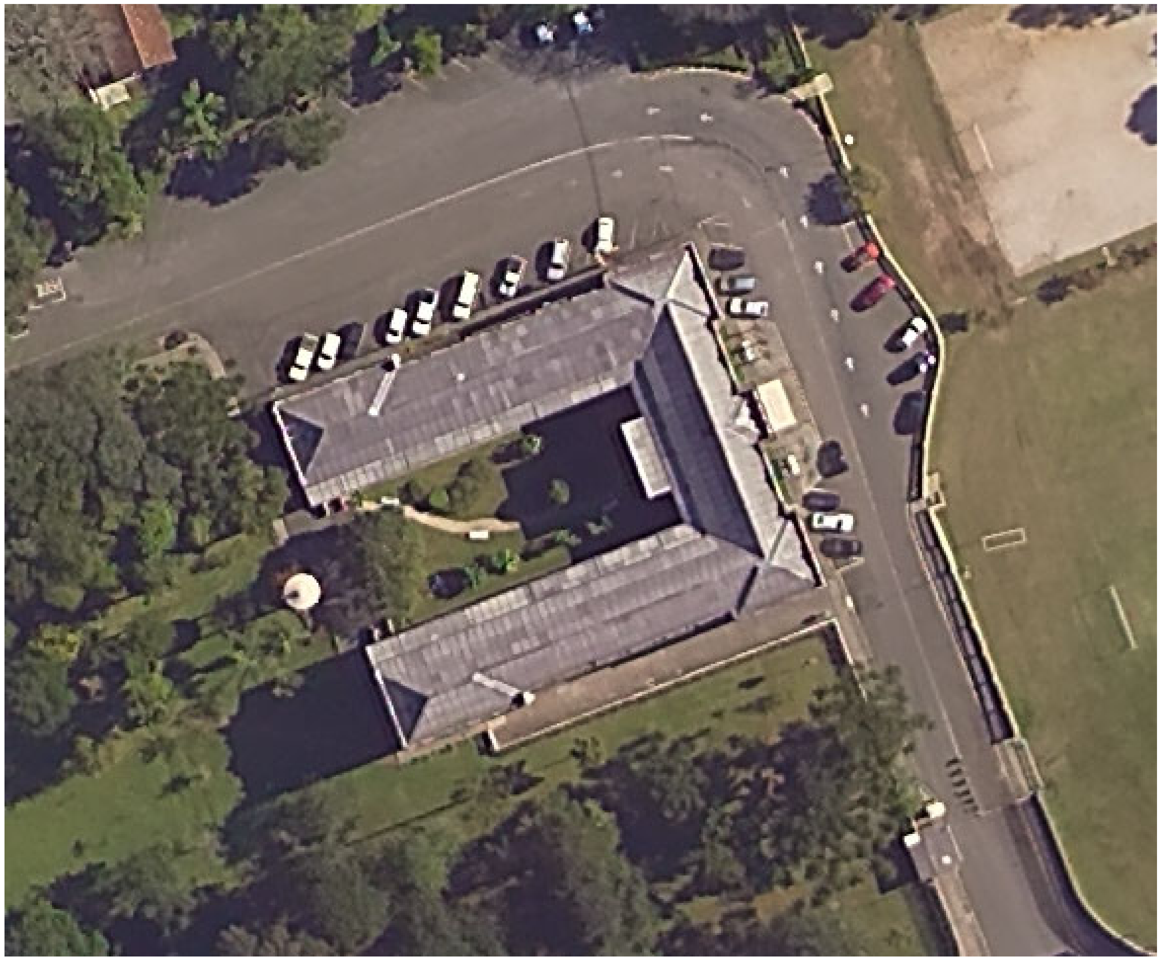


Before



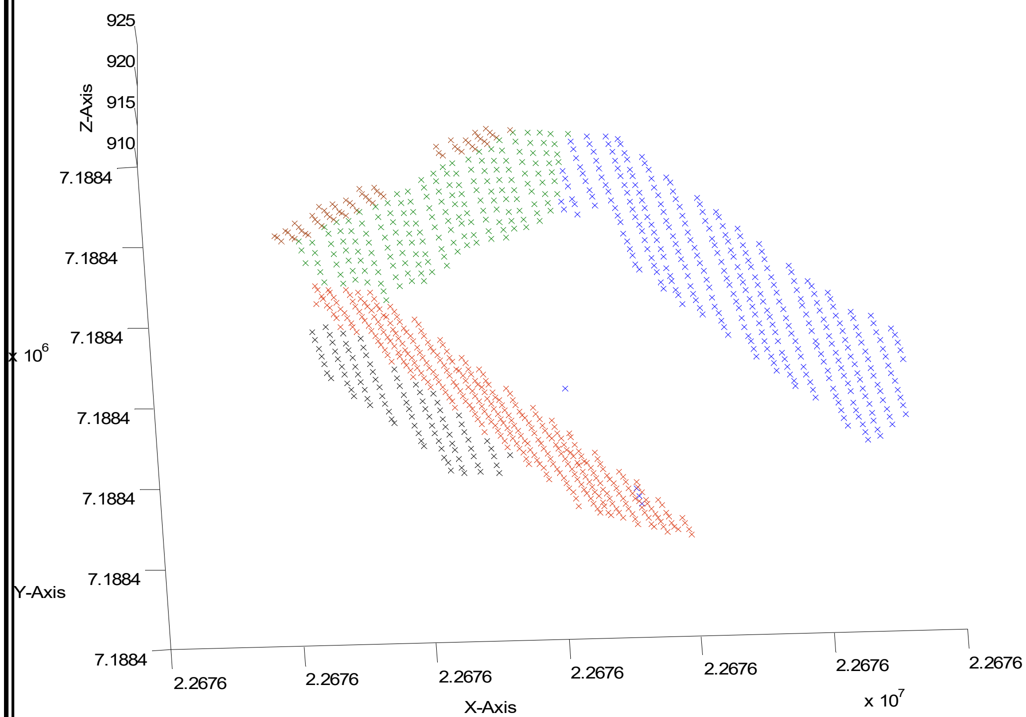
After

IQC: LiDAR Quality Control (#4)

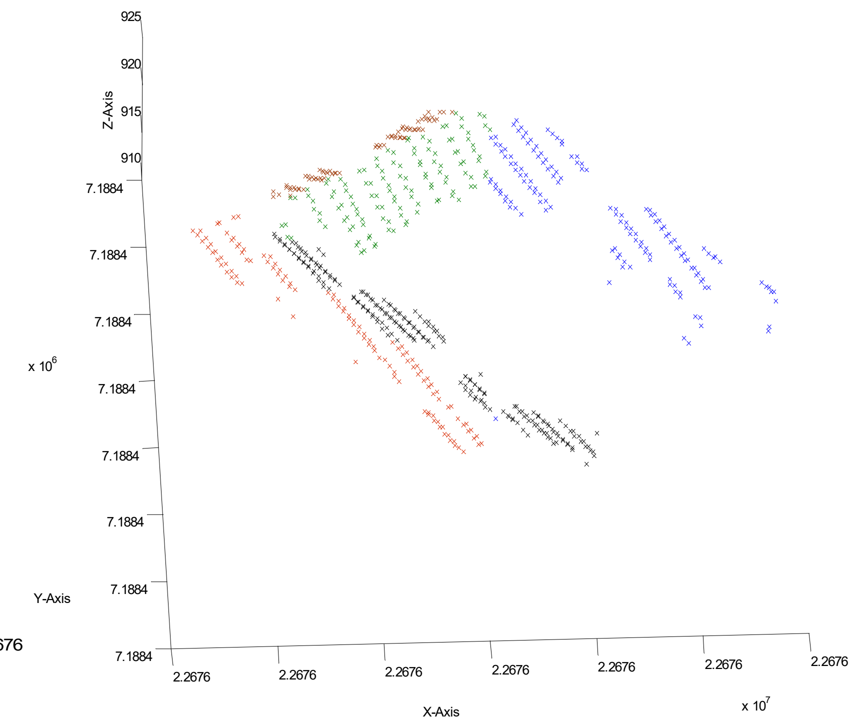


- Conceptual Basis: Check the quality of coincidence of conjugate planar patches

IQC: LiDAR Quality Control (#4)



Strip # 3



Strip # 4

IQC: LiDAR Quality Control (#4)

- Overlapping strips: Conjugate patch pairs

ROI* selection

↓

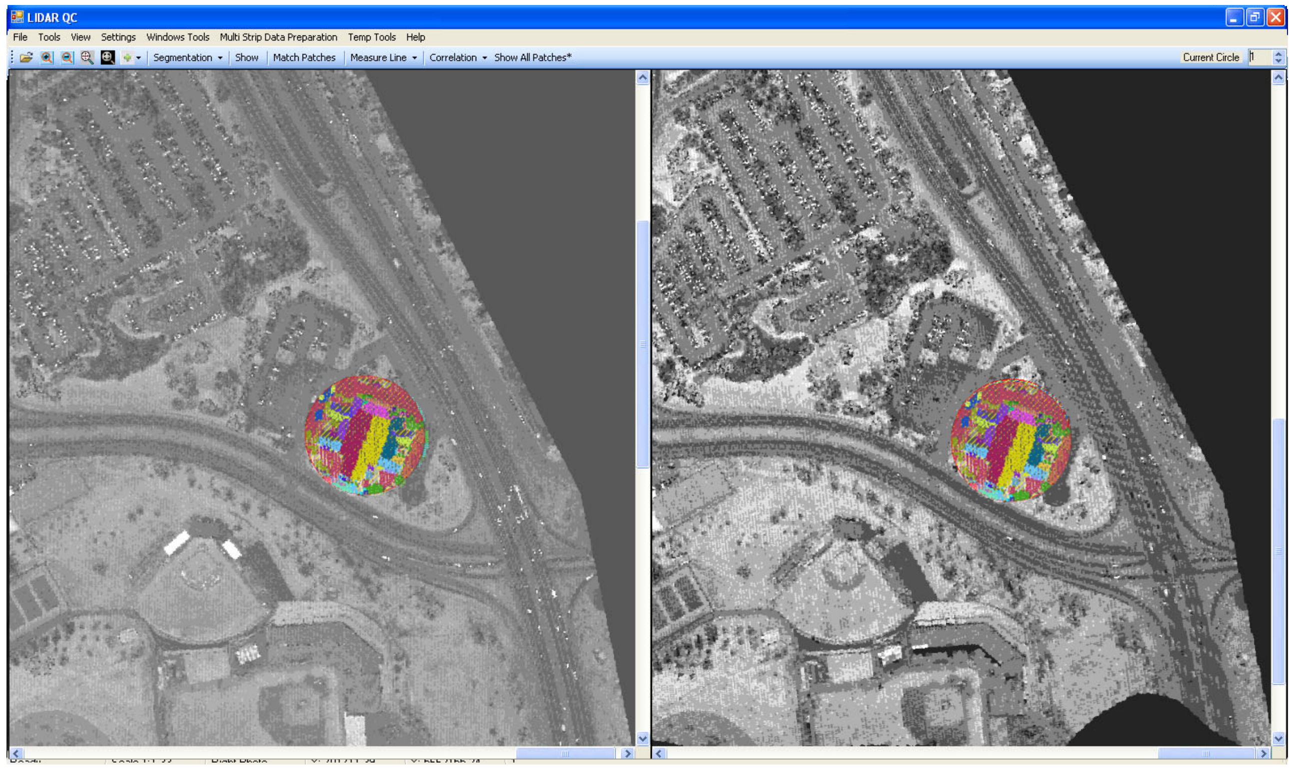
Data extraction in overlapping Strips

↓

Segmentation

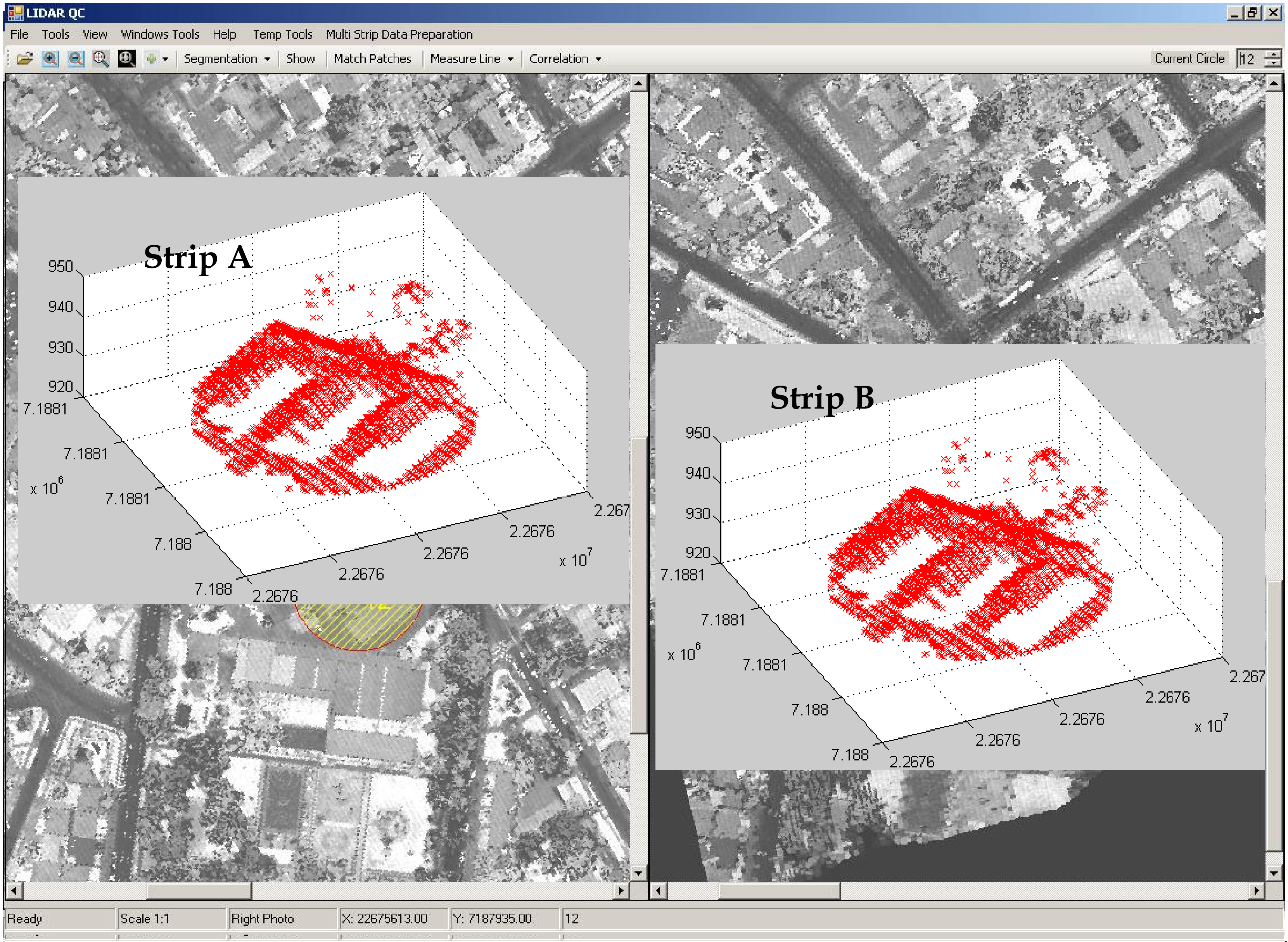
↓

Patch matching



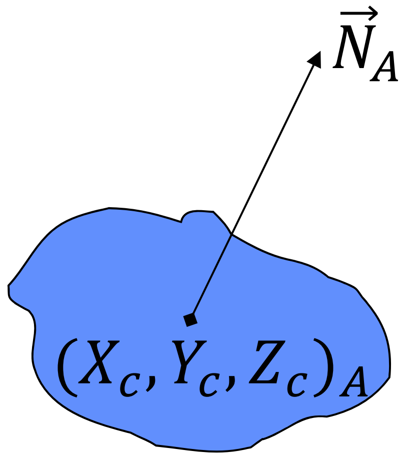
* Region of Interest

IQC: LiDAR Quality Control (#4)



IQC: LiDAR Quality Control (#4)

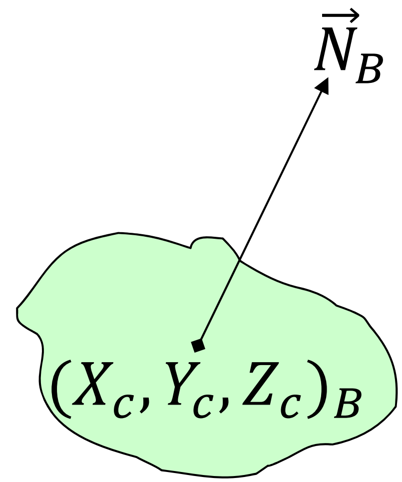
- Overlapping strips: Conjugate patch pairs



Planar Patch in Strip A

$\vec{N}_A$ & $\vec{N}_B$: *Surface Normal*

X_c, Y_c, Z_c: *Patch centroid*



Planar Patch in Strip B

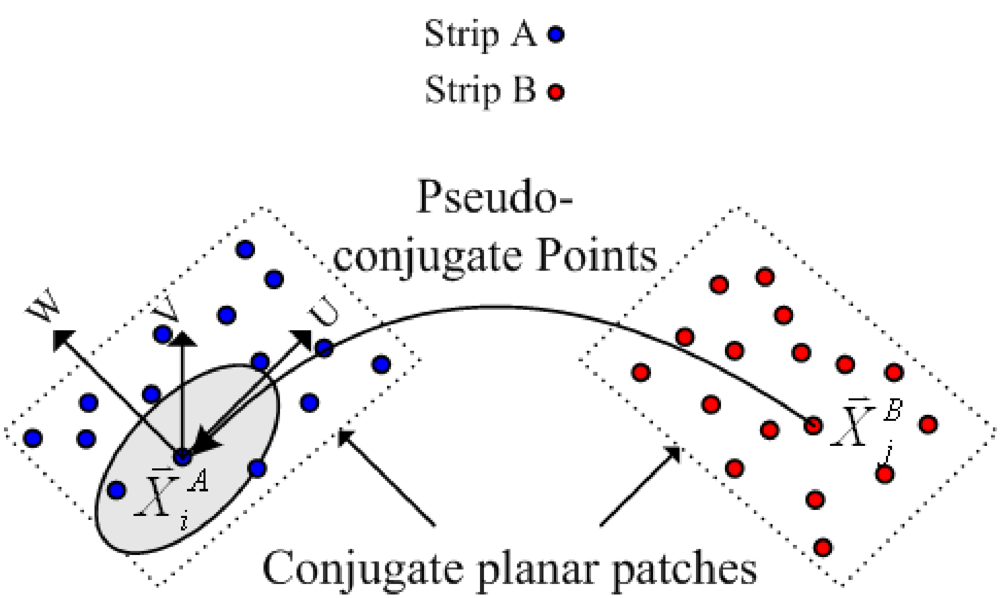
$$\theta = COS^{-1}\left[\frac{\vec{N}_A \odot \vec{N}_B}{\|\vec{N}_A\|\|\vec{N}_B\|}\right] \leq threshold$$

$$\Delta D = \sqrt{\Delta X_c^2 + \Delta Y_c^2 + \Delta Z_c^2} \leq threshold$$

Matching Procedure

IQC: LiDAR Quality Control (#4)

- Overlapping strips: Conjugate patch pairs
  - Modified weight matrix is used for pseudo-conjugate points on conjugate planar patches.



Weight Restriction

$$r_i^A(biased) = r_B^A + S\,R_B^A\,r_j^B(biased) + \bar{e}_{ij}$$

One equation for each pseudo-conjugate points

IQC: LiDAR Quality Control (#4)

Conjugate Planar Features:

$$r_i^A(biased) = r_B^A + S\,R_B^A\,r_j^B(biased) + \bar{e}_{ij}$$

Only if we are dealing with conjugate points

$$r_i^A(biased) + \vec{D} = r_B^A + S\,R_B^A\,r_j^B(biased) + \bar{e}_{ij}$$

If we are dealing with non-conjugate points

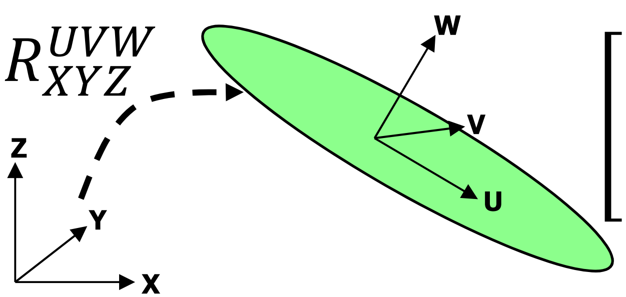
- $\vec{D}$ represents the difference vector between non-conjugate points along conjugate planar features (pseudo-conjugate points).
- $\vec{D}$ is aligned along the planar feature.

Least Squares Adjustment Target Function:

$$\sum \bar{e}_{ij}^T P'_{XYZ} \bar{e}_{ij} = \min(r_B^A, S, R_B^A, \vec{D})$$

IQC: LiDAR Quality Control (#4)

- Overlapping strips: Conjugate patch pairs
  - Modified weight matrix is used for pseudo-conjugate points on conjugate planar patches.



$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = R_{XYZ}^{UVW} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad \Sigma_{XYZ} = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{YX} & \sigma_Y^2 & \sigma_{YZ} \\ \sigma_{ZX} & \sigma_{ZY} & \sigma_Z^2 \end{bmatrix}$$

- UVW is defined with the W-axis aligned along the normal to the planar feature.

$$P_{XYZ} = \Sigma_{XYZ}^{-1} \;\Rightarrow\; P_{UVW} = R_{XYZ}^{UVW} P_{XYZ} R_{UVW}^{XYZ}$$

Weight Restriction $\Rightarrow$

$$P'_{UVW} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & P_W \end{bmatrix} \;\Rightarrow\; P'_{XYZ} = R_{UVW}^{XYZ} P'_{UVW} R_{XYZ}^{UVW}$$

IQC: LiDAR Quality Control (#4)

Least Squares Adjustment Target Function:

$$\sum \bar{e}_{ij}^{T} P'_{XYZ} \bar{e}_{ij} = min(r_B^A, S, R_B^A, \vec{D})$$

$$\bar{e}_{ij} = r_i^A(biased) - r_B^A - S\, R_B^a\, r_j^B(biased) + \vec{D}$$

$$P'_{XYZ}\vec{D} = R_{UVW}^{XYZ} P'_{UVW} R_{XYZ}^{UVW} \begin{bmatrix} D_X \\ D_Y \\ D_Z \end{bmatrix} = R_{UVW}^{XYZ} P'_{UVW} \begin{bmatrix} D_U \\ D_V \\ D_W \end{bmatrix}$$

$$P'_{XYZ}\vec{D} = R_{UVW}^{XYZ} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & P_W \end{bmatrix} \begin{bmatrix} D_U \\ D_V \\ 0 \end{bmatrix} = 0$$

- $[D_U \quad D_V \quad D_W]^T$ represents the difference vector relative to the plane coordinate system.
- Since $[D_U \quad D_V \quad D_W]^T$ represents the difference vector relative to the plane coordinate system, then $D_W = 0$

IQC: LiDAR Quality Control (#4)

Least Squares Adjustment Target Function:

$$\sum \bar{e}_{ij}^{T} P'_{XYZ} \bar{e}_{ij} = min(r_B^A, S, R_B^A, \vec{D})$$

$$\bar{e}_{ij} = r_i^A(biased) - r_B^A - S\, R_B^a\, r_j^B(biased) + \vec{D}$$

$$\boldsymbol{\sum \bar{e}_{ij}^{T} P'_{XYZ} \bar{e}_{ij} = min(r_B^A, S, R_B^A)}$$

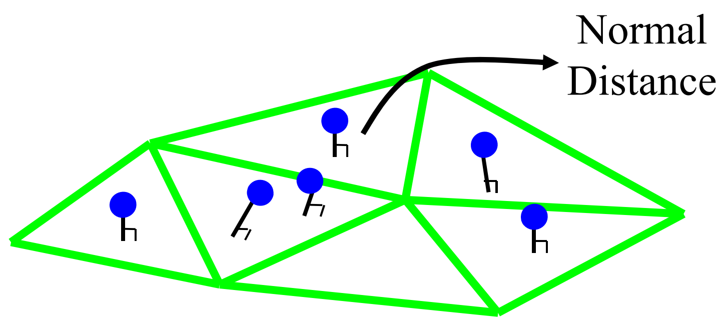
- Thus, utilizing the modified weight matrix would eliminate the discrepancy vector $\vec{D}$, which arises from the utilization of non-conjugate points along conjugate planar features – pseudo conjugate points, from the LSA target function.

IQC: LiDAR Quality Control (#4)

Transformation parameter	Planar-Based Approach
Scale Factor	0.9985
X_T (m)	0.75
Y_T (m)	-0.11
Z_T (m)	0.13
Ω (°)	-0.0305
Φ (°)	0.0391
K (°)	0.1950

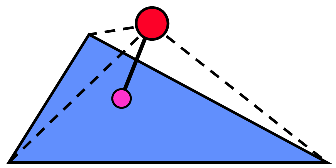
IQC: LiDAR Quality Control (#5)

- The first surface is represented by distinct points.
- The second surface is represented by triangular patches (TIN structure).
- The similarity transformation parameters, which minimize the normal distance between points and corresponding patches, are estimated through a least squares adjustment procedure.
- Significant deviation between the estimated parameters and the optimal values ($X_T = 0.0$, $Y_T = 0.0$, $Z_T = 0.0$, $S = 1.0$, $\omega = 0.0°$, $\varphi = 0.0°$, $\kappa = 0.0°$) indicates the presence of biases in the LiDAR system.



IQC: LiDAR Quality Control (#5)

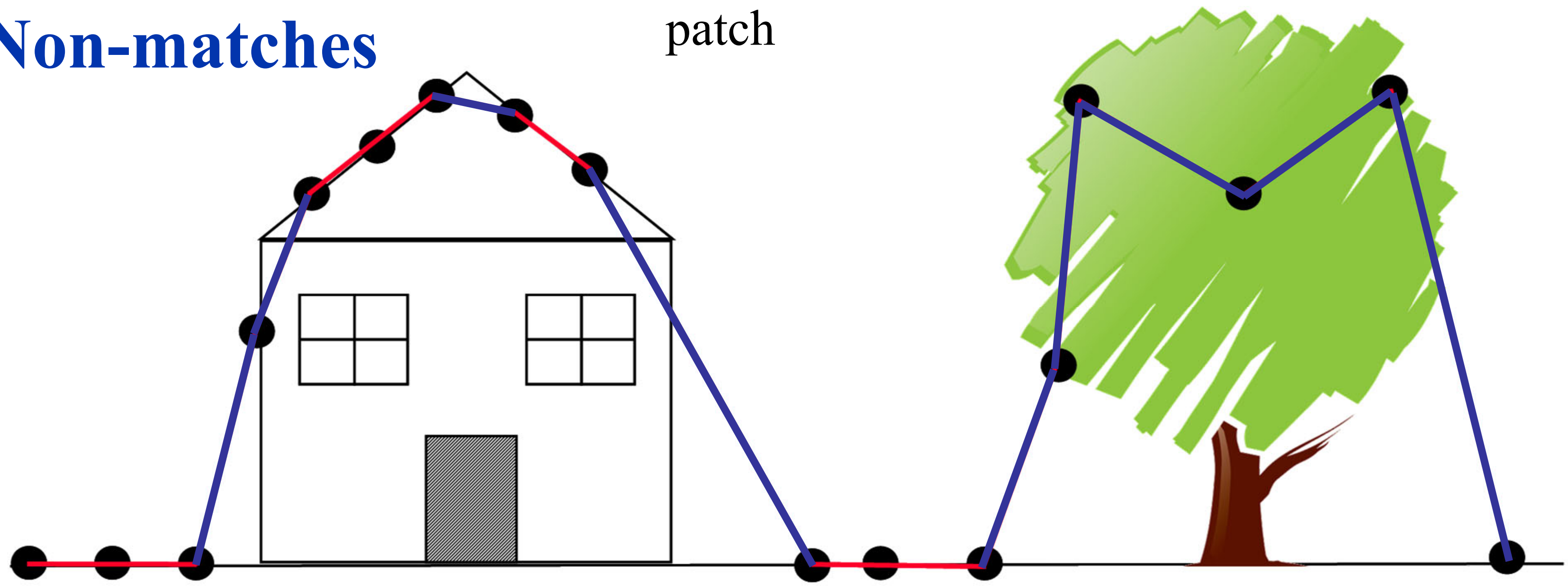
Point/Patch Pairs: Closest Patch Procedure



Conditions:

- Closest patch (within a threshold)
- Point located within the patch

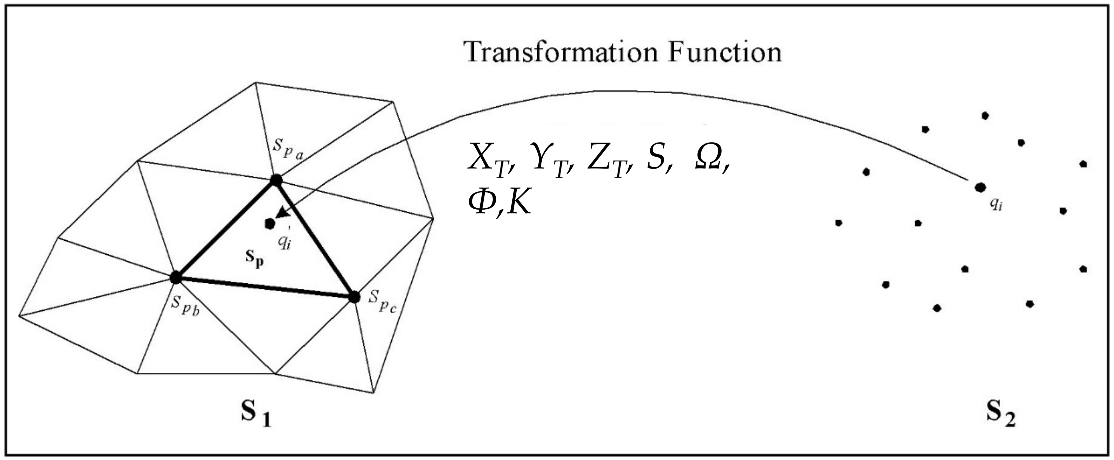
Non-matches

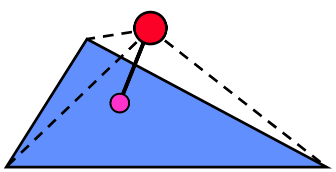


We will have conjugate point-patch pairs only whenever the TIN patches represent the physical surface.

IQC: LiDAR Quality Control (#5)

Point/Patch Pairs: Closest Patch Procedure





Conditions:

- Closest patch
- Point located within the patch

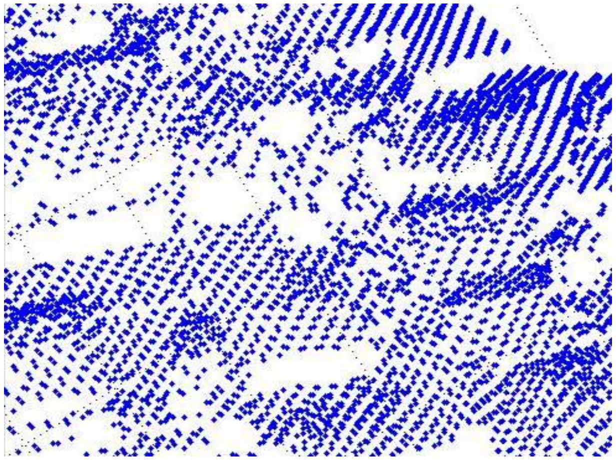
$$\begin{vmatrix} X_{q_i'} & Y_{q_i'} & Z_{q_i'} & 1 \\ X_{p_a} & Y_{p_a} & Z_{p_a} & 1 \\ X_{p_b} & Y_{p_b} & Z_{p_b} & 1 \\ X_{p_c} & Y_{p_c} & Z_{p_c} & 1 \end{vmatrix} = 0$$

Where:

$$\begin{bmatrix} X_{q_i'} \\ Y_{q_i'} \\ Z_{q_i'} \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + S\,R \begin{bmatrix} X_{q_i} \\ Y_{q_i} \\ Z_{q_i} \end{bmatrix}$$

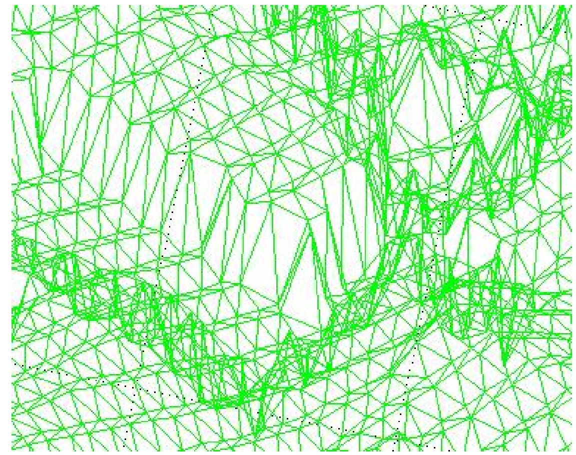
$$(X_T, Y_T, Z_T, S, \omega, \phi, \kappa) \Longleftarrow$$

IQC: LiDAR Quality Control (#5)



Surface 1: 44,156 points

Register

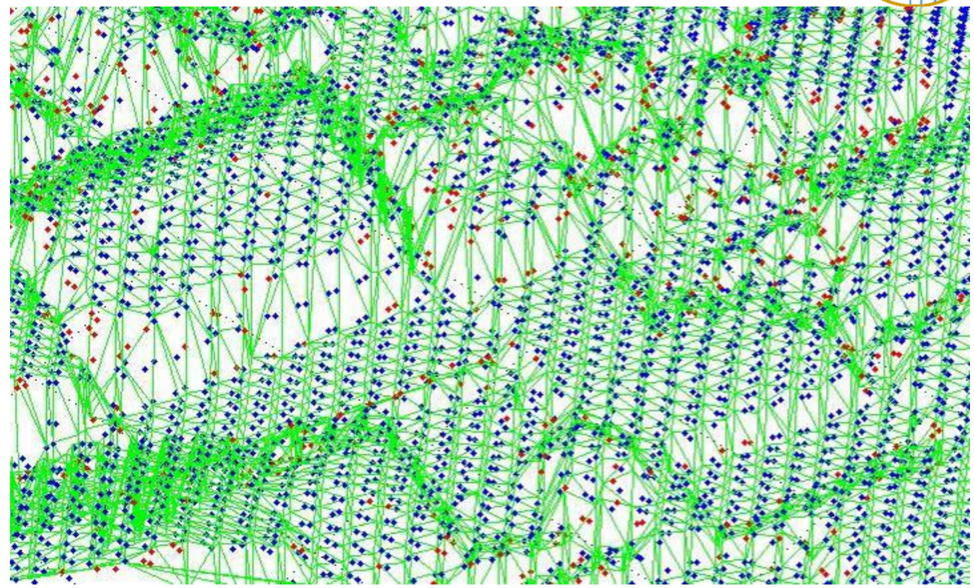


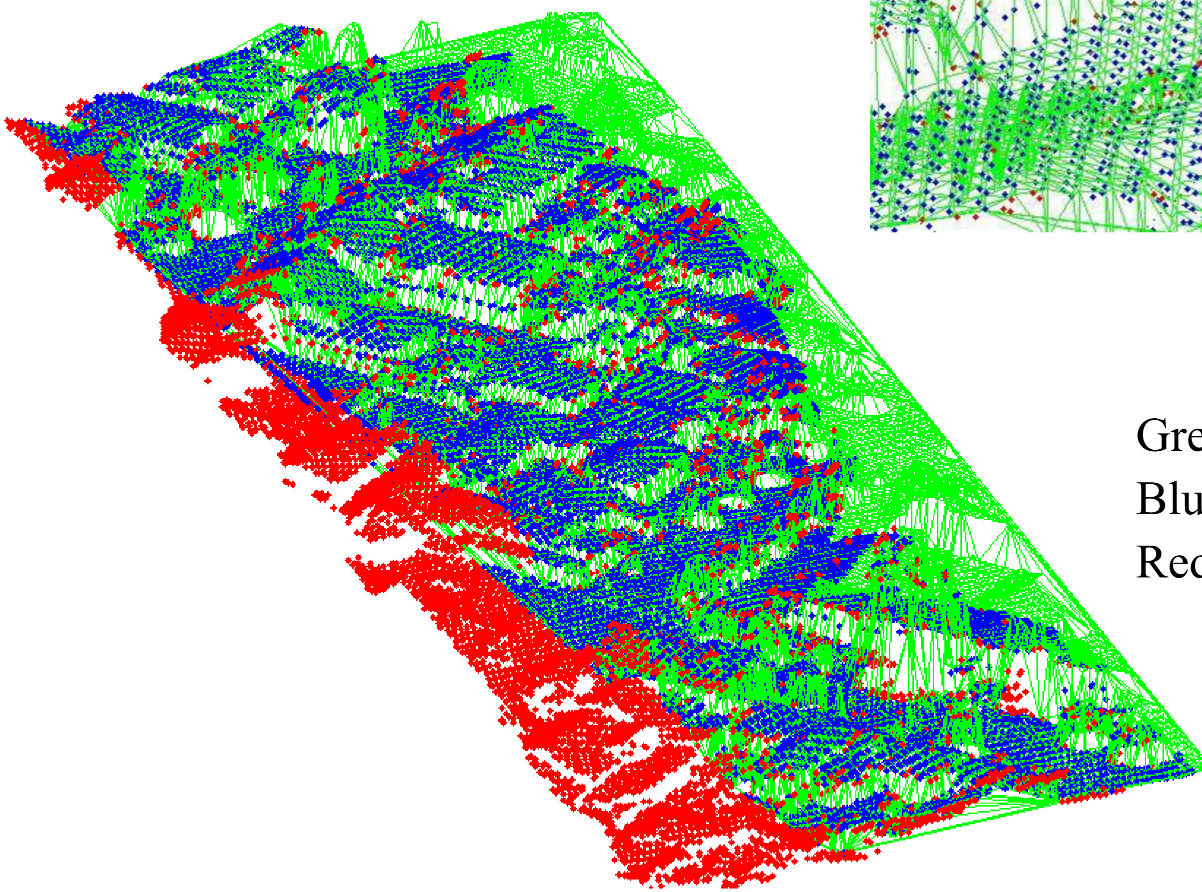
Surface 2: 45,520 patches

	X_T (m)	Y_T (m)	Z_T (m)	S	ω (°)	ϕ (°)	κ (°)
Optimal Para.*	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Estimated	-0.660	-0.367	0.007	1.001	-0.017	0.002	0.003
Estimated Variance Component				0.122			
Average Normal Distance				0.142 m			

* Assuming the LiDAR data has no biases

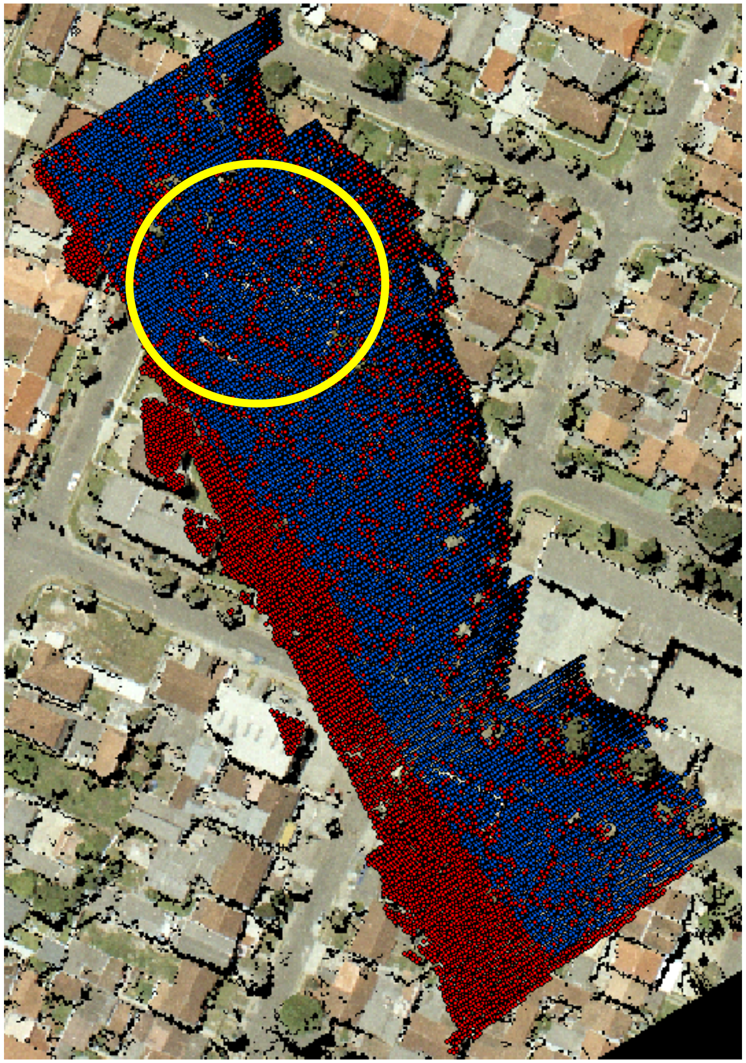
IQC: LiDAR Quality Control (#5)

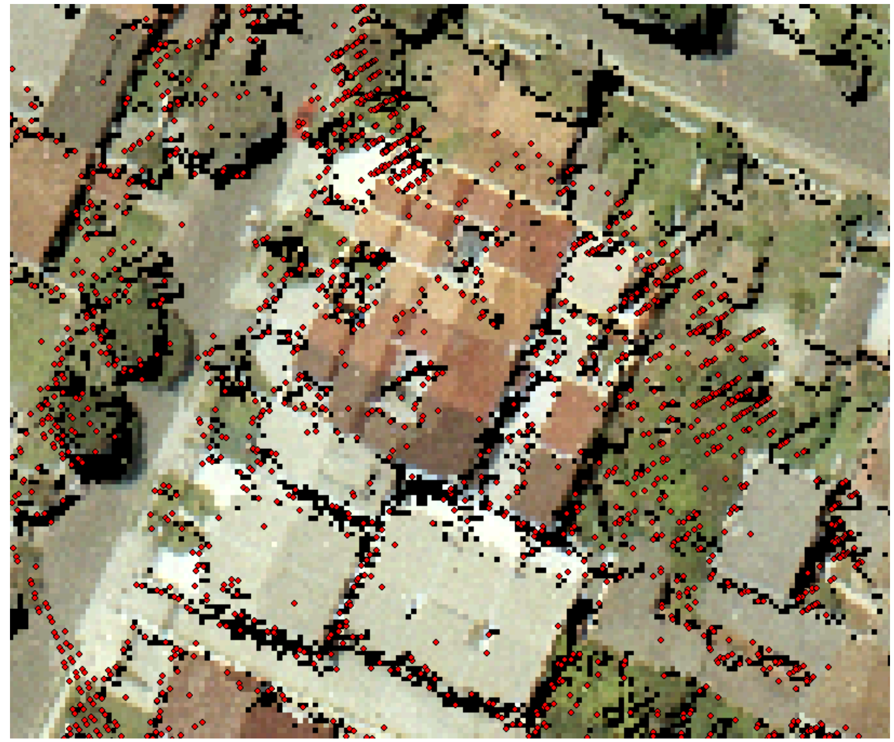




Green: Reference Surface
Blue: Matches
Red: Non-matches

IQC: LiDAR Quality Control (#5)

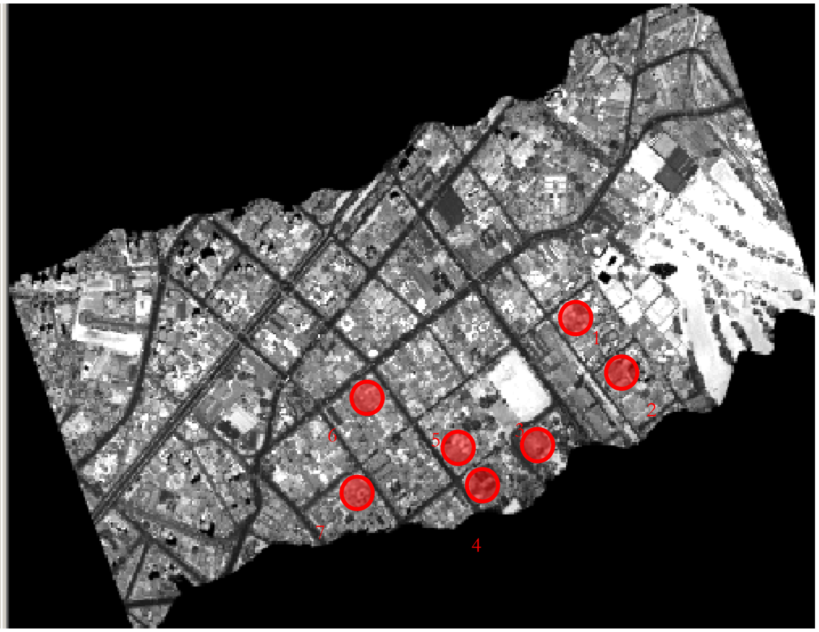




Non-matches are typically along edges of buildings and around areas with vegetations

IQC: LiDAR Quality Control (#5)

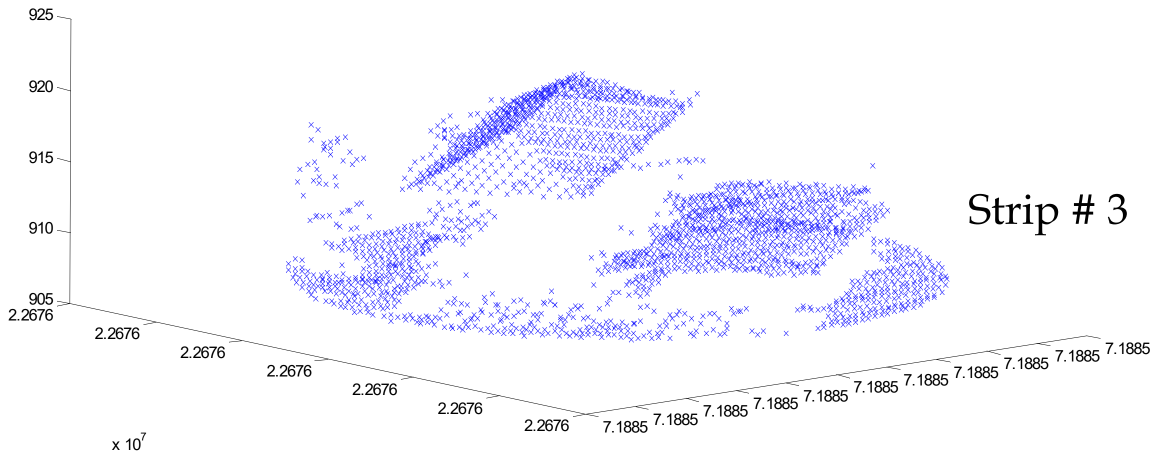
Strip # 3

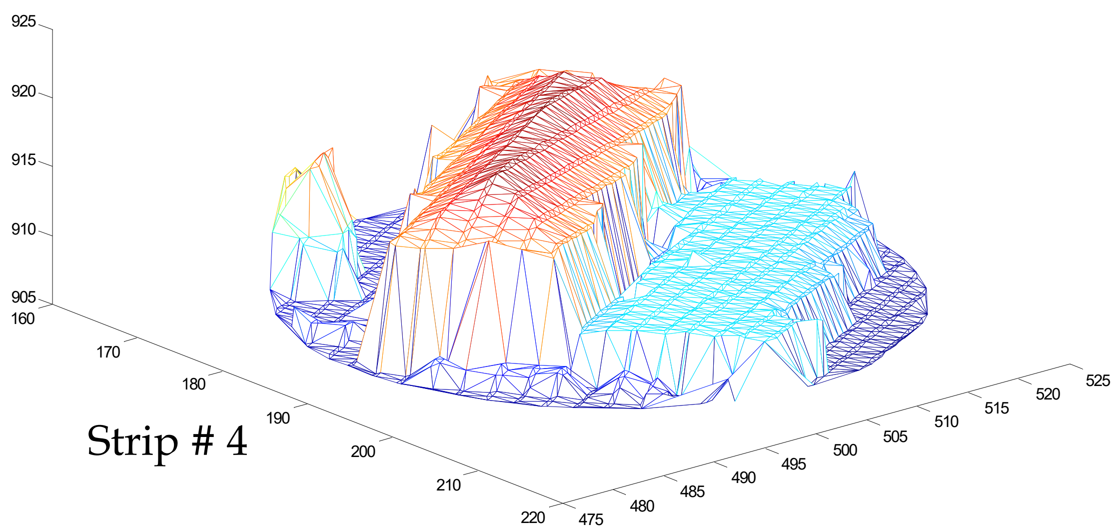


Strip # 4

IQC: LiDAR Quality Control (#5)

IQC: LiDAR Quality Control (#5)

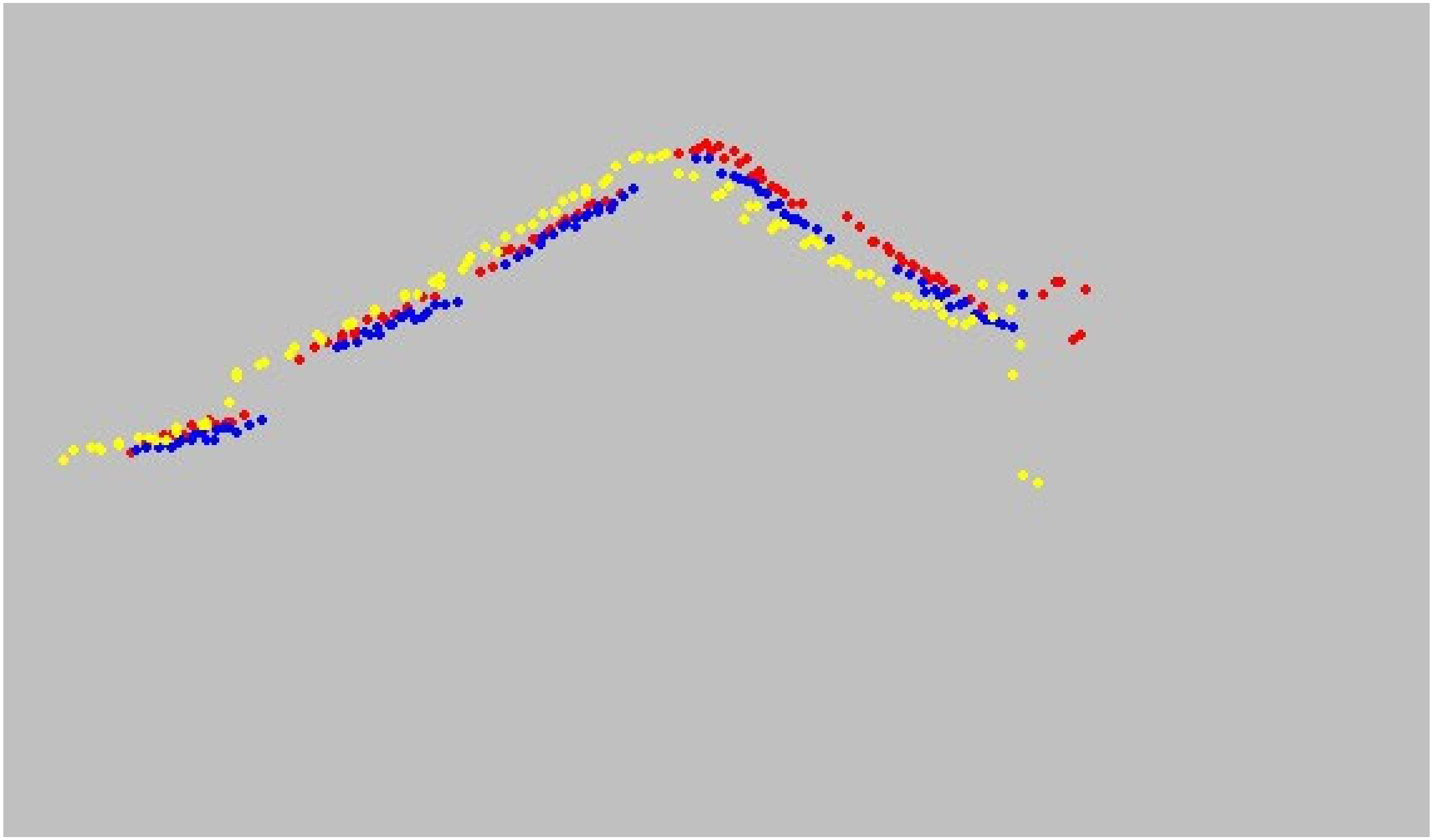




IQC: LiDAR Quality Control (#5)

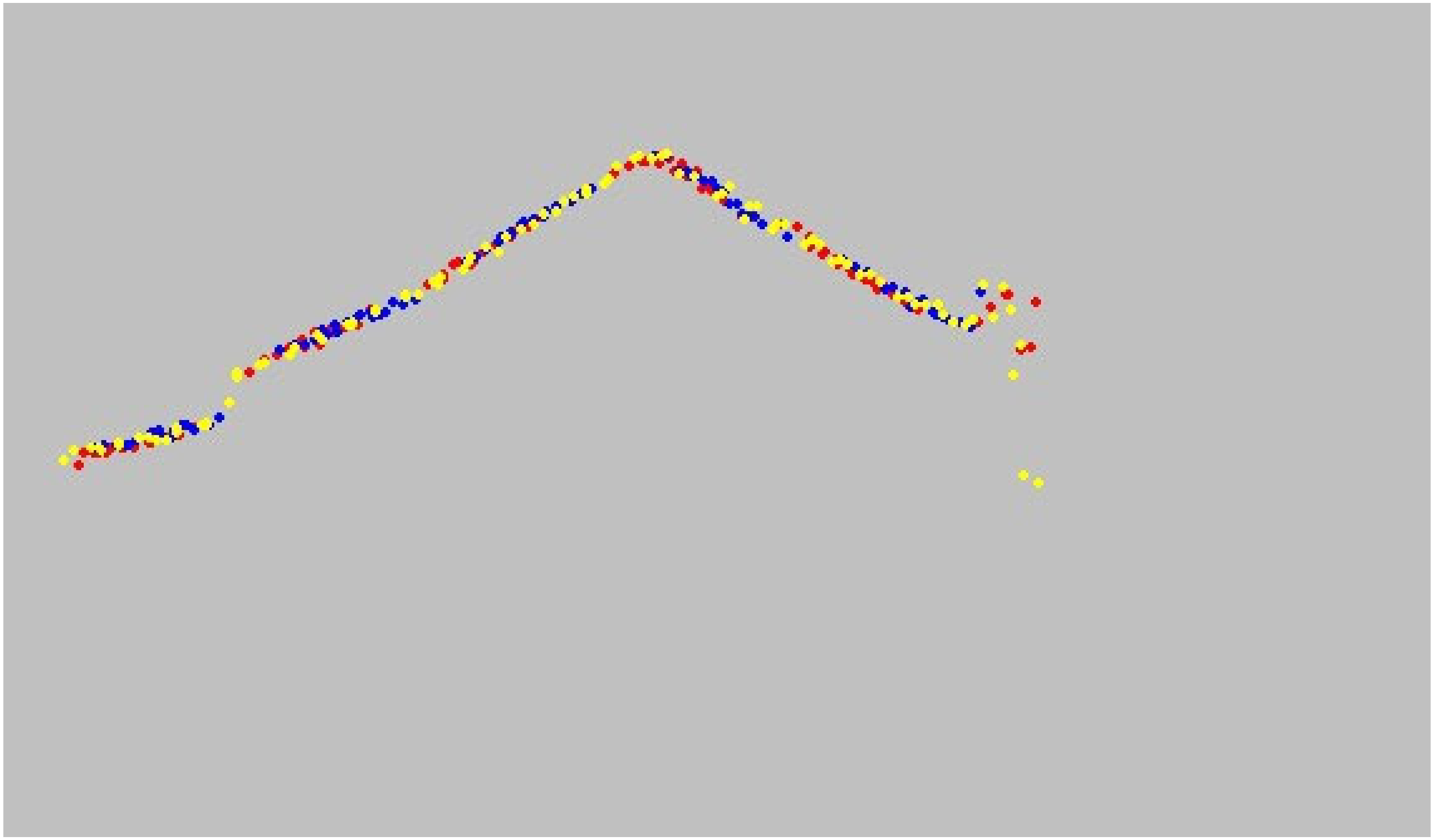
	One Building (1)	Three Building Areas (1,2,3)	Seven Building Areas
Scale Factor	0.9997	0.9998	0.9998
X_T (m)	0.85	0.56	0.75
Y_T (m)	-0.07	-0.26	-0.13
Z_T (m)	0.15	0.09	0.12
ω (°)	-0.0218	-0.0200	-0.0267
ϕ (°)	-0.0201	-0.0034	-0.0088
κ (°)	0.1239	-0.0189	-0.0003
Average Normal Distance, m	0.10	0.09	0.09

IQC: LiDAR Quality Control



Check for the presence of biases

IQC: LiDAR Quality Control



Check the noise level in the point cloud after bias removal

IQC: LiDAR Quality Control

- Checking the noise level in the point cloud: The quality of fit between conjugate entities after removing existing biases
  - Average normal distance between conjugate planar patches
  - Average normal distance between conjugate linear features
  - Average normal distance between conjugate point-patch pairs in the ICPatch

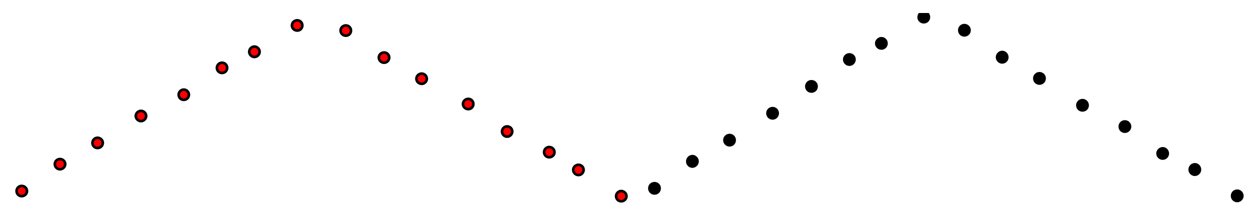
LiDAR Quality Control (IQC & EQC)

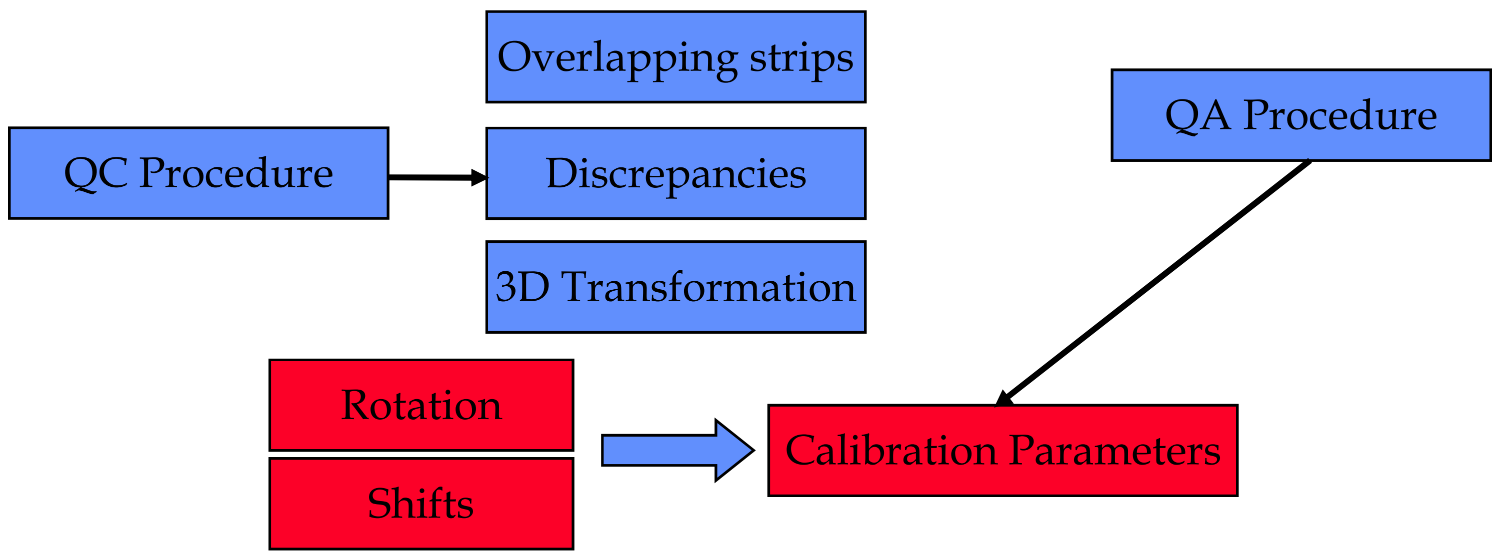
- The previous IQC measures can be used for EQC.
- In such a case, instead of comparing overlapping strips, the EQC can be evaluated by comparing the LiDAR point cloud to an independently collected surface.
- The last three QC measures (line-based, plane-based, and ICPatch approaches) will lead to more reliable estimation of the internal and external quality of the LiDAR data.
- The last QC measure (ICPatch approach) is preferred since it is based on the original/irregular LiDAR point cloud.

LiDAR QA/QC: Closed-Loop Approach

• LiDAR Data in Overlapping Parallel Strips

- ✓ Point cloud coordinates
- ✓ Raw measurements are not necessarily available





Experimental Results

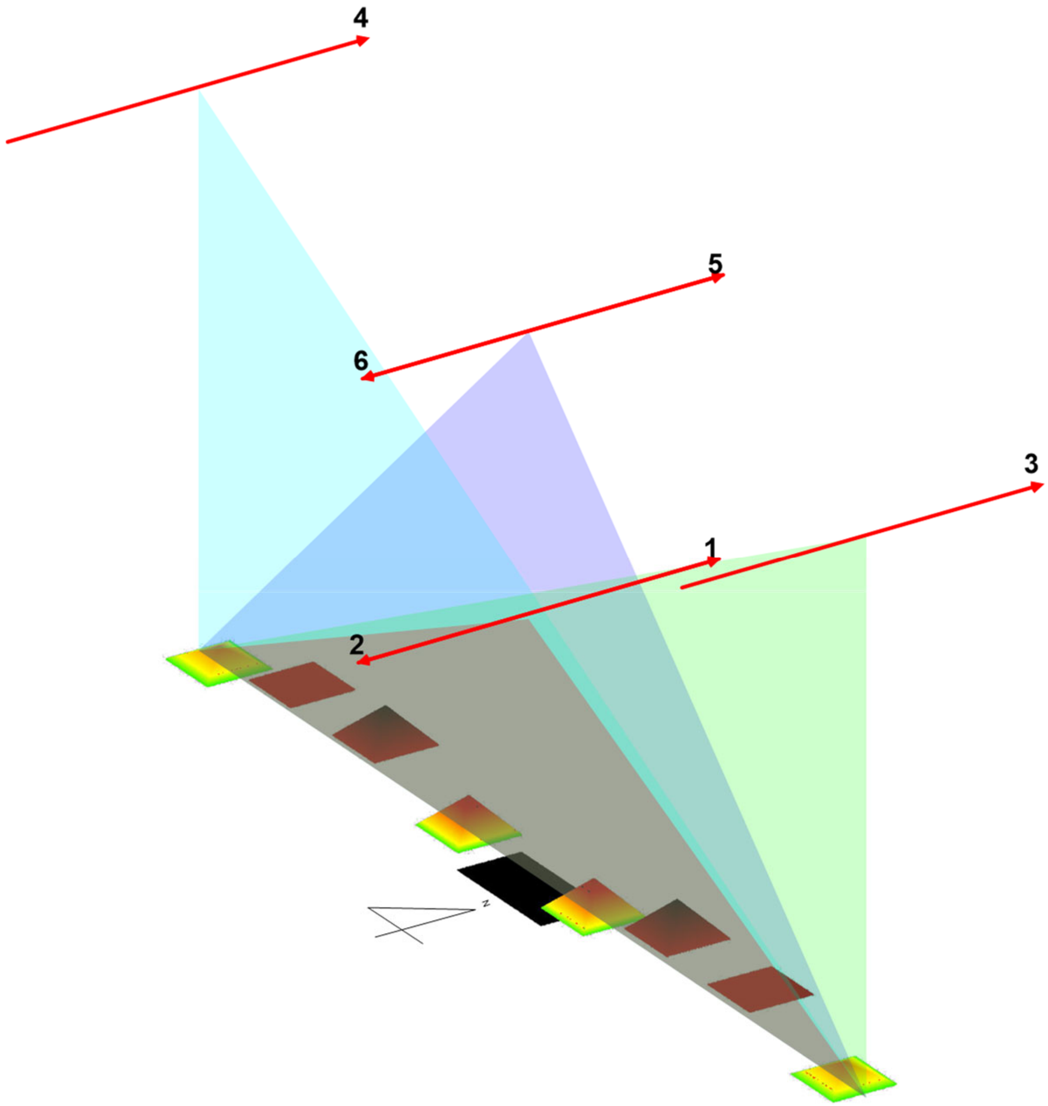
Simulated & Real Datasets

LiDAR QA/QC: Experimental Results (I)

- Simulated System Specifications:
  - Pulse repetition rate: 167kHz
  - Scan frequency: 100Hz
  - Scan angle range: -22° – +22°
  - Position accuracy: ±0.10m horizontal & ±0.15m vertical
  - Orientation accuracy: roll and pitch: ±0.01° & heading: ±0.016°
  - Lever-arm offset accuracy: ±0.005m, ±0.005m, and ±0.005m
  - Boresight accuracy: ±10.0", ± 10.0", and ± 10.0"

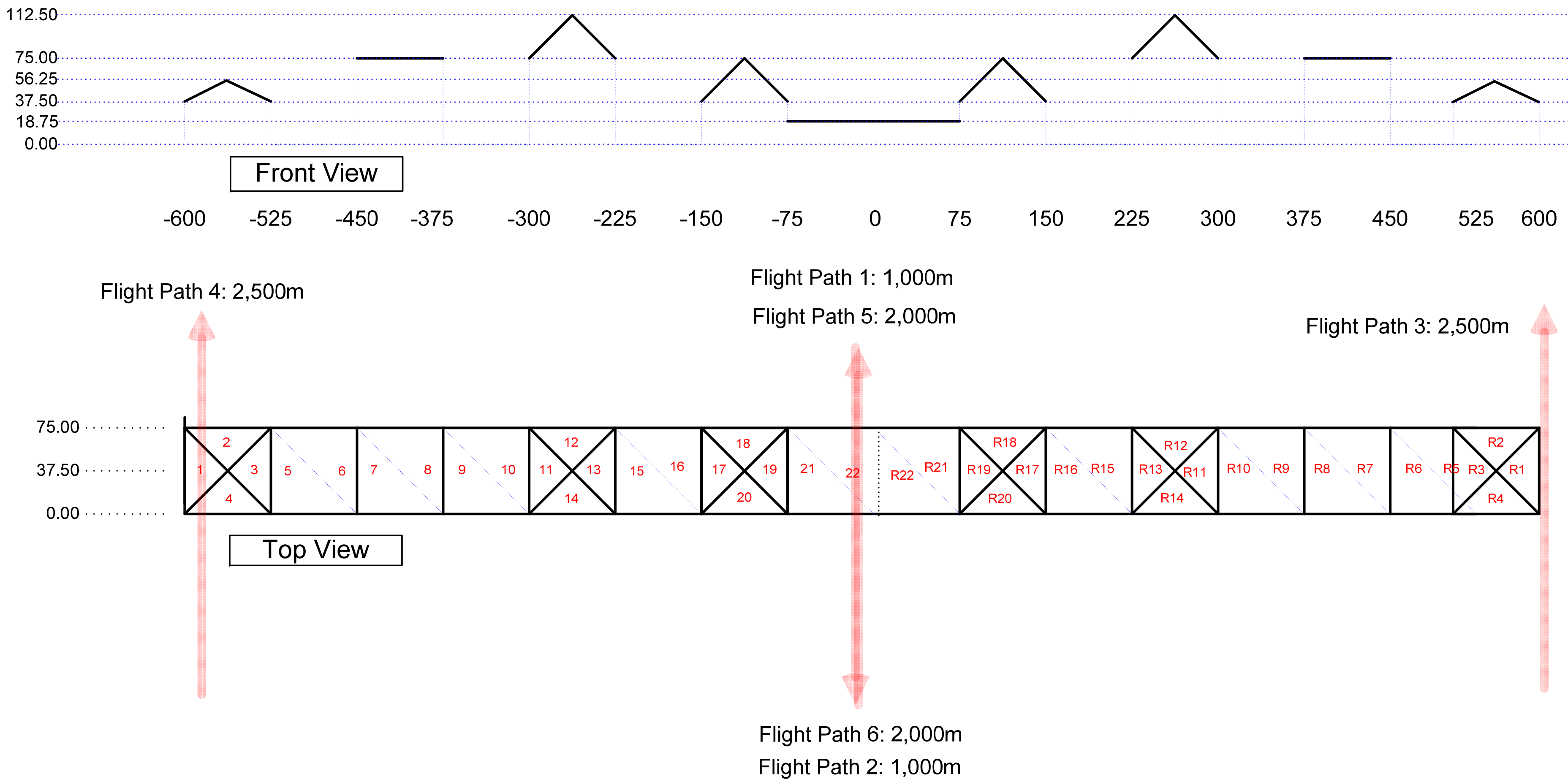
LiDAR QA/QC: Experimental Results (I)

- Simulated Flight Path and Surface



LiDAR QA/QC: Experimental Results (I)

- Simulated Flight Path and Surface



LiDAR QA/QC: Experimental Results (I)

- Simulated Strip & System Parameters:

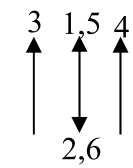
	Strip 1	Strip 2	Strip 3	Strip 4	Strip 5	Strip 6
Speed	216 km/h					
Flight heading	0°	180°	0°	0°	0°	180°
(Position in X axis)	0	0	600	-600	0	0
Flying Height	1,000 m	1,000 m	2,500 m	2,500 m	2,000 m	2,000 m

Expected Accuracy [m]		
σ_X	σ_Y	σ_Z
0.37	0.33	0.21

Simulated System Parameters							
$\delta\Delta X$[m]	$\delta\Delta Y$[m]	$\delta\Delta Z$[m]	$\delta\Delta\omega$[°]	$\delta\Delta\varphi$[°]	$\delta\Delta\kappa$[°]	$\delta\rho$ [m]	δS
0.05	0.05	0.05	0.01	0.01	0.01	0.5	1.001

LiDAR QA/QC: Experimental Results (I)

- Detected Discrepancies and Calibration Results



QC

CASE-I (1 & 2)			CASE-II (4 & 3)			CASE-III (5 & 6)		
Xt	Yt	Zt	Xt	Yt	Zt	Xt	Yt	Zt
-0.23	0.42	0.00	-1.42	-0.20	0.23	-0.58	0.78	0.00
ω°	φ°	κ°	ω°	φ°	κ°	ω°	φ°	κ°
0.004	0.020	0.001	-0.004	0.058	-0.001	0.002	0.020	0.001
S	$\hat{\sigma}_o$	Norm	S	$\hat{\sigma}_o$	Norm	S	$\hat{\sigma}_o$	Norm
1.00000	0.31906	0.12117	1.000	0.57325	0.21769	1.00000	0.45300	0.17026

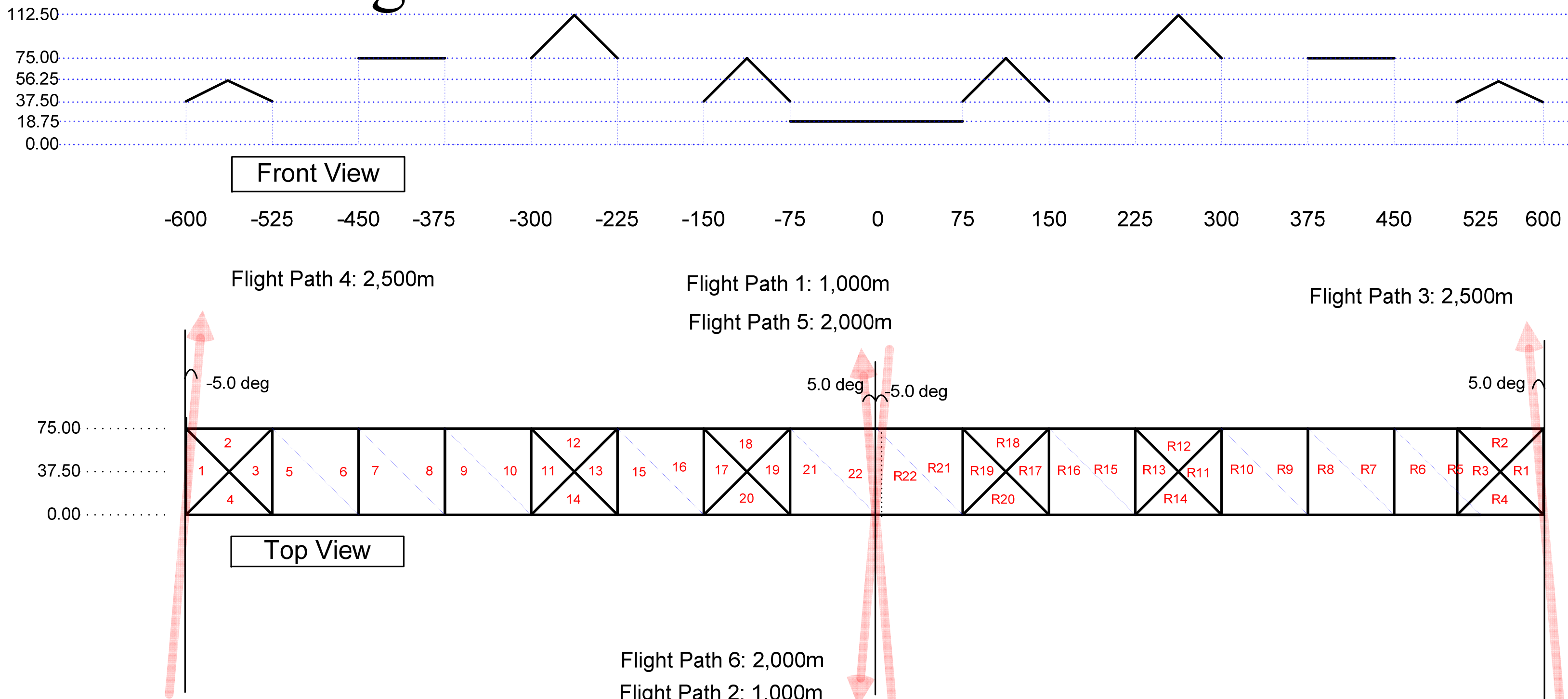
Simulated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[°]	δΔφ[°]	δΔκ[°]	δρ [m]	δS
0.05	0.05	0.05	0.01	0.01	0.01	0.5	0.001

QA

Estimated System Parameters (Simplified Calibration)							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[°]	δΔφ[°]	δΔκ[°]	δρ [m]	δS
0.050	0.040	???	0.0103	0.0100	0.0095	0.37	0.0011

LiDAR QA/QC: Experimental Results (I)

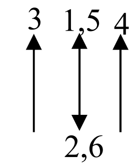
- Simulated Flight Path & Surface:



	Strip 1	Strip 2	Strip 3	Strip 4	Strip 5	Strip 6
Speed	216 km/h					
Flight heading	5°	175°	5°	-5°	5°	175°
(Position in X axis)	0	0	600	-600	0	0
Flying Height	1,000 m	1,000 m	2,500 m	2,500 m	2,000 m	2,000 m

LiDAR QA/QC: Experimental Results (I)

- Detected Discrepancies and Calibration Results



QC

CASE-I (1 & 2)			CASE-II (4 & 3)			CASE-III (5 & 6)		
Xt	Yt	Zt	Xt	Yt	Zt	Xt	Yt	Zt
-0.24	0.42	0.00	-1.47	-0.30	0.26	-0.58	0.76	0.00
ω°	φ°	κ°	ω°	φ°	κ°	ω°	φ°	κ°
0.001	0.021	0.038	0.001	0.057	0.014	-0.003	0.021	0.041
S	$\hat{\sigma}_o$	Norm	S	$\hat{\sigma}_o$	Norm	S	$\hat{\sigma}_o$	Norm
1.000	0.350	0.136	1.000	0.571	0.219	1.000	0.475	0.187

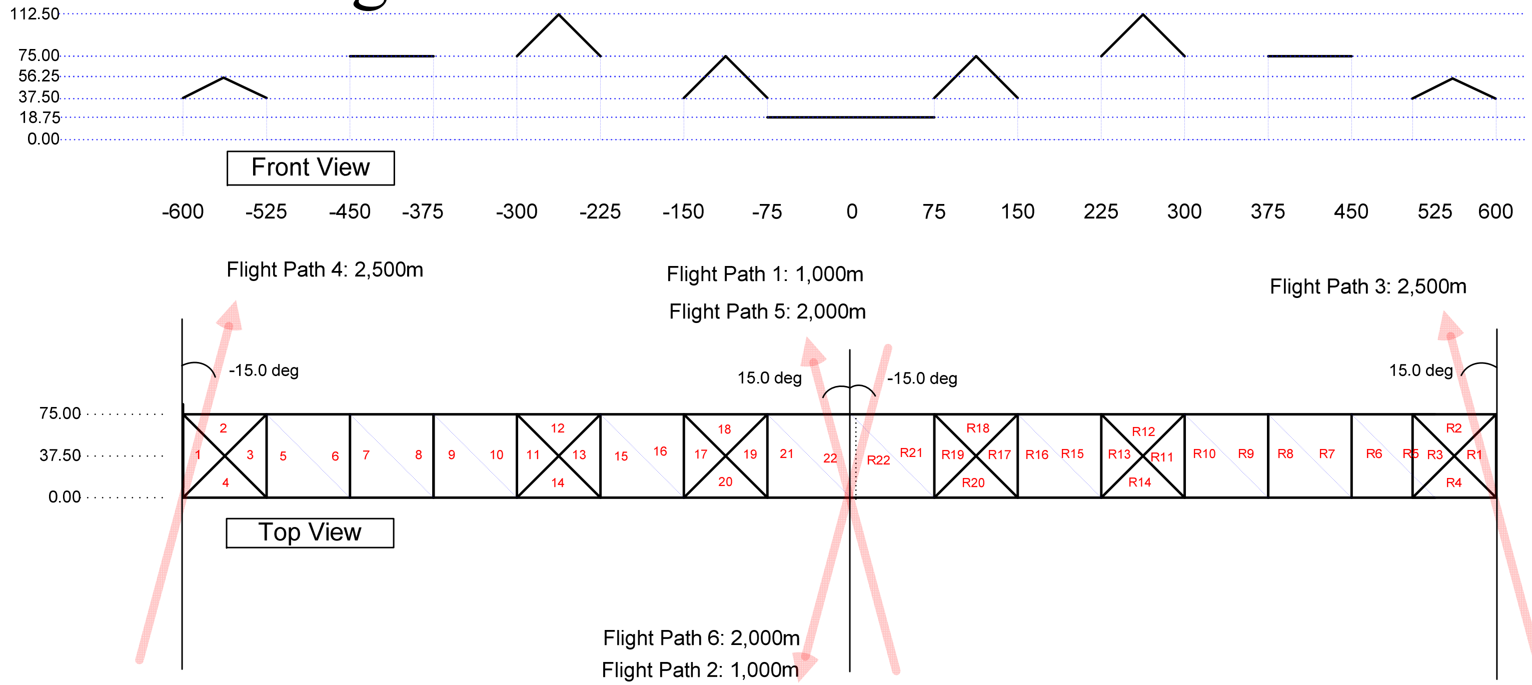
Simulated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.05	0.05	0.05	0.01	0.01	0.01	0.5	0.001

QA

Estimated System Parameters (Simplified Calibration)							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.060	0.050	???	0.0097	0.0105	0.0143	0.52	0.0011

LiDAR QA/QC: Experimental Results (I)

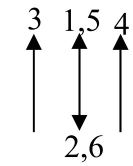
- Simulated Flight Path & Surface:



	Strip 1	Strip 2	Strip 3	Strip 4	Strip 5	Strip 6
Speed	216 km/h					
Flight heading	15°	165°	15°	-15°	15°	165°
(Position in X axis)	0	0	600	-600	0	0
Flying Height	1,000 m	1,000 m	2,500 m	2,500 m	2,000 m	2,000 m

LiDAR QA/QC: Experimental Results (I)

- Detected Discrepancies and Calibration Results



QC

CASE-I (1 & 2)			CASE-II (4 & 3)			CASE-III (5 & 6)		
Xt	Yt	Zt	Xt	Yt	Zt	Xt	Yt	Zt
-0.23	0.41	-0.00	-1.54	-0.39	0.22	-0.54	0.75	-0.00
ω°	φ°	κ°	ω°	φ°	κ°	ω°	φ°	κ°
0.002	0.019	0.045	-0.003	0.054	0.034	0.003	0.018	0.037
S	$\hat{\sigma}_o$	Norm	S	$\hat{\sigma}_o$	Norm	S	$\hat{\sigma}_o$	Norm
1.000	0.284	0.123	1.000	0.440	0.191	1.000	0.378	0.164

Simulated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.05	0.05	0.05	0.01	0.01	0.01	0.5	0.001

QA

Estimated System Parameters (Simplified Calibration)							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.047	0.050	???	0.0096	0.0094	0.0189	0.83	0.0009

LiDAR QA/QC: Experimental Results (I)

Parallel Strips

Simulated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.05	0.05	0.05	0.01	0.01	0.01	0.5	0.001

Simplified Approach

Estimated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.050	0.040	???	0.0103	0.0100	0.0095	0.37	0.0011

Quasi-Rigorous Approach

Estimated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.050	0.040	???	0.0103	0.0100	0.0095	0.37	0.0011

LiDAR QA/QC: Experimental Results (I)

5° deviation from Parallelism

Simulated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.05	0.05	0.05	0.01	0.01	0.01	0.5	0.001

Simplified Approach

Estimated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.060	0.050	???	0.0097	0.0105	0.0143	0.52	0.0011

Quasi-Rigorous Approach

Estimated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.049	0.048	???	0.0101	0.0100	0.0096	0.50	0.0009

LiDAR QA/QC: Experimental Results (I)

15° deviation from Parallelism

Simulated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.05	0.05	0.05	0.01	0.01	0.01	0.5	0.001

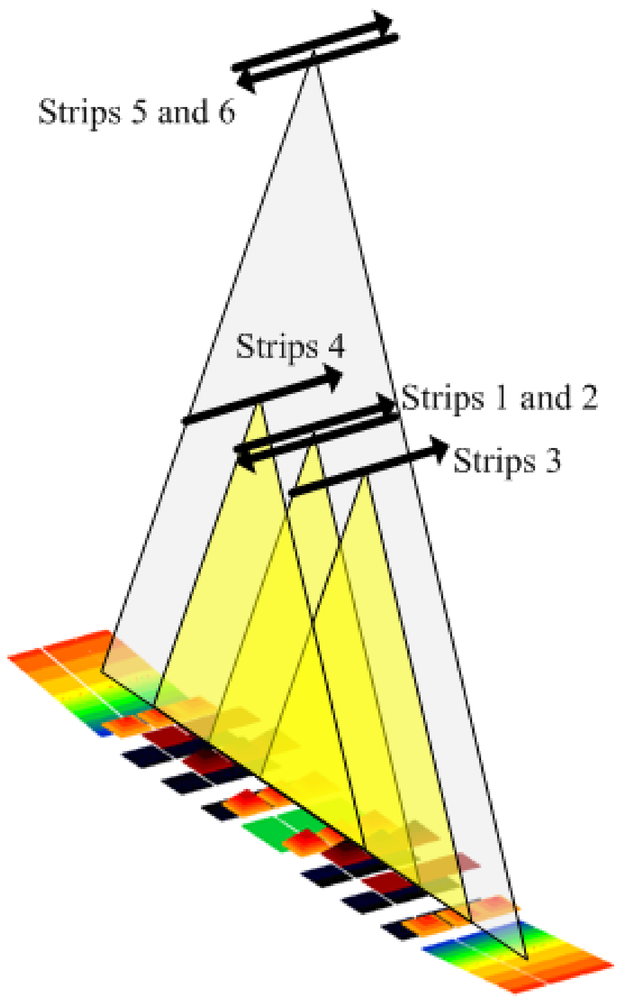
Simplified Approach

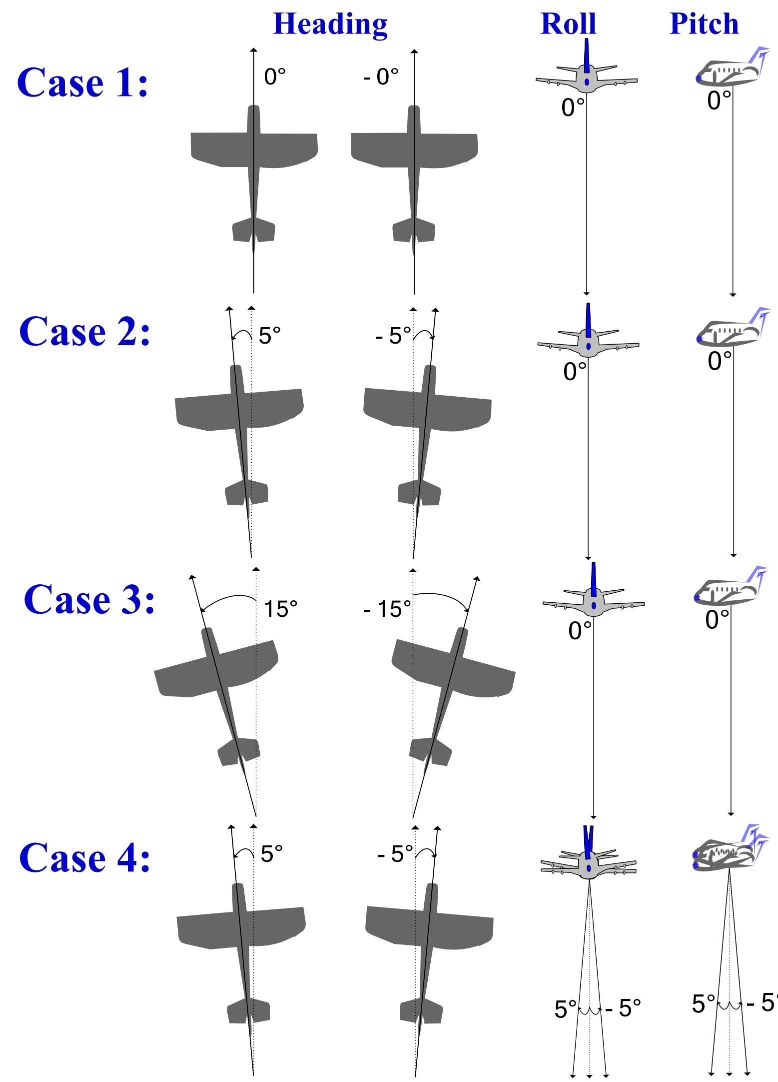
Estimated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.047	0.050	???	0.0096	0.0094	0.0189	0.83	0.0009

Quasi-Rigorous Approach

Estimated System Parameters							
δΔX[m]	δΔY[m]	δΔZ[m]	δΔω[˚]	δΔφ[˚]	δΔκ[˚]	δρ [m]	δS
0.049	0.049	???	0.0100	0.0100	0.0096	0.53	0.0010

LiDAR QA/QC: Experimental Results (I)





LiDAR QA/QC: Experimental Results (I)

Comparison between true and noise/bias-contaminated coordinates

	Mean			RMSE		
	X (m)	*Y* (m)	*Z* (m)	*X* (m)	*Y* (m)	*Z* (m)
	Parallel overlapping strips					
Strip3 (1,000m)	**-0.065**	**0.216**	**-0.370**	0.456	0.301	0.413
Strip6 (2,000m)	**-0.289**	**0.391**	**-0.303**	0.828	0.555	0.393
	Non-parallel overlapping strips (10˚)					
Strip3 (1,000m)	**-0.065**	**0.220**	**-0.378**	0.436	0.310	0.418
Strip6 (2,000m)	**0.224**	**-0.414**	**-0.303**	0.820	0.566	0.394
	Non-parallel overlapping strips (30˚)					
Strip3 (1,000m)	**-0.071**	**0.217**	**-0.389**	0.403	0.326	0.426
Strip6 (2,000m)	**0.275**	**-0.438**	**-0.305**	0.833	0.587	0.407
	Non-parallel (10˚) and un-levelled overlapping strips(5˚)					
Strip3 (1,000m)	**-0.129**	**0.238**	**-0.359**	0.447	0.323	0.401
Strip6 (2,000m)	**0.287**	**-0.419**	**-0.281**	0.812	0.574	0.371

LiDAR QA/QC: Experimental Results (I)

Comparison between true and adjusted coordinates using the simplified reconstruction formula and estimated biases

	Mean			RMSE		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)
	Parallel overlapping strips					
Strip3 (1,000m)	**0.011**	**0.006**	**0.005**	0.247	0.207	0.163
Strip6 (2,000m)	**-0.011**	**-0.003**	**-0.009**	0.477	0.384	0.195
	Non-parallel overlapping strips (10˚)					
Strip3 (1,000m)	**0.006**	**0.003**	**0.006**	0.247	0.207	0.163
Strip6 (2,000m)	**-0.006**	**-0.001**	**-0.008**	0.475	0.384	0.195
	Non-parallel overlapping strips (30˚)					
Strip3 (1,000m)	**-0.013**	**-0.000**	**0.217**	0.247	0.213	0.270
Strip6 (2,000m)	**0.010**	**-0.012**	**-0.211**	0.474	0.387	0.284
	Non-parallel (10˚) and un-levelled overlapping strips(5˚)					
Strip3 (1,000m)	**0.011**	**0.006**	**0.160**	0.264	0.207	0.229
Strip6 (2,000m)	**0.017**	**-0.016**	**0.162**	0.504	0.382	0.257

LiDAR QA/QC: Experimental Results (I)

Comparison between true and adjusted coordinates
using the quasi-rigorous reconstruction formula and estimated biases

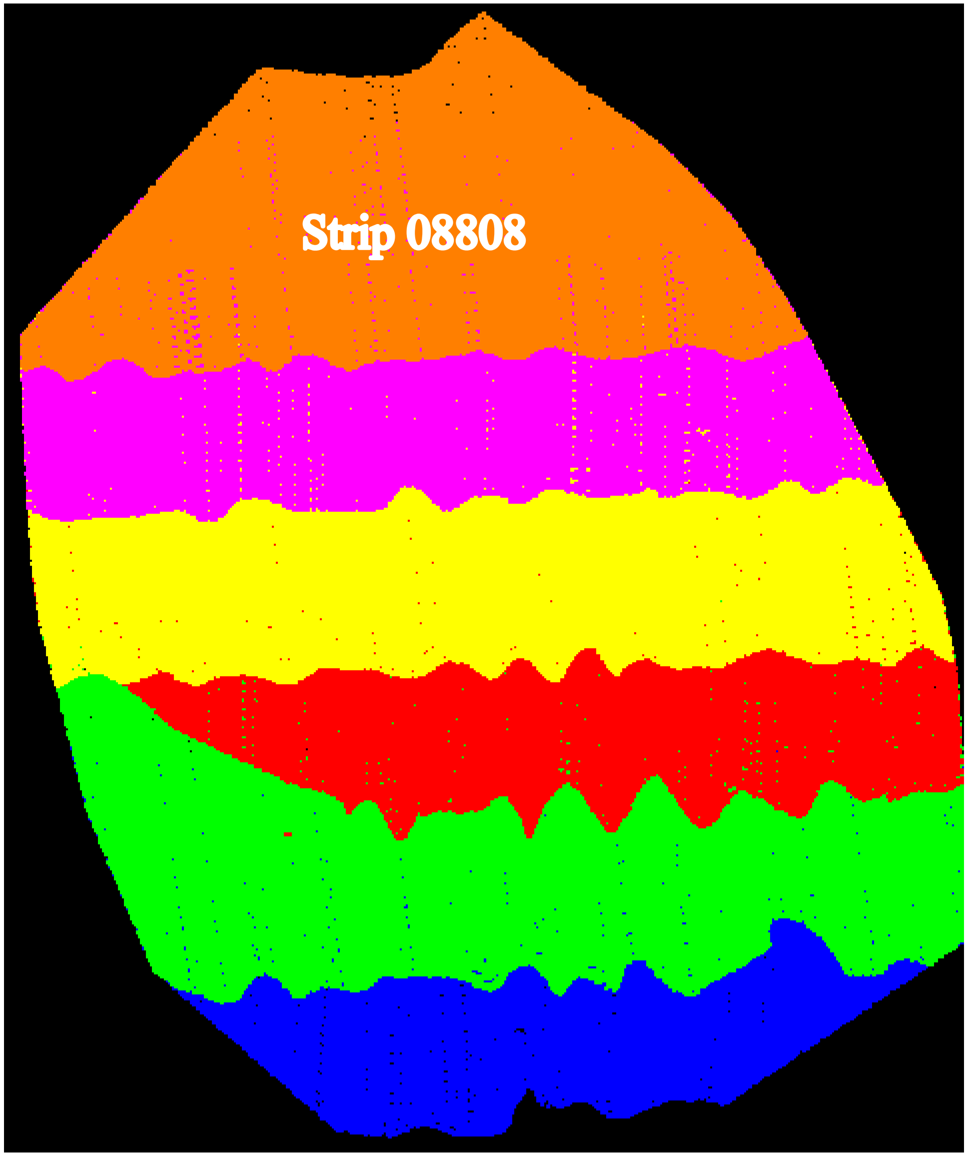
	Mean			RMSE		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)
	Parallel overlapping strips					
Strip3 (1,000m)	**0.000**	**0.001**	**0.022**	0.244	0.206	0.164
Strip6 (2,000m)	**-0.001**	**0.002**	**0.022**	0.468	0.383	0.195
	Un-parallel overlapping strips (10˚)					
Strip3 (1,000m)	**0.003**	**0.001**	**0.022**	0.244	0.206	0.164
Strip6 (2,000m)	**0.009**	**0.007**	**0.022**	0.466	0.384	0.195
	Un-parallel overlapping strips (30˚)					
Strip3 (1,000m)	**-0.015**	**-0.032**	**0.017**	0.248	0.211	0.163
Strip6 (2,000m)	**-0.000**	**0.005**	**0.022**	0.463	0.385	0.191
	Non-parallel (10˚) and un-levelled overlapping strips(5˚)					
Strip3 (1,000m)	**0.003**	**-0.001**	**0.092**	0.253	0.207	0.187
Strip6 (2,000m)	**0.007**	**0.013**	**0.101**	0.487	0.385	0.221

LiDAR QA/QC: Experimental Results (II)

- Dataset Specifications

Sensor Model	Optech 3100
Ground Point Spacing	~0.75m
Surveying Date	Julian Day: 088 6 strips @1000m AGH Julian Day: 130 4 strips @1400m AGH

LiDAR QA/QC: Experimental Results (II)

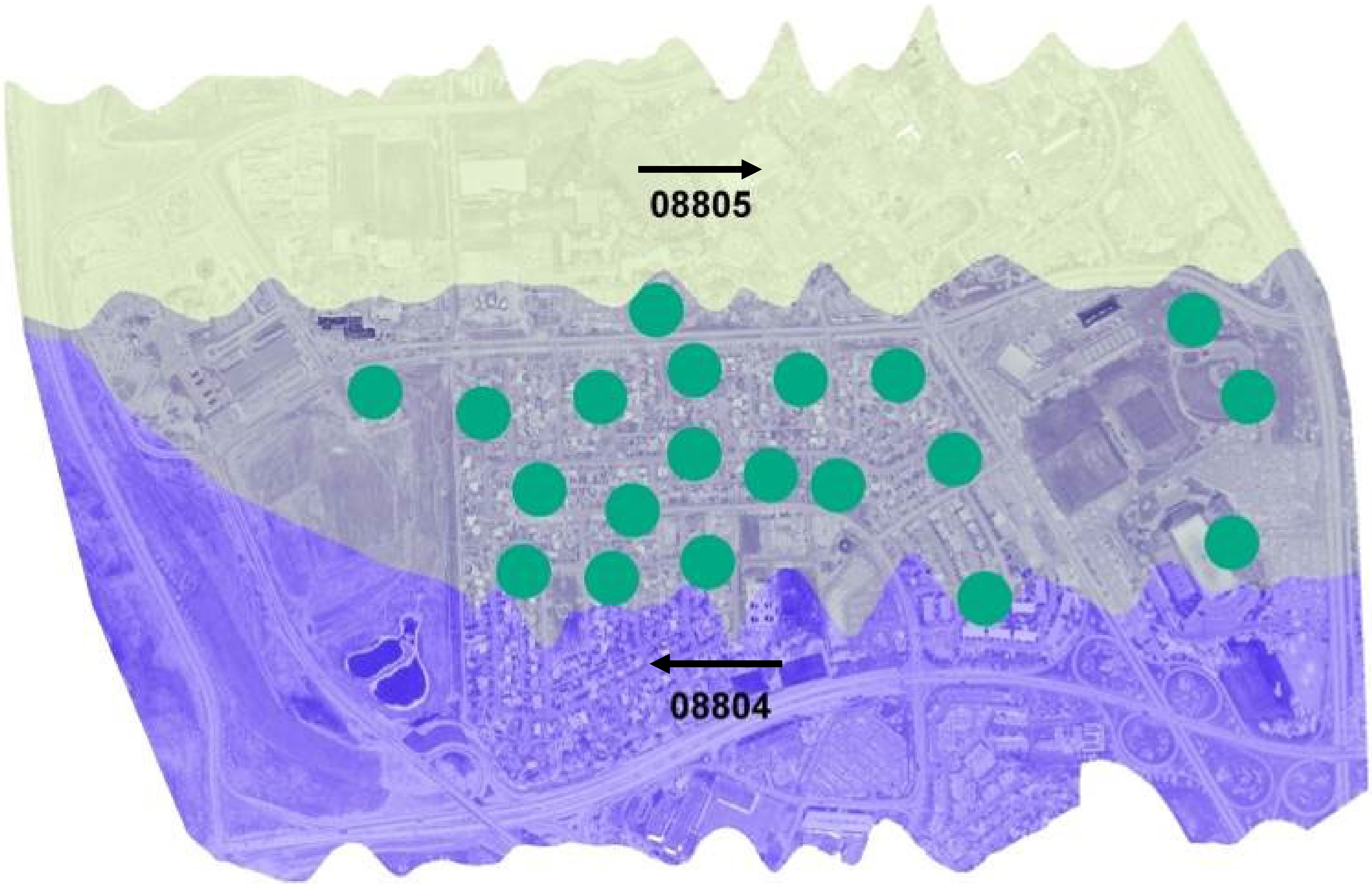


LiDAR QA/QC: Experimental Results (II)

- Strips 08803 & 08804

LiDAR QA/QC: Experimental Results (II)

- Strips 08804 & 08805



LiDAR QA/QC: Experimental Results (II)

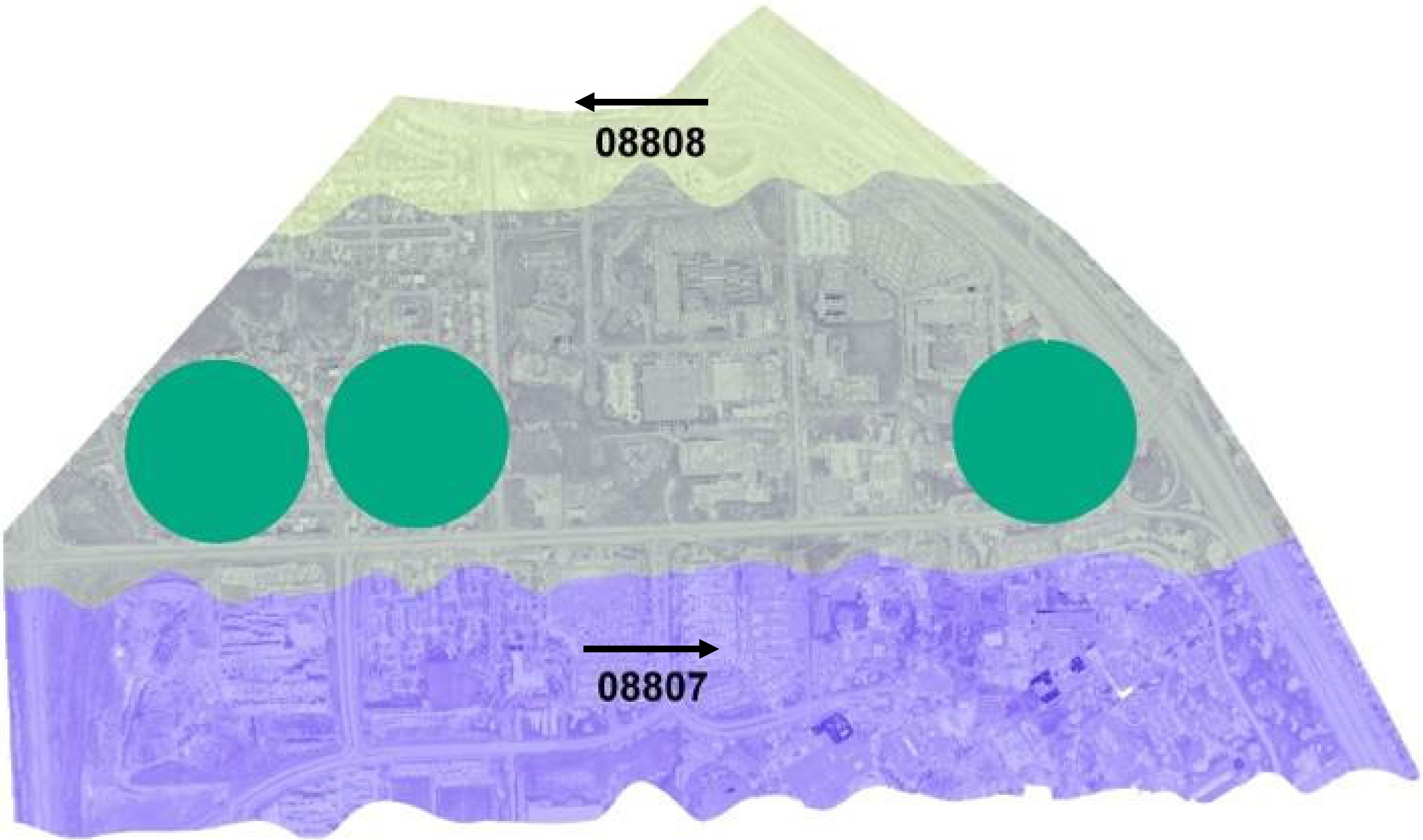
- Strips 08805 & 08806

LiDAR QA/QC: Experimental Results (II)

- Strips 08806 & 08807

LiDAR QA/QC: Experimental Results (II)

- Strips 08807 & 08808



LiDAR QA/QC: Experimental Results (II)

- Strips 08803 & 08805

LiDAR QA/QC: Experimental Results (II)

- Strips 08805 & 08807

LiDAR QA/QC: Experimental Results (II)

- System Diagnosis

	X_T (m)	Y_T (m)	Z_T (m)	Φ (°)
3 – 4	-0.14	0.03	-0.01	0.0061
5 – 4	-0.16	0.90	-0.02	0.0094
5 – 6	-0.09	-0.06	0.00	0.0110
7 – 6	-0.12	0.84	0.07	0.0071
7 – 8	-0.10	-0.15	0.02	0.0109

$$\begin{bmatrix} \tilde{X}_A^{Biased} \\ \tilde{Y}_A^{Biased} \\ \tilde{Z}_A^{Biased} \end{bmatrix} = \begin{bmatrix} 2\ \delta\Delta X - 2\ H\ \delta\Delta\varphi \mp D/H\ \delta\rho \mp H\ \delta\theta \\ 2\,\delta\Delta Y + 2\ H\ \delta\Delta\omega \mp D\ \delta\Delta\kappa \\ 0 \end{bmatrix} + R_{(2\delta\Delta\varphi \pm 2\delta\theta)} \begin{bmatrix} \tilde{X}_B^{Biased} \\ \tilde{Y}_B^{Biased} \\ \tilde{Z}_B^{Biased} \end{bmatrix} + \vec{e}_{AB}$$

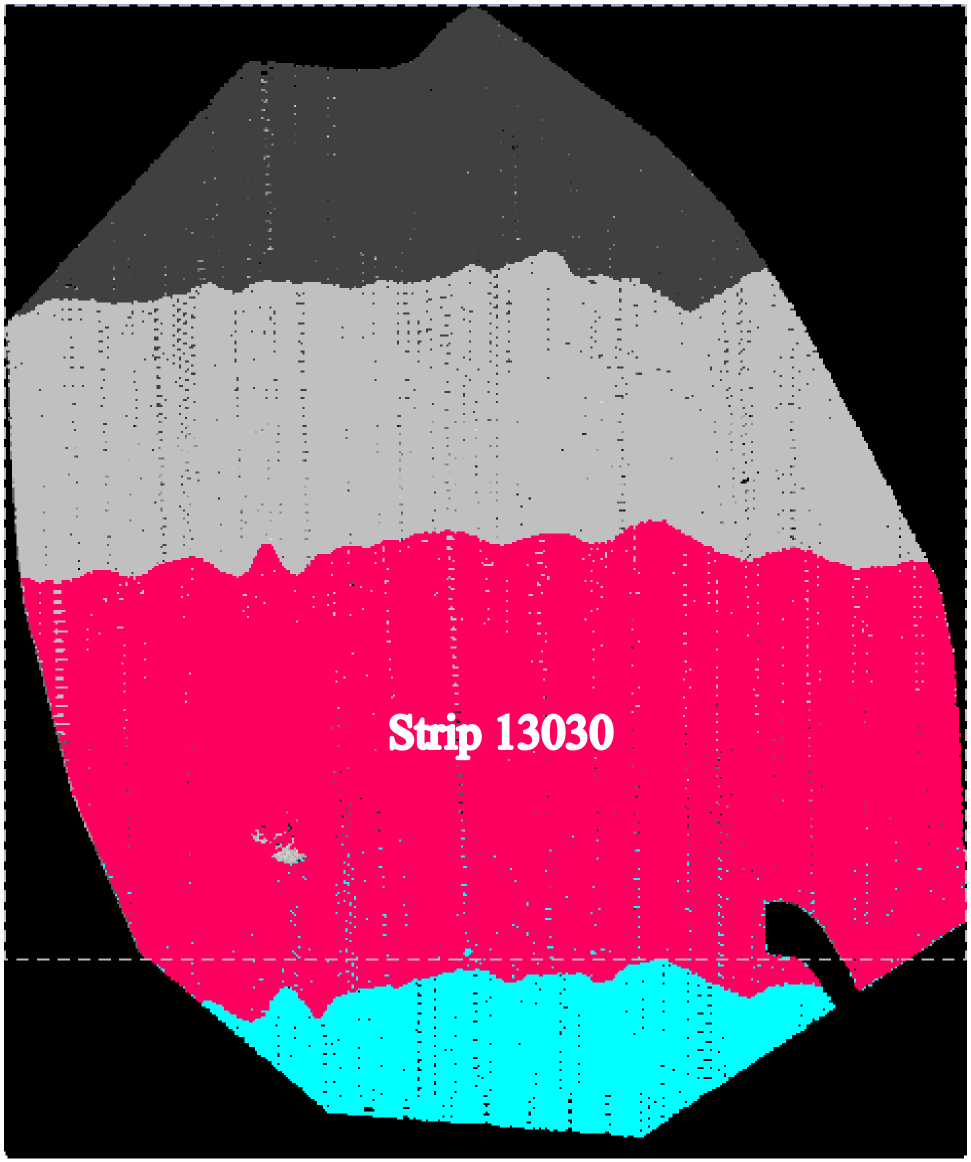
LiDAR QA/QC: Experimental Results (II)

- System Diagnosis

	X_T (m)	Y_T (m)	Z_T (m)	Φ (°)
3 – 5	-0.04	-0.81	0.07	-0.0030
5 – 7	0.04	-0.89	0.02	0.0034

$$\begin{bmatrix} \tilde{X}_A^{Biased} \\ \tilde{Y}_A^{Biased} \\ \tilde{Z}_A^{Biased} \end{bmatrix} = \begin{bmatrix} -D/H\ \delta\rho - H\ \delta\theta \\ -D\ \delta\Delta\kappa \\ D\ \delta\Delta\varphi \end{bmatrix} + R_{2\ \delta\theta} \begin{bmatrix} \tilde{X}_B^{Biased} \\ \tilde{Y}_B^{Biased} \\ \tilde{Z}_B^{Biased} \end{bmatrix} + \vec{e}_{AB}$$

LiDAR QA/QC: Experimental Results (II)

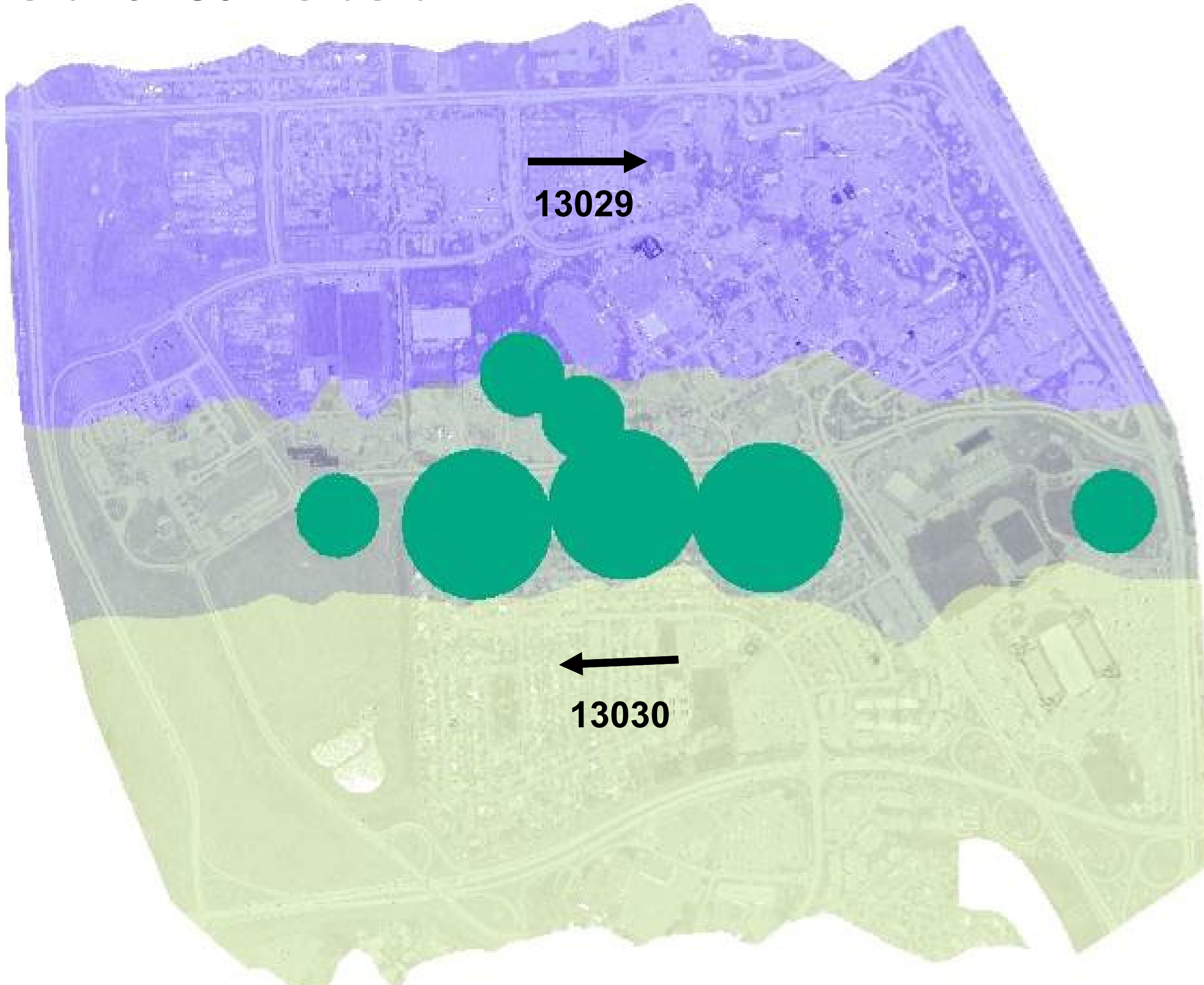


LiDAR QA/QC: Experimental Results (II)

- Strips 13027 & 13030

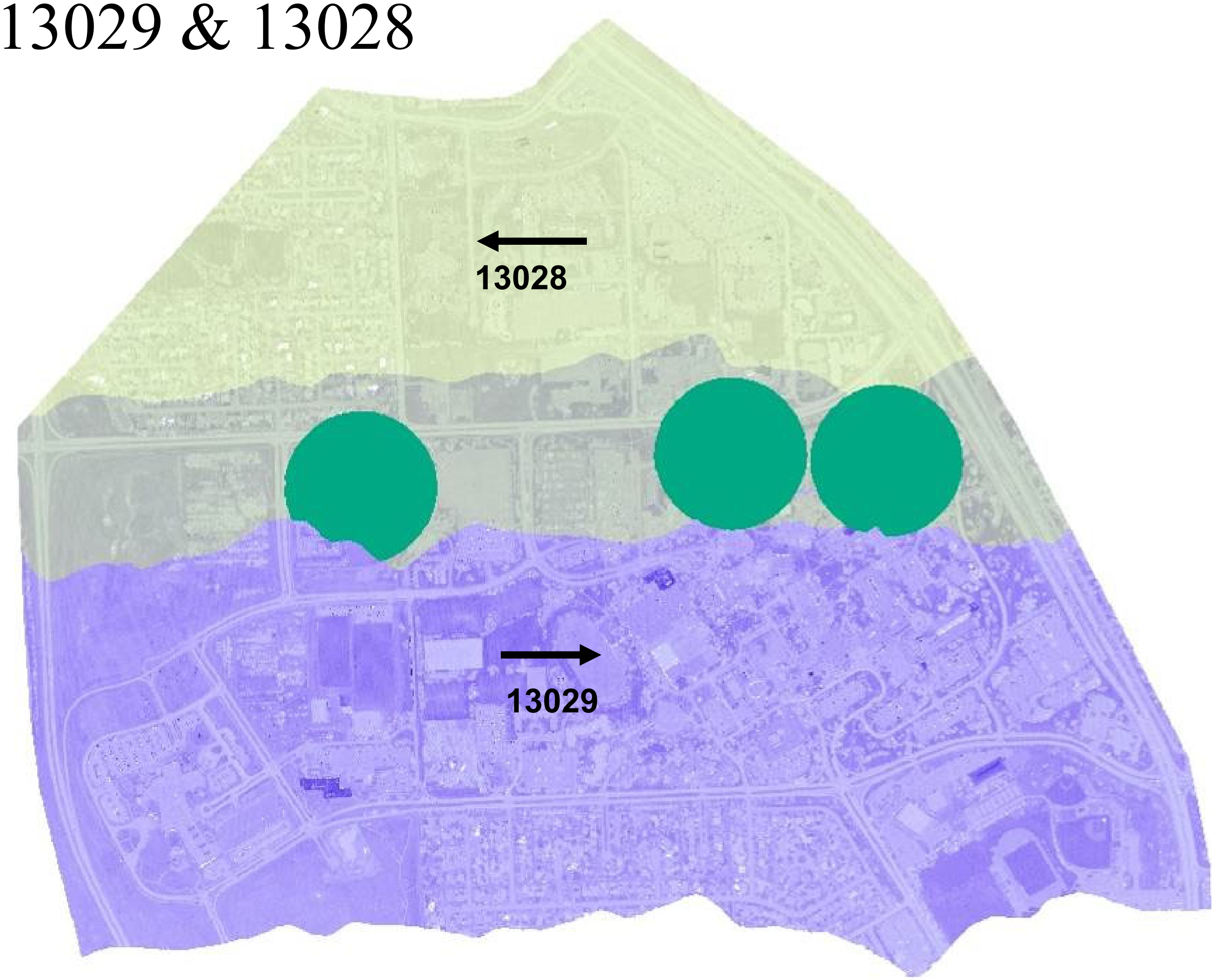
LiDAR QA/QC: Experimental Results (II)

- Strips 13029 & 13030



LiDAR QA/QC: Experimental Results (II)

- Strips 13029 & 13028



LiDAR QA/QC: Experimental Results (II)

- System Diagnosis

	X_T (m)	Y_T (m)	Z_T (m)	Φ (°)
27 – 30	-0.46	-1.36	0.11	0.0471
29 – 30	0.37	0.32	0.01	-0.0162
29 – 28	-0.33	-1.28	-0.06	0.0462

$$\begin{bmatrix} \tilde{X}_A^{Biased} \\ \tilde{Y}_A^{Biased} \\ \tilde{Z}_A^{Biased} \end{bmatrix} = \begin{bmatrix} 2\ \delta\Delta X - 2\ H\ \delta\Delta\varphi \mp D / H\ \delta\rho \mp H\ \delta\theta \\ 2\,\delta\Delta Y + 2\ H\ \delta\Delta\omega \mp D\ \delta\Delta\kappa \\ 0 \end{bmatrix} + R_{(2\,\delta\Delta\varphi\,\pm\,2\,\delta\theta)} \begin{bmatrix} \tilde{X}_B^{Biased} \\ \tilde{Y}_B^{Biased} \\ \tilde{Z}_B^{Biased} \end{bmatrix} + \vec{e}_{AB}$$

LiDAR QA/QC: Experimental Results (II)

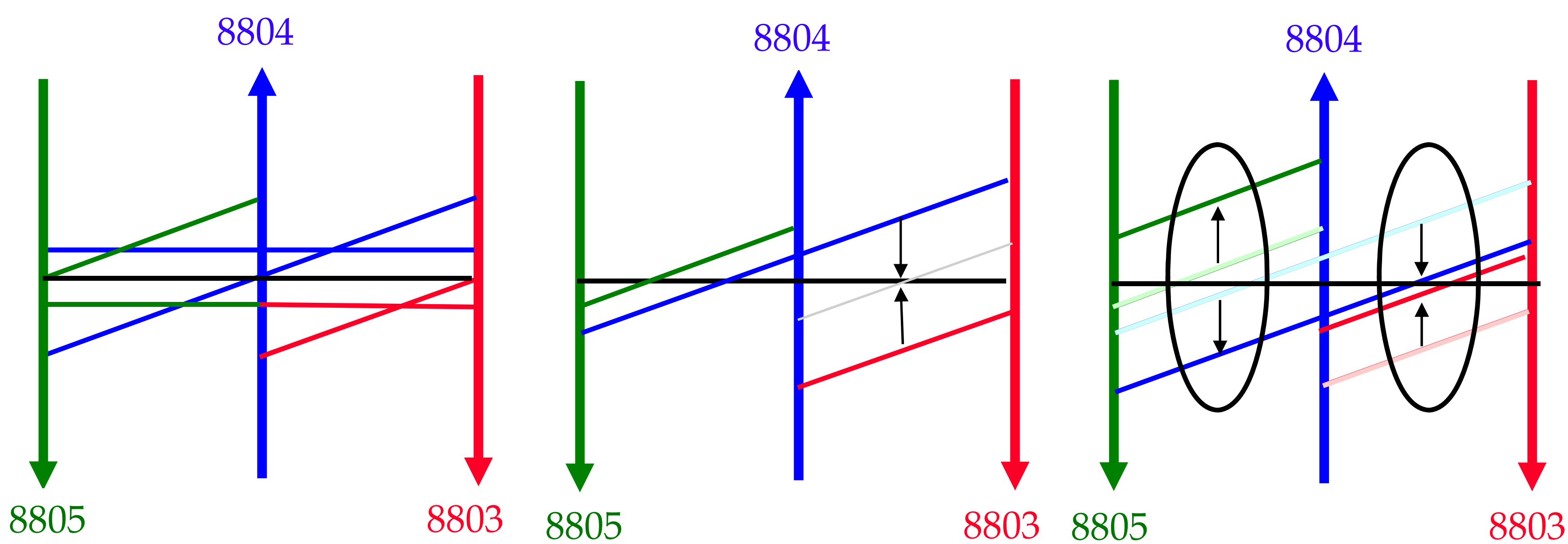
- System Diagnosis
  - The most obvious discrepancy is the one observed along the flight directions.
  - There are heading and pitch boresight biases in the system calibration parameters.
  - There is a smaller bias in the roll boresight parameters.
  - The system parameters changed between the two flights (there was an aircraft change).

$$\begin{bmatrix} \delta\Delta X \\ \delta\Delta\omega \\ \delta\Delta\phi \\ \delta\Delta\kappa \\ \delta\rho \\ \delta S \end{bmatrix}_{88} = \begin{bmatrix} 0.02m \\ 41'' \\ 16'' \\ 195'' \\ -0.02m \\ 0.000005 \end{bmatrix} \qquad \begin{bmatrix} \delta\Delta X \\ \delta\Delta\omega \\ \delta\Delta\phi \\ \delta\Delta\kappa \\ \delta\rho \\ \delta S \end{bmatrix}_{130} = \begin{bmatrix} 0.18m \\ -37'' \\ 27'' \\ 259'' \\ -0.00m \\ 0.000629 \end{bmatrix}$$

LiDAR QA/QC: Experimental Results (II)

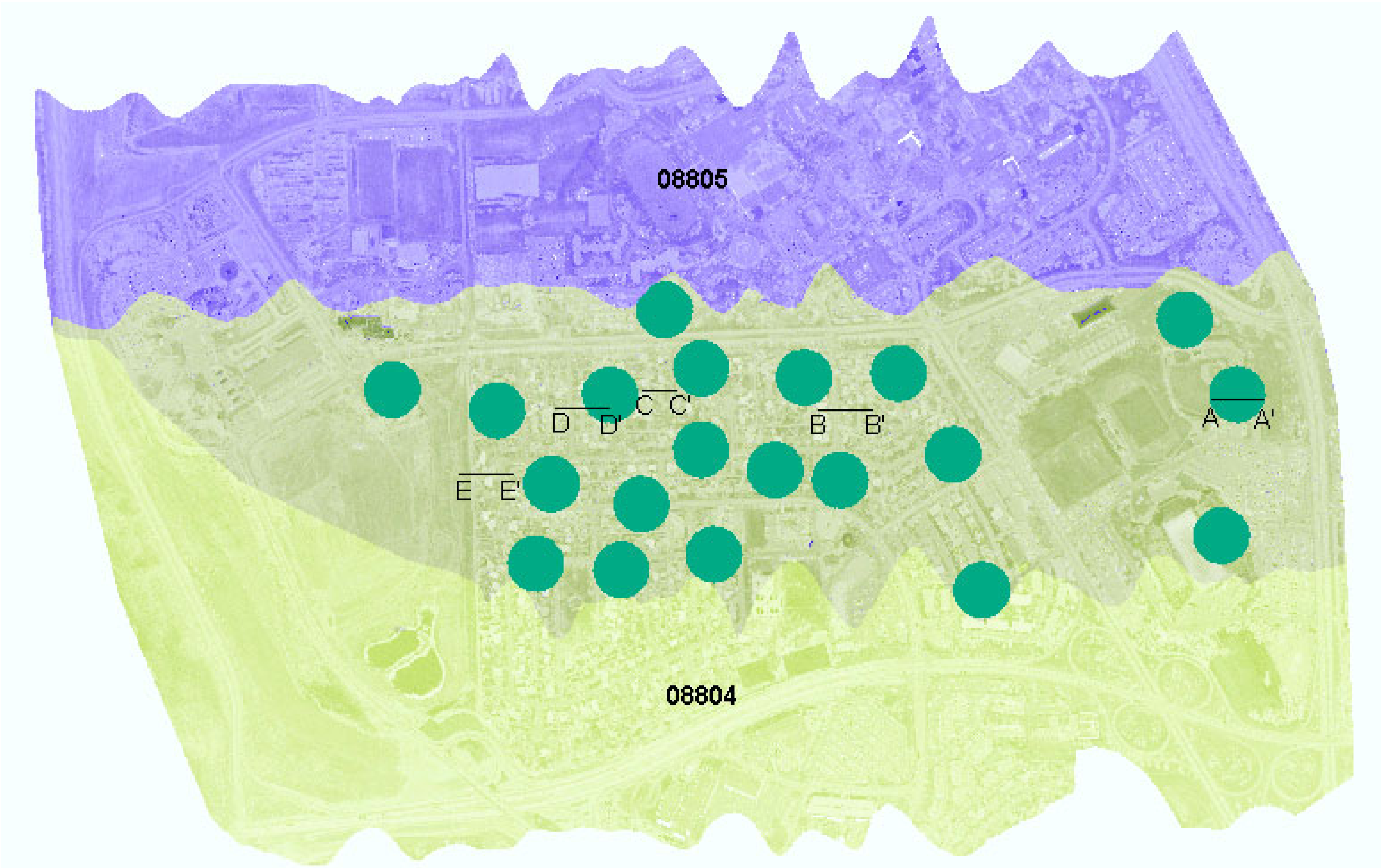
- System Diagnosis

Individual impact of boresighting pitch and heading errors	Accumulated impact of these errors	Incompatibility between strips 8803 & 8804 removed by adjusting the bore-sighting pitch angle



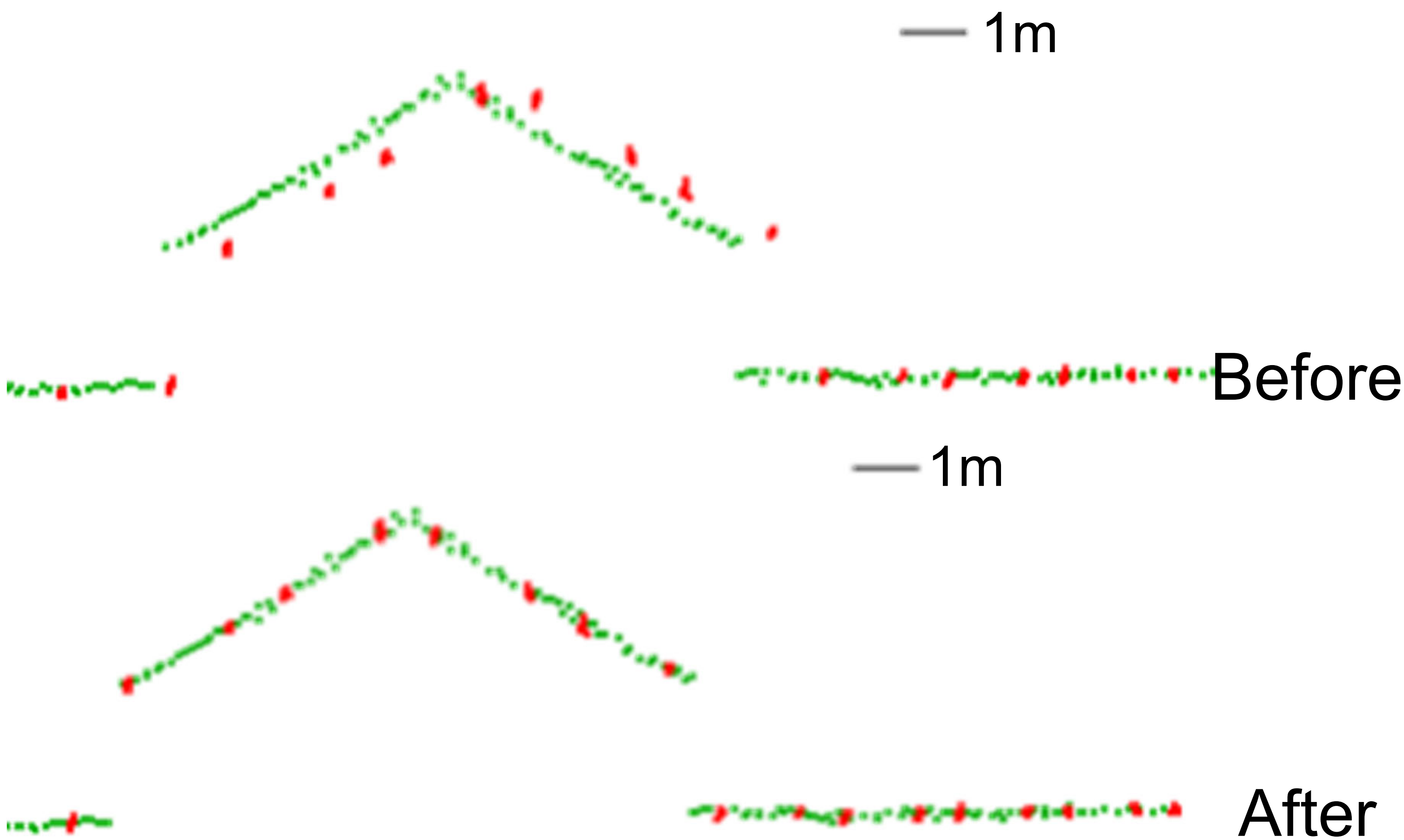
LiDAR QA/QC: Experimental Results (II)

- Investigated Profiles



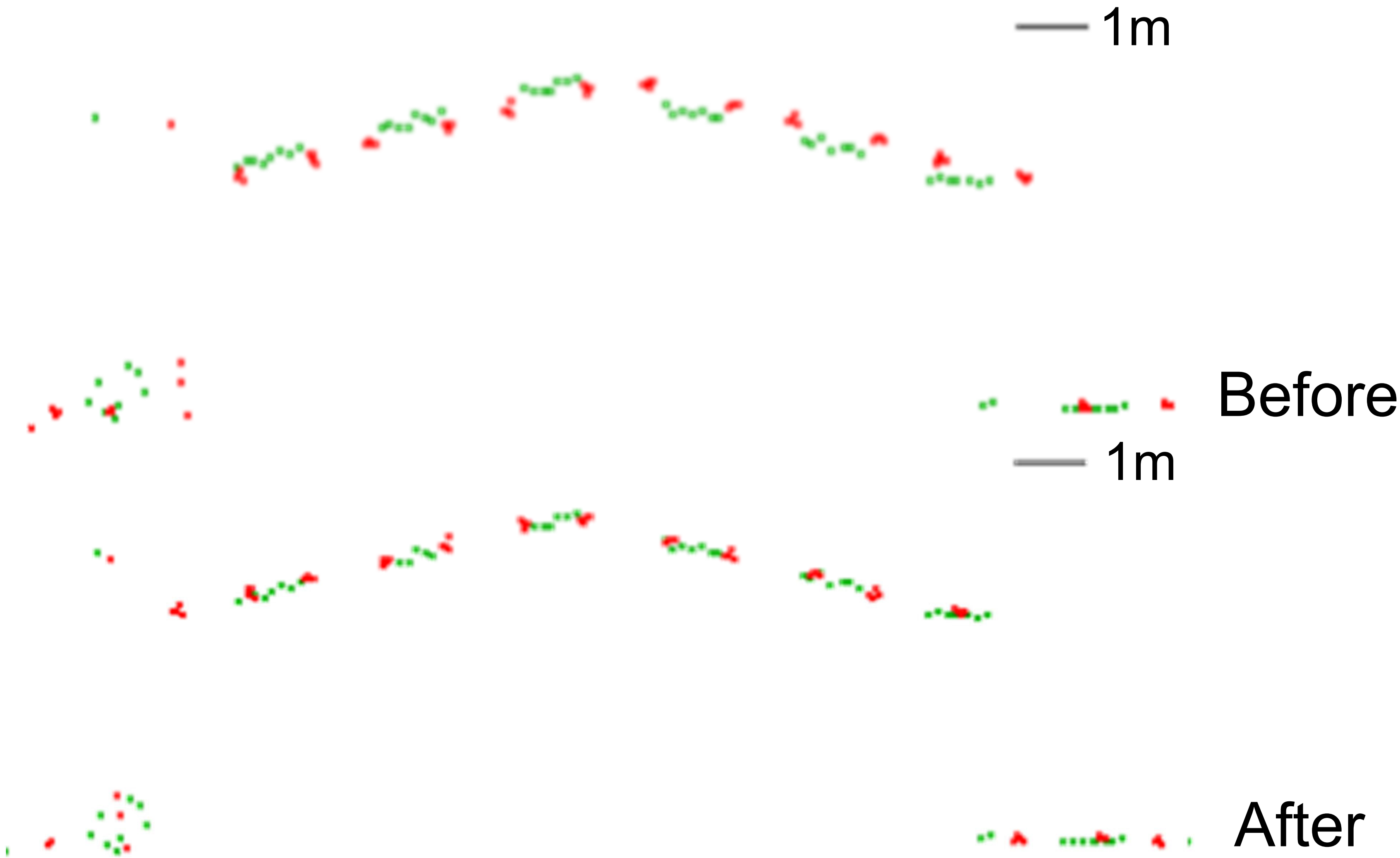
LiDAR QA/QC: Experimental Results (II)

- Profile: AA'



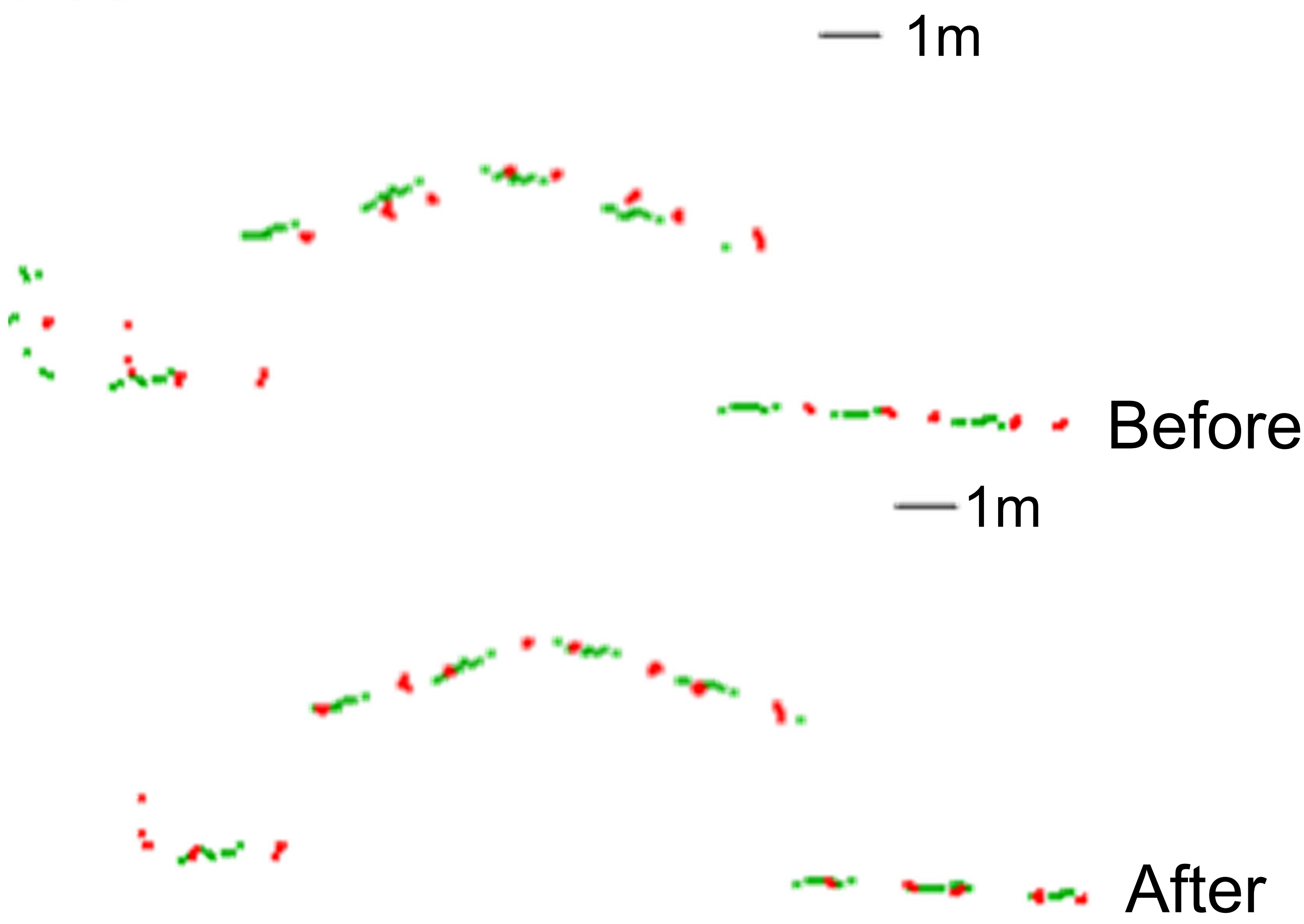
LiDAR QA/QC: Experimental Results (II)

- Profile BB'



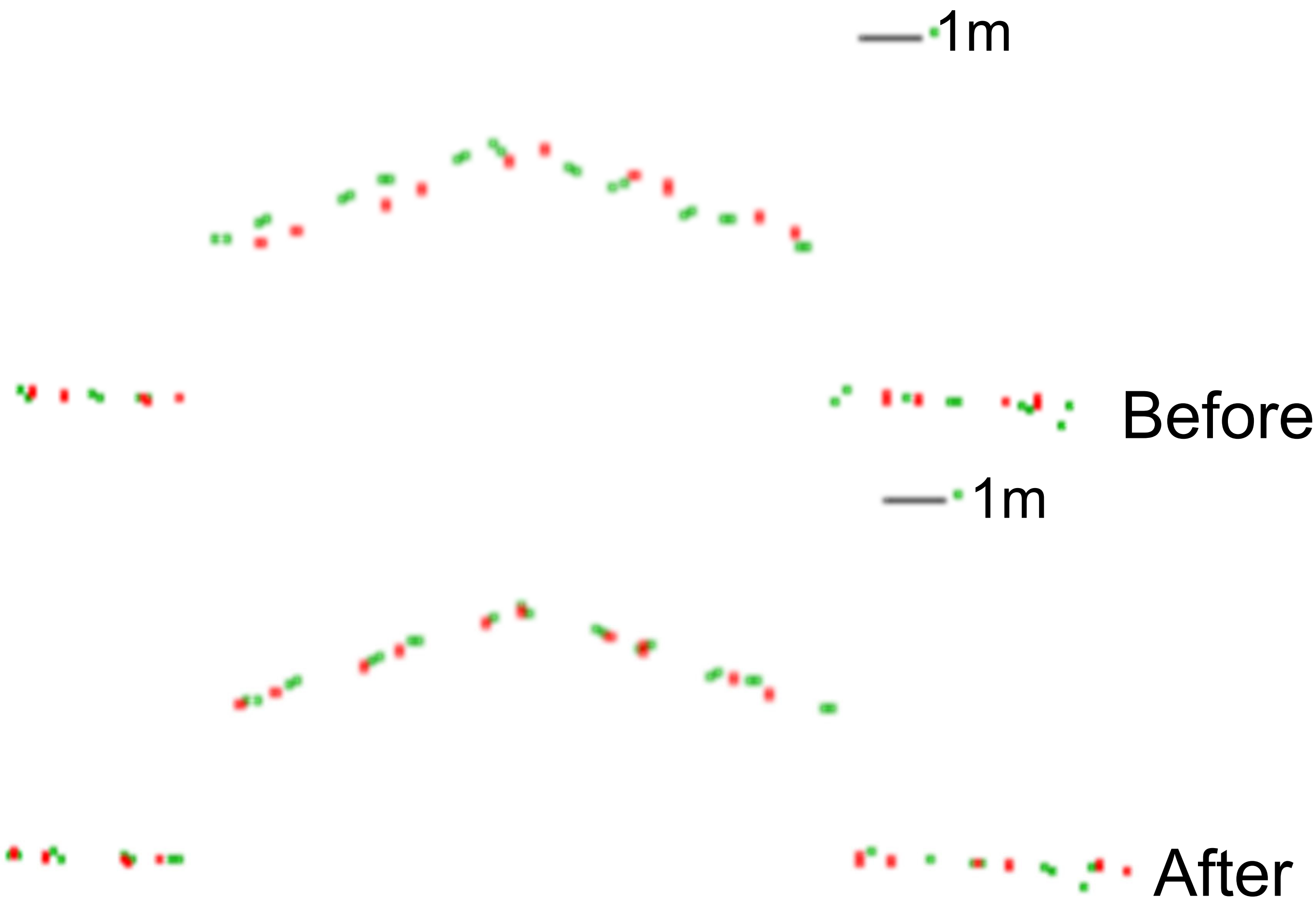
LiDAR QA/QC: Experimental Results (II)

- Profile CC'



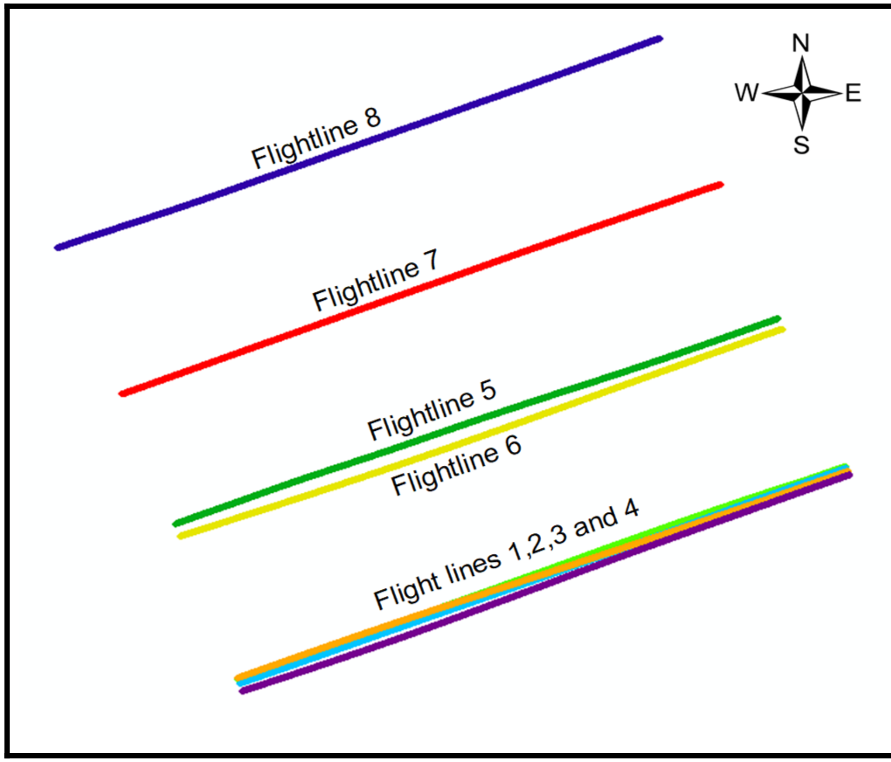
LiDAR QA/QC: Experimental Results (II)

- Profile DD'



LiDAR QA/QC: Experimental Results (III)

- Data Description

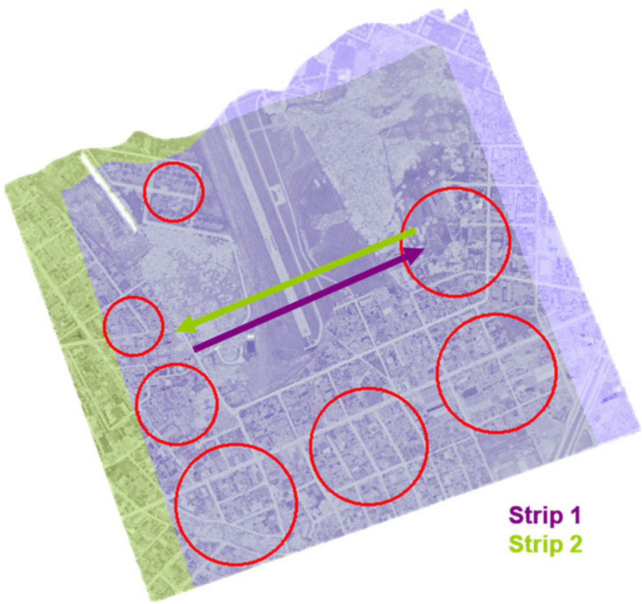


Strip Number	Flying Height	Direction
1	2000 m	SW-NE
2	2000 m	NE-SW
3	1000 m	SW-NE
4	1000 m	NE-SW
5	1000 m	SW-NE
6	2000 m	NE-SW
7	1000 m	NE-SW
8	1000 m	SW-NE

LiDAR QA/QC: Experimental Results (III)

- Overlap pairs:

Overlapping Strips Cases	% of Overlap	Direction
(i) Strips 1&2	100%	Opposite directions



LiDAR QA/QC: Experimental Results (III)

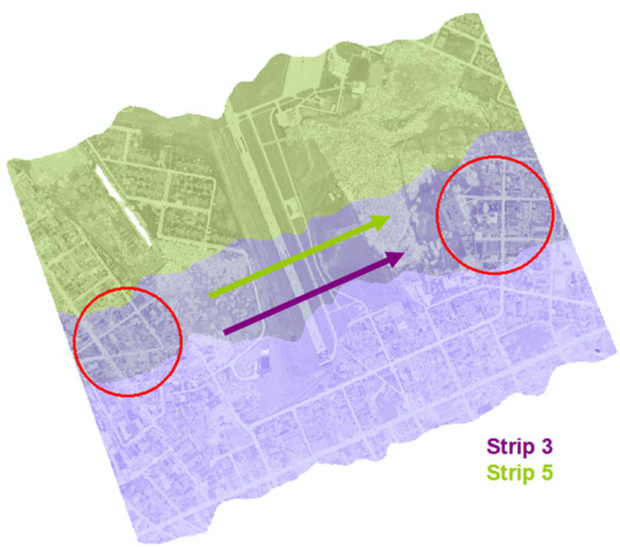
- Overlap pairs:

Overlapping Strips Cases	% of Overlap	Direction
(ii) Strips 3&4	100%	Opposite directions

LiDAR QA/QC: Experimental Results (III)

- Overlap pairs:

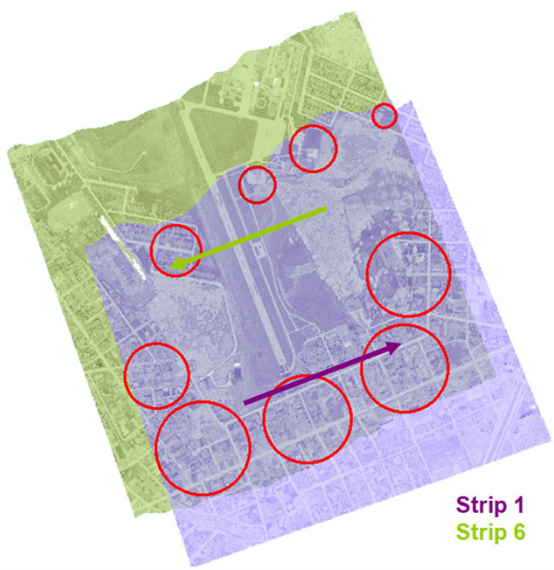
Overlapping Strips Cases	% of Overlap	Direction
(iii) Strips 3&5	50%	Same direction



LiDAR QA/QC: Experimental Results (III)

- Overlap pairs:

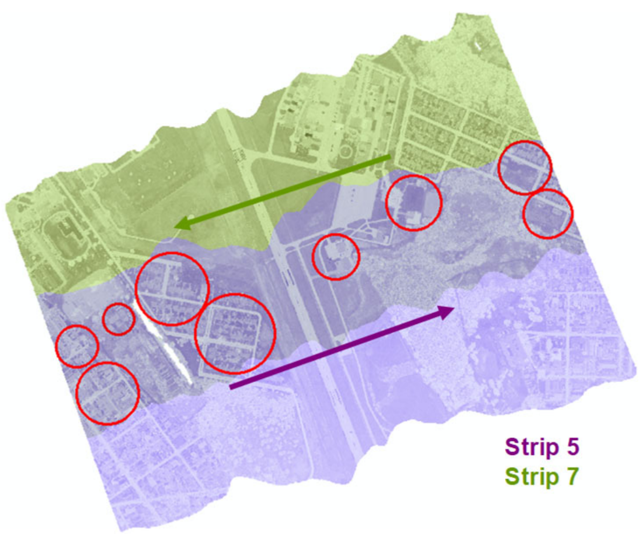
Overlapping Strips Cases	% of Overlap	Direction
(iv) Strips 1&6	70%	Opposite directions



LiDAR QA/QC: Experimental Results (III)

- Overlap pairs:

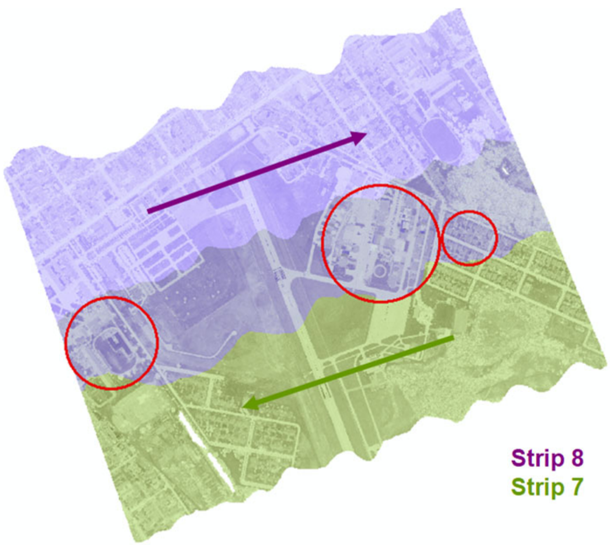
Overlapping Strips Cases	% of Overlap	Direction
(v) Strips 5&7	50%	Opposite directions



LiDAR QA/QC: Experimental Results (III)

- Overlap pairs:

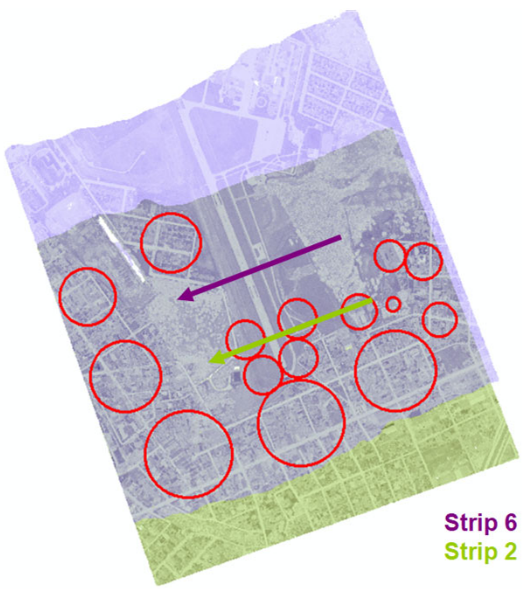
Overlapping Strips Cases	% of Overlap	Direction
(vi) Strips 7&8	40%	Opposite directions



LiDAR QA/QC: Experimental Results (III)

- Overlap pairs:

Overlapping Strips Cases	% of Overlap	Direction
(vii) Strips 2&6	70%	Same direction



LiDAR QA/QC: Experimental Results (III)

- ICPatch results for the overlap pairs

	X_T (m)	Y_T (m)	Z_T (m)	ω (sec)	ϕ (sec)	κ (sec)
Strips 1&2	-0.25	1.27	-0.01	10.54	1.34	67.68
Strips 3&4	-0.01	0.52	0.02	-2.59	-9.72	20.52
Strips 3&5	-0.32	-0.19	-0.06	7.20	96.48	6.48
Strips 2&6	-0.42	0.15	0.01	-4.65	74.61	-136.10
Strips 1&6	-0.67	1.51	-0.06	4.68	91.08	71.64
Strips 5&7	-0.13	0.55	0.04	0.68	12.96	-5.40
Strips 7&8	0.48	0.82	0.06	1.62	-166.32	-2.84

LiDAR QA/QC: Experimental Results (III)

- Overlap pairs used for the simplified/Quazi-Rigorous method

Case no.	Overlapping Cases
I	(i), (ii), and (iii)
II	(i), (ii), (iii), and (vii)
III	(i), (ii), (iii), (iv), (v), and (vi)

?

- Estimated system parameters (Simplified Approach)

Case no.	$\delta\Delta X$(m)	$\delta\Delta Y$(m)	$\delta\Delta\omega$(")	$\delta\Delta\varphi$(")	$\delta\Delta\kappa$(")	$\delta\rho$(m)	δS
I	-0.07	-0.11	75	-1	80	0.26	0.000565
II	-0.08	-0.11	75	-1	-39.5	0.22	0.000567
III	-0.11	-0.10	86	-16	41	0.28	0.000670

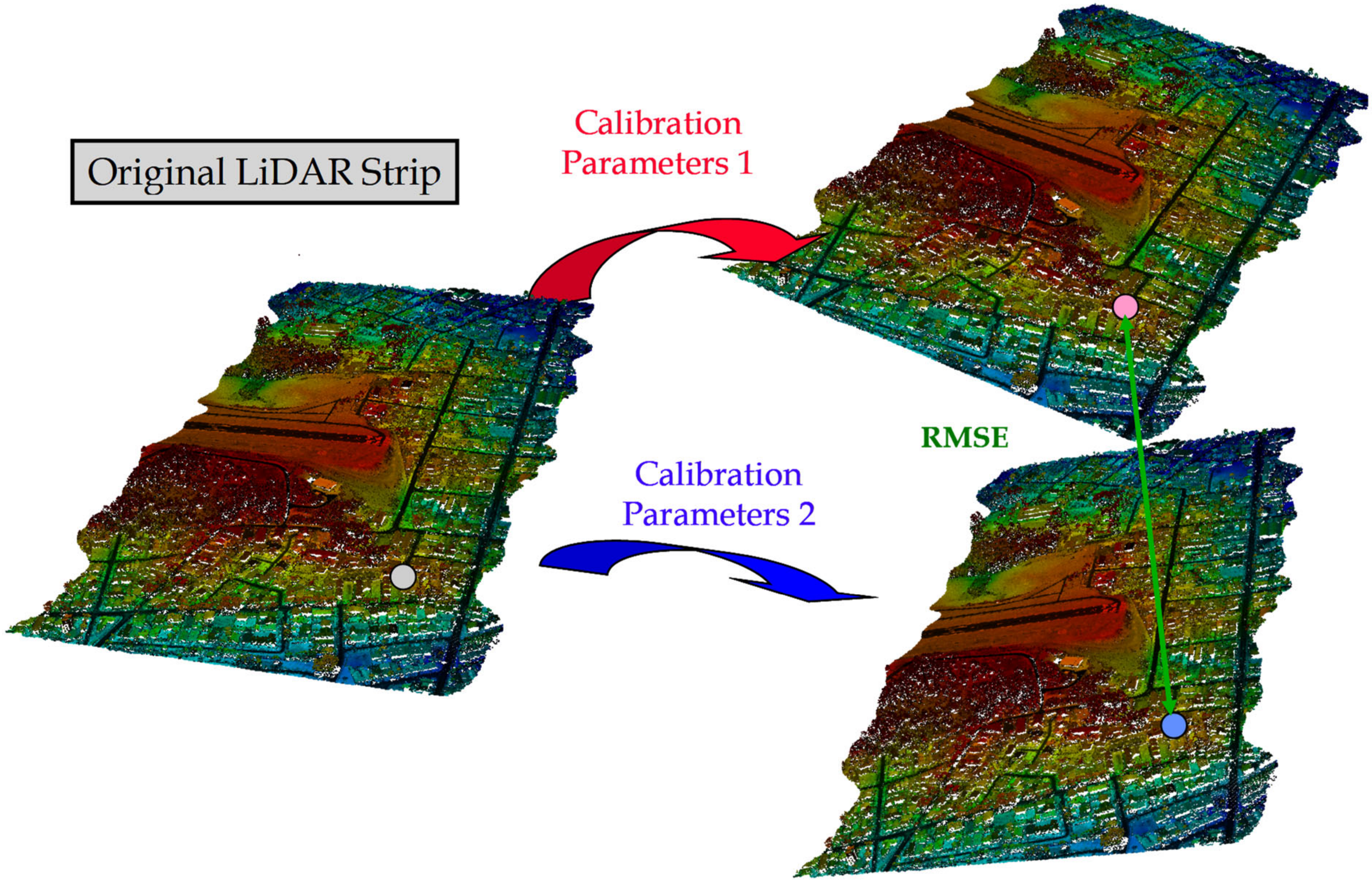
- Estimated System Parameters (Quazi-Rigorous Approach)

Configuration Case	$\delta\Delta X$ (m)	$\delta\Delta Y$ (m)	$\delta\Delta\omega$ (")	$\delta\Delta\phi$ (")	$\delta\Delta\kappa$ (")	$\delta\rho$ (m)	δS
I	-0.07	-0.11	79.6	-2.6	52.5	0.59	0.00038
II	-0.0					0.00	0.00097
III	-0.05	-0.09	[illegible]	-1.2	[illegible]	-0.09	0.00103

Are these equivalent estimates?

LiDAR QA/QC: Experimental Results (III)

- RMSE Analysis for Equivalency Testing:



LiDAR QA/QC: Experimental Results (III)

- RMSE Analysis for Equivalency Testing:

		Strip 1			Strip 3		
		I vs. II	I vs. III	II vs. III	I vs. II	I vs. III	II vs. III
Mean	X (m)	0.01	0.06	-0.05	0.00	0.05	-0.04
	Y (m)	0.02	0.03	-0.02	0.00	-0.00	0.00
	Z (m)	0.62	0.71	-0.09	0.60	0.69	-0.09
Std	X (m)	0.02	0.01	0.03	0.03	0.02	0.01
	Y (m)	0.13	0.12	0.00	0.01	0.00	0.01
	Z (m)	0.03	0.04	0.01	0.01	0.01	0.00
RMSE	X (m)	0.03	0.06	0.06	0.03	0.05	0.05
	Y (m)	0.13	0.13	0.02	0.01	0.00	0.01
	Z (m)	0.62	0.71	0.09	0.60	0.69	0.09

LiDAR QA/QC: Experimental Results (III)

- Correlation Matrix (Configuration I):

	$\delta\Delta X$	$\delta\Delta Y$	$\delta\Delta\omega$	$\delta\Delta\phi$	$\delta\Delta\kappa$	$\delta\rho$	δS
$\delta\Delta X$	1.000	-0.011	0.009	0.822	0.001	0.127	-0.124
$\delta\Delta Y$	-0.011	1.000	-0.945	-0.011	-0.004	-0.010	0.010
$\delta\Delta\omega$	0.009	-0.945	1.000	0.010	0.031	0.014	-0.014
$\delta\Delta\phi$	0.822	-0.011	0.010	1.000	-0.006	0.228	-0.232
$\delta\Delta\kappa$	0.001	-0.004	0.031	-0.006	1.000	-0.005	0.013
$\delta\rho$	0.127	-0.010	0.014	0.228	-0.005	1.000	-0.979
δS	-0.124	0.010	-0.014	-0.232	0.013	-0.979	1.000

LiDAR QA/QC: Experimental Results (III)

- Correlation Matrix (Configuration II):

	$\delta\Delta X$	$\delta\Delta Y$	$\delta\Delta\omega$	$\delta\Delta\phi$	$\delta\Delta\kappa$	$\delta\rho$	δS
$\delta\Delta X$	1.000	-0.010	0.008	0.805	0.003	0.090	-0.099
$\delta\Delta Y$	-0.010	1.000	-0.945	-0.009	-0.006	-0.004	0.004
$\delta\Delta\omega$	0.008	-0.945	1.000	0.007	0.026	0.004	-0.005
$\delta\Delta\phi$	0.805	-0.009	0.007	1.000	-0.001	0.109	-0.134
$\delta\Delta\kappa$	0.003	-0.006	0.026	-0.001	1.000	0.024	-0.012
$\delta\rho$	0.090	-0.004	0.004	0.109	0.024	1.000	-0.872
δS	-0.099	0.004	-0.005	-0.134	-0.012	-0.872	1.000

LiDAR QA/QC: Experimental Results (III)

- Correlation Matrix (Configuration III):

	$\delta\Delta X$	$\delta\Delta Y$	$\delta\Delta\omega$	$\delta\Delta\phi$	$\delta\Delta\kappa$	$\delta\rho$	δS
$\delta\Delta X$	1.000	-0.002	0.003	0.850	0.014	0.402	-0.441
$\delta\Delta Y$	-0.002	1.000	-0.938	-0.003	-0.156	0.005	0.000
$\delta\Delta\omega$	0.003	-0.938	1.000	0.002	0.283	0.000	-0.002
$\delta\Delta\phi$	0.850	-0.003	0.002	1.000	0.001	0.498	-0.602
$\delta\Delta\kappa$	0.014	-0.156	0.283	0.001	1.000	0.015	-0.003
$\delta\rho$	0.402	0.005	0.000	0.498	0.015	1.000	-0.912
δS	-0.441	0.000	-0.002	-0.602	-0.003	-0.912	1.000

LiDAR QA/QC: Experimental Results (III)

- Check the compatibility between the strips after correcting the point cloud coordinates using the estimated parameters from the different configurations

Compatibility using the original point cloud coordinates

	X_T (m)	Y_T (m)	Z_T (m)	ω (sec)	ϕ (sec)	κ (sec)
Strips 1&2	-0.25	1.27	-0.01	10.54	1.34	67.68
Strips 3&4	-0.01	0.52	0.02	-2.59	-9.72	20.52
Strips 3&5	-0.32	-0.19	-0.06	7.20	96.48	6.48
Strips 2&6	-0.42	0.15	0.01	-4.65	74.61	-136.10
Strips 1&6	-0.67	1.51	-0.06	4.68	91.08	71.64
Strips 5&7	-0.13	0.55	0.04	0.68	12.96	-5.40
Strips 7&8	0.48	0.82	0.06	1.62	-166.32	-2.84

LiDAR QA/QC: Experimental Results (III)

- Check the compatibility between the strips after correcting the point cloud coordinates using the estimated parameters from the different configurations

I

Strips 1&2		
X_T (m)	Y_T (m)	Z_T (m)
0.20	0.04	0.01
ω(sec)	ϕ (sec)	κ (sec)
-6.48	-6.48	-57.24
Strips 1&6		
X_T (m)	Y_T (m)	Z_T (m)
0.38	-0.25	0.04
ω(sec)	ϕ (sec)	κ (sec)
-1.76	-48.96	-73.80

II

Strips 1&2		
X_T (m)	Y_T (m)	Z_T (m)
0.21	0.18	0.01
ω(sec)	ϕ (sec)	κ (sec)
-5.76	-0.90	-70.56
Strips 1&6		
X_T (m)	Y_T (m)	Z_T (m)
0.25	-0.07	0.01
ω(sec)	ϕ (sec)	κ (sec)
-1.73	-5.40	-76.68

III

Strips 1&2		
X_T (m)	Y_T (m)	Z_T (m)
0.21	0.06	0.02
ω(sec)	ϕ (sec)	κ (sec)
-5.82	-8.18	-71.28
Strips 1&6		
X_T (m)	Y_T (m)	Z_T (m)
0.28	-0.17	0.02
ω(sec)	ϕ (sec)	κ (sec)
-1.62	-16.34	-73.44

Same level of compatibility from the different configurations

LiDAR QA/QC: Experimental Results (III)

- Check the compatibility between the strips after correcting the point cloud coordinates using the estimated parameters from the different configurations

Strips 3&4

Parameter	I	II	III
X_T (m)	-0.09	-0.06	-0.09
Y_T (m)	0.03	0.12	0.03
Z_T (m)	-0.02	-0.02	-0.02
ω (sec)	1.80	1.84	1.80
ϕ (sec)	7.92	12.96	4.71
κ (sec)	-26.64	-26.64	-26.64

Strips 3&5

Parameter	I	II	III
X_T (m)	-0.08	-0.07	-0.08
Y_T (m)	0.02	0.06	0.09
Z_T (m)	0.05	0.05	0.05
ω (sec)	-5.76	-5.04	-5.15
ϕ (sec)	15.12	71.64	68.25
κ (sec)	-7.56	[illegible].48	-6.84

Same level of compatibility from the different configurations

LiDAR QA/QC: Experimental Results (III)

- Check the compatibility between the strips after correcting the point cloud coordinates using the estimated parameters from the different configurations

I

Strips 5&7		
X_T (m)	Y_T (m)	Z_T (m)
-0.31	-0.13	-0.03
ω(sec)	ϕ (sec)	κ (sec)
1.62	87.84	7.56
Strips 7&8		
X_T (m)	Y_T (m)	Z_T (m)
0.220	0.210	0.050
ω(sec)	ϕ (sec)	κ (sec)
2.59	-45.72	-9.36
Strips 2&6		
X_T (m)	Y_T (m)	Z_T (m)
-0.13	0.33	-0.340

II

Strips 5&7		
X_T (m)	Y_T (m)	Z_T (m)
-0.27	-0.02	-0.03
ω(sec)	ϕ (sec)	κ (sec)
2.63	138.24	8.64
Strips 7&8		
X_T (m)	Y_T (m)	Z_T (m)
0.200	0.160	0.050
ω(sec)	ϕ (sec)	κ (sec)
27.72	12.60	-8.64
Strips 2&6		
X_T (m)	Y_T (m)	Z_T (m)
-0.05	0.20	-0.02

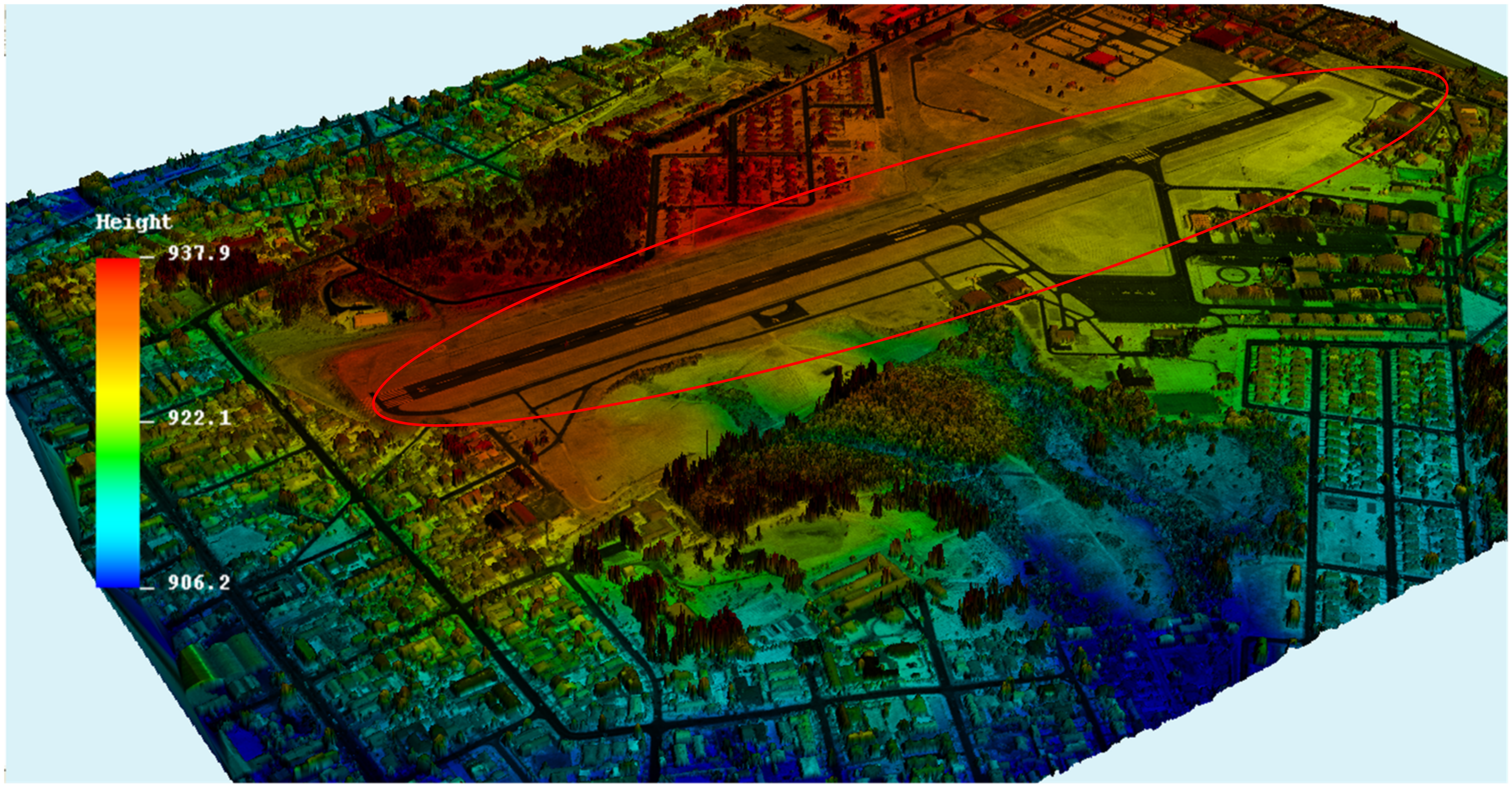
III

Strips 5&7		
X_T (m)	Y_T (m)	Z_T (m)
-0.31	-0.07	-0.03
ω(sec)	ϕ (sec)	κ (sec)
2.25	129.01	7.58
Strips 7&8		
X_T (m)	Y_T (m)	Z_T (m)
0.23	0.28	0.05
ω(sec)	ϕ (sec)	κ (sec)
3.21	8.41	-10.08
Strips 2&6		
X_T (m)	Y_T (m)	Z_T (m)
-0.04	0.18	-0.01

Same level of compatibility from the different configurations

LiDAR QA/QC: Experimental Results (III)

- Control Surface



900 GPS points measured over the airport runway

LiDAR QA/QC: Experimental Results (III)

- Estimated calibration parameters using overlapping strips & 3D control points

Configuration Case	$\delta\Delta X$ (m)	$\delta\Delta Y$ (m)	$\delta\Delta\omega$ (")	$\delta\Delta\phi$ (")	$\delta\Delta\kappa$ (")	$\delta\rho$ (m)	δS
I	-0.07	-0.12	81.15	-3.64	50.02	-0.04	0.00089
II	-0.08	-0.12	80.59	-5.20	18.82	-0.06	0.00099
III	-0.04	-0.03	67.07	-0.87	33.67	-0.06	0.00099

√

LiDAR QA/QC: Experimental Results (III)

- Correlation Matrix: 3D control surface – Configuration I

	$\delta\Delta X$	$\delta\Delta Y$	$\delta\Delta\omega$	$\delta\Delta\phi$	$\delta\Delta\kappa$	$\delta\rho$	δS
$\delta\Delta X$	1.000	-0.013	0.011	0.800	0.002	0.025	-0.015
$\delta\Delta Y$	-0.013	1.000	-0.944	-0.011	-0.004	-0.002	0.001
$\delta\Delta\omega$	0.011	-0.944	1.000	0.009	0.032	0.002	-0.003
$\delta\Delta\phi$	0.800	-0.011	0.009	1.000	-0.005	0.041	-0.064
$\delta\Delta\kappa$	0.002	-0.004	0.032	-0.005	1.000	0.002	0.034
$\delta\rho$	0.025	-0.002	0.002	0.041	0.002	1.000	-0.605
δS	-0.015	0.001	-0.003	-0.064	0.034	-0.605	1.000

LiDAR QA/QC: Experimental Results (III)

- Correlation Matrix: 3D control surface – Configuration II

	$\delta\Delta X$	$\delta\Delta Y$	$\delta\Delta\omega$	$\delta\Delta\phi$	$\delta\Delta\kappa$	$\delta\rho$	δS
$\delta\Delta X$	1.000	-0.013	0.010	0.781	0.000	0.029	-0.050
$\delta\Delta Y$	-0.013	1.000	-0.944	-0.010	-0.006	-0.001	0.001
$\delta\Delta\omega$	0.010	-0.944	1.000	0.008	0.026	0.001	-0.002
$\delta\Delta\phi$	0.781	-0.010	0.008	1.000	-0.004	0.034	-0.089
$\delta\Delta\kappa$	0.000	-0.006	0.026	-0.004	1.000	0.011	0.009
$\delta\rho$	0.029	-0.001	0.001	0.034	0.011	1.000	-0.523
δS	-0.050	0.001	-0.002	-0.089	0.009	-0.523	1.000

LiDAR QA/QC: Experimental Results (III)

- Correlation Matrix: 3D control surface – Configuration III

	$\delta\Delta X$	$\delta\Delta Y$	$\delta\Delta\omega$	$\delta\Delta\phi$	$\delta\Delta\kappa$	$\delta\rho$	δS
$\delta\Delta X$	1.000	-0.007	0.007	0.805	0.011	0.161	-0.255
$\delta\Delta Y$	-0.007	1.000	-0.937	-0.010	-0.140	0.003	0.006
$\delta\Delta\omega$	0.007	-0.937	1.000	0.009	0.265	-0.001	-0.003
$\delta\Delta\phi$	0.805	-0.010	0.009	1.000	-0.005	0.200	-0.445
$\delta\Delta\kappa$	0.011	-0.140	0.265	-0.005	1.000	0.008	0.014
$\delta\rho$	0.161	0.003	-0.001	0.200	0.008	1.000	-0.635
δS	-0.255	0.006	-0.003	-0.445	0.014	-0.635	1.000

LiDAR QA/QC: Experimental Results (III)

- Estimated calibration parameters using overlapping strips & vertical control points

Configuration Case	$\delta\Delta X$ (m)	$\delta\Delta Y$ (m)	$\delta\Delta\omega$ (")	$\delta\Delta\phi$ (")	$\delta\Delta\kappa$ (")	$\delta\rho$ (m)	δS
I	-0.07	-0.12	81.63	-3.30	51.12	0.01	0.00088
II	-0.08	-0.12	81.37	-4.87	17.42	-0.01	0.00098
III	-0.04	-0.09	84.49	-0.79	32.52	-0.01	0.00099

√

LiDAR QA/QC: Experimental Results (III)

- Correlation Matrix: Vertical control – Configuration I

	$\delta\Delta X$	$\delta\Delta Y$	$\delta\Delta\omega$	$\delta\Delta\phi$	$\delta\Delta\kappa$	$\delta\rho$	δS
$\delta\Delta X$	1.000	-0.010	0.008	0.821	0.002	0.026	-0.014
$\delta\Delta Y$	-0.010	1.000	-0.945	-0.009	-0.004	-0.002	0.002
$\delta\Delta\omega$	0.008	-0.945	1.000	0.006	0.031	0.003	-0.003
$\delta\Delta\phi$	0.821	-0.009	0.006	1.000	-0.005	0.043	-0.060
$\delta\Delta\kappa$	0.002	-0.004	0.031	-0.005	1.000	0.001	0.030
$\delta\rho$	0.026	-0.002	0.003	0.043	0.001	1.000	-0.636
δS	-0.014	0.002	-0.003	-0.060	0.030	-0.636	1.000

LiDAR QA/QC: Experimental Results (III)

- Correlation Matrix: Vertical control – Configuration II

	$\delta\Delta X$	$\delta\Delta Y$	$\delta\Delta\omega$	$\delta\Delta\phi$	$\delta\Delta\kappa$	$\delta\rho$	δS
$\delta\Delta X$	1.000	-0.010	0.007	0.803	0.001	0.032	-0.051
$\delta\Delta Y$	-0.010	1.000	-0.945	-0.008	-0.006	-0.002	0.002
$\delta\Delta\omega$	0.007	-0.945	1.000	0.006	0.026	0.001	-0.003
$\delta\Delta\phi$	0.803	-0.008	0.006	1.000	-0.004	0.037	-0.088
$\delta\Delta\kappa$	0.001	-0.006	0.026	-0.004	1.000	0.010	0.009
$\delta\rho$	0.032	-0.002	0.001	0.037	0.010	1.000	-0.555
δS	-0.051	0.002	-0.003	-0.088	0.009	-0.555	1.000

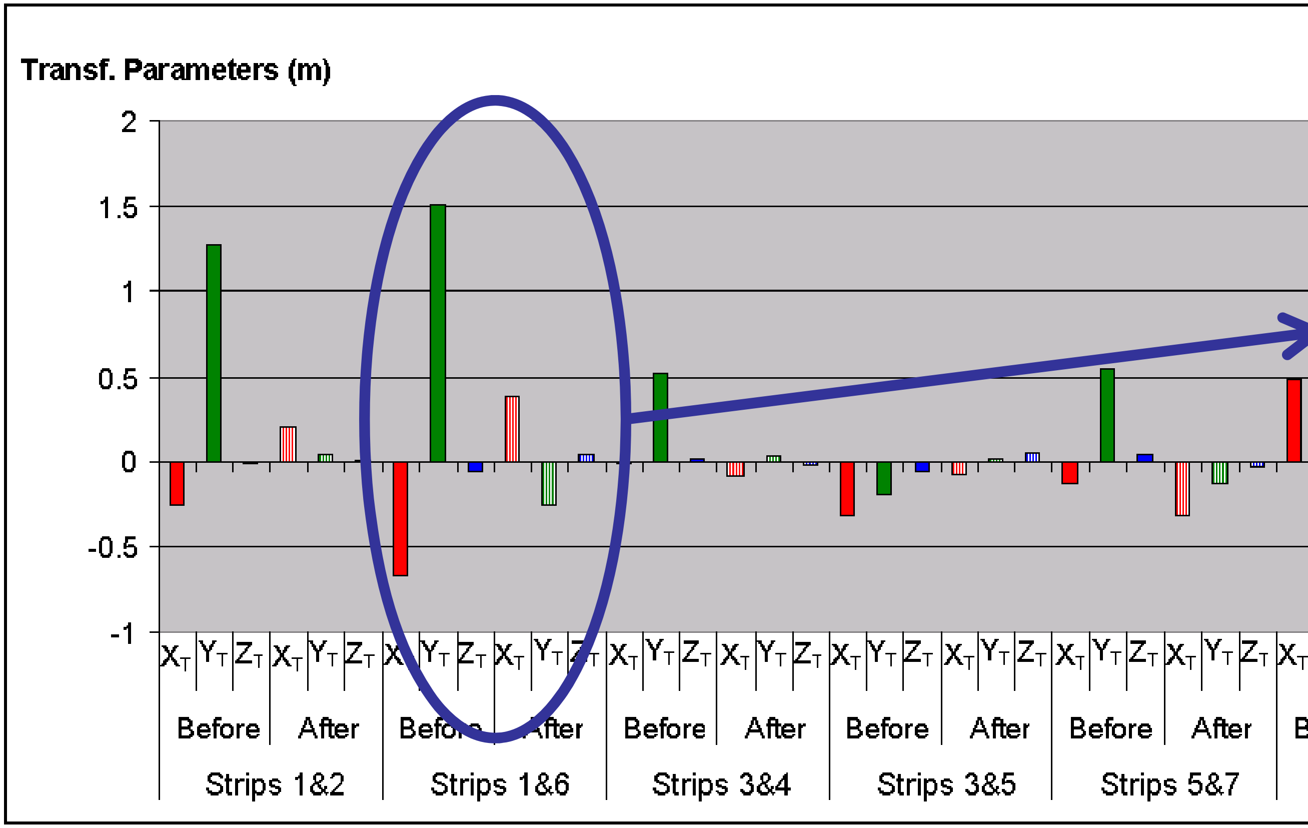
LiDAR QA/QC: Experimental Results (III)

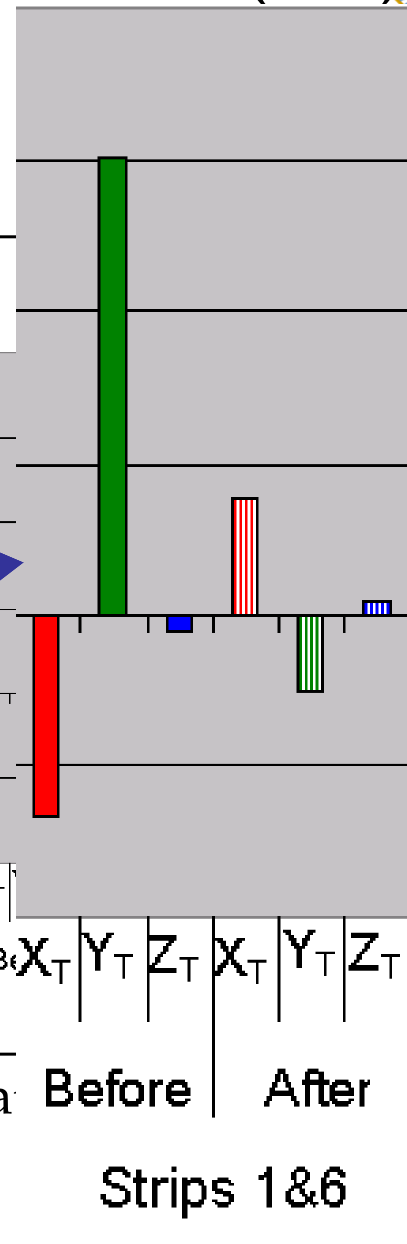
- Correlation Matrix: Vertical control – Configuration III

	$\delta\Delta X$	$\delta\Delta Y$	$\delta\Delta\omega$	$\delta\Delta\phi$	$\delta\Delta\kappa$	$\delta\rho$	δS
$\delta\Delta X$	1.000	-0.004	0.003	0.824	0.009	0.170	-0.259
$\delta\Delta Y$	-0.004	1.000	-0.938	-0.006	-0.157	0.002	0.006
$\delta\Delta\omega$	0.003	-0.938	1.000	0.002	0.283	0.000	-0.003
$\delta\Delta\phi$	0.824	-0.006	0.002	1.000	-0.006	0.216	-0.445
$\delta\Delta\kappa$	0.009	-0.157	0.283	-0.006	1.000	0.007	0.015
$\delta\rho$	0.170	0.002	0.000	0.216	0.007	1.000	-0.664
δS	-0.259	0.006	-0.003	-0.445	0.015	-0.664	1.000

LiDAR QA/QC: Experimental Results (III)

- Quantitative evaluation

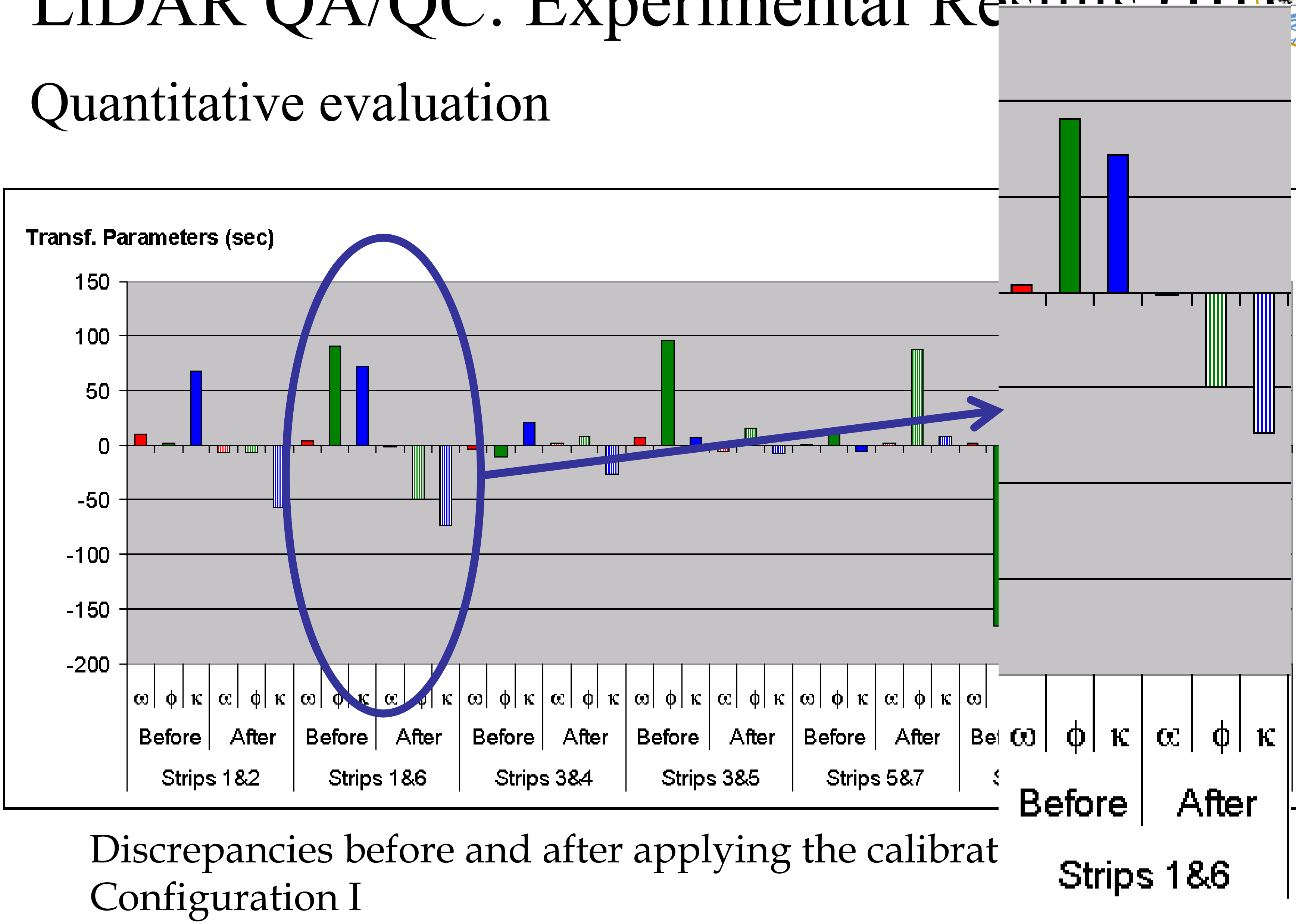




Discrepancies before and after applying the calibra
Configuration I

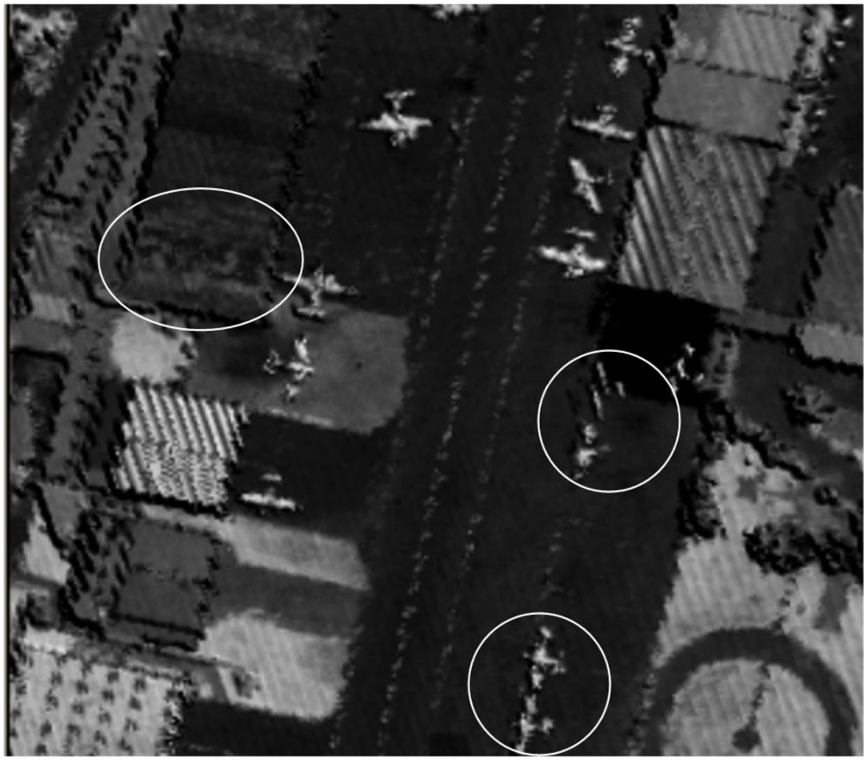
LiDAR QA/QC: Experimental Results (III)

- Quantitative evaluation

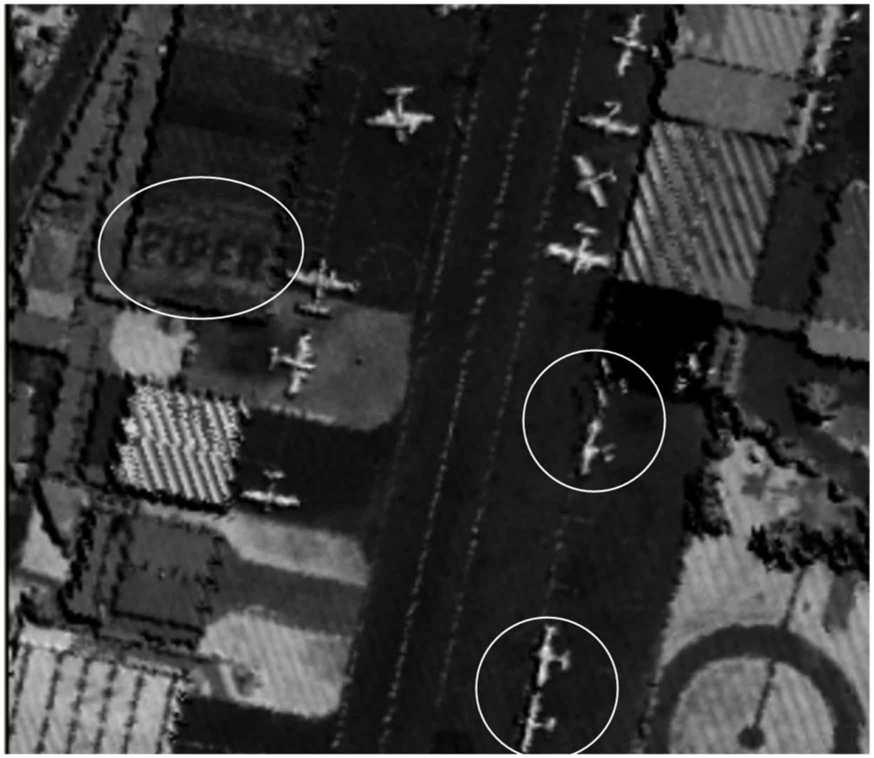


Discrepancies before and after applying the calibrat
Configuration I

LiDAR QA/QC: Experimental Results (III)



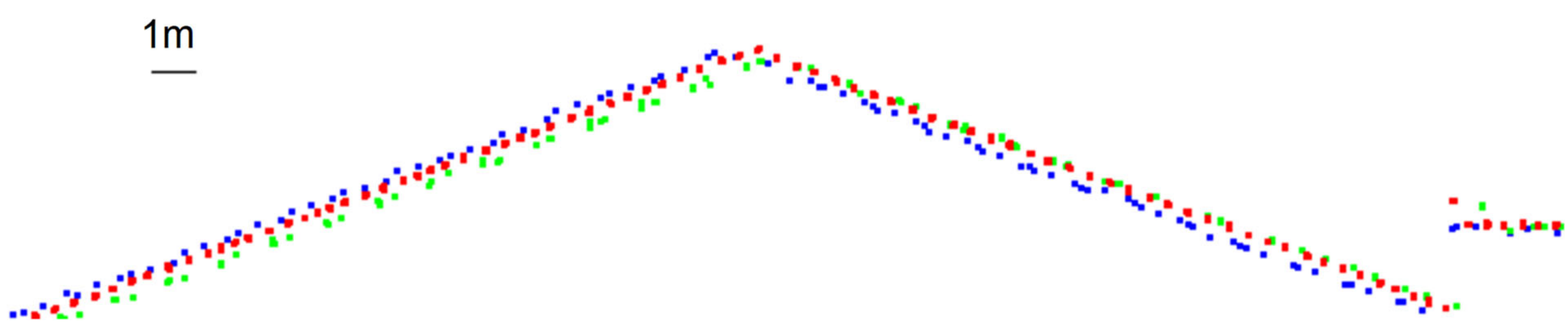
Intensity Image (Before)



Intensity Image (After)

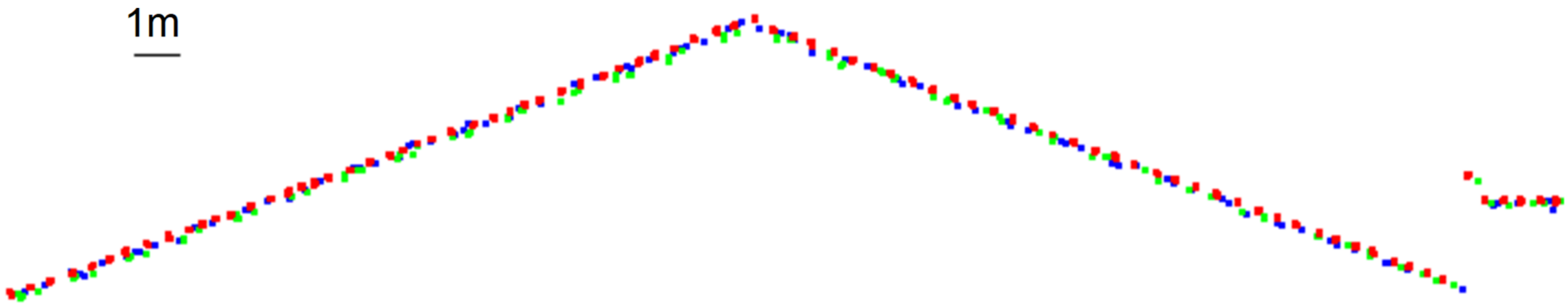
Qualitative Evaluation

LiDAR QA/QC: Experimental Results (III)



Original Point Cloud

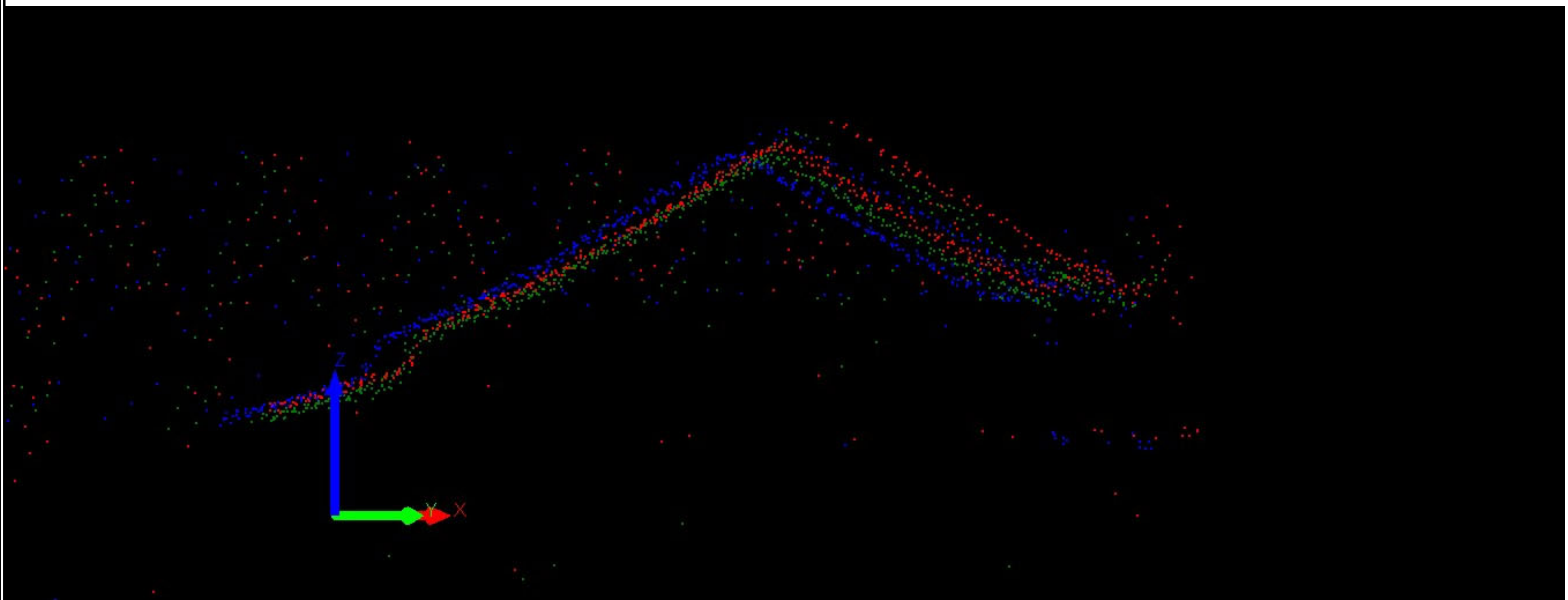
LiDAR QA/QC: Experimental Results (III)



Adjusted Point Cloud

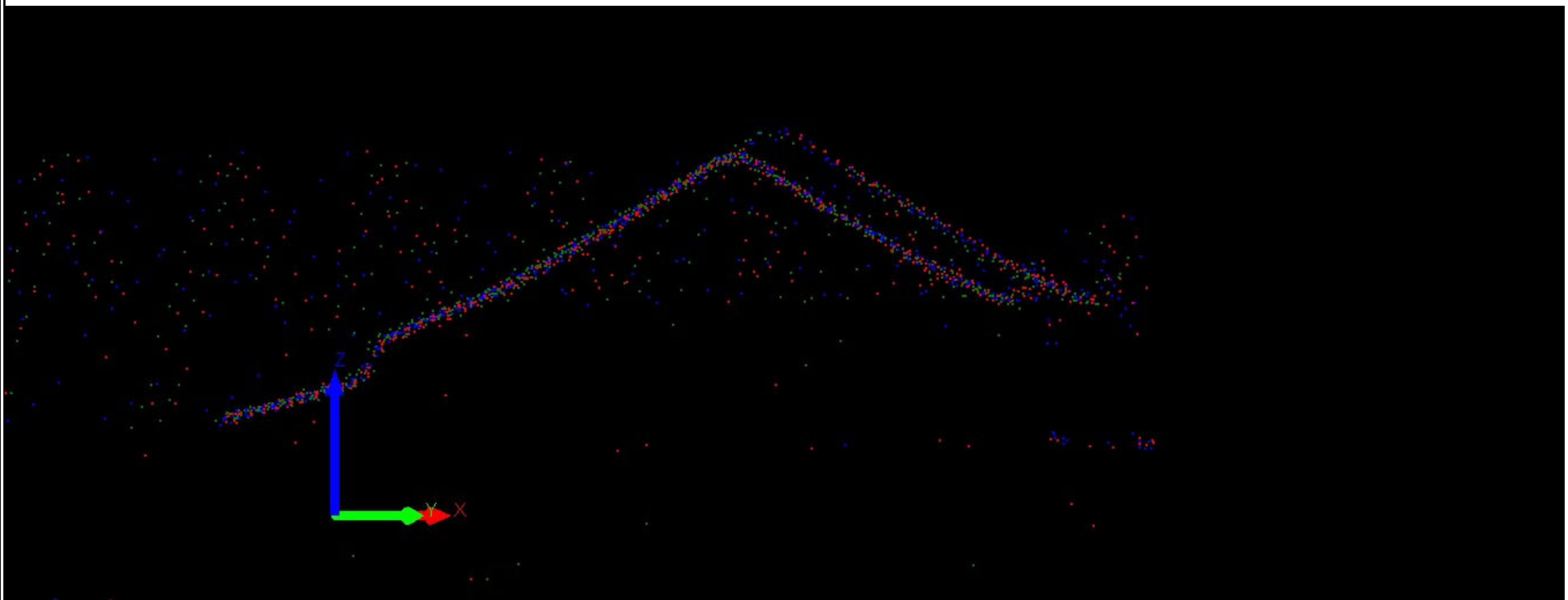
Relative Accuracy (IQC) Evaluation

LiDAR QA/QC: Experimental Results (III)



Before QA/QC

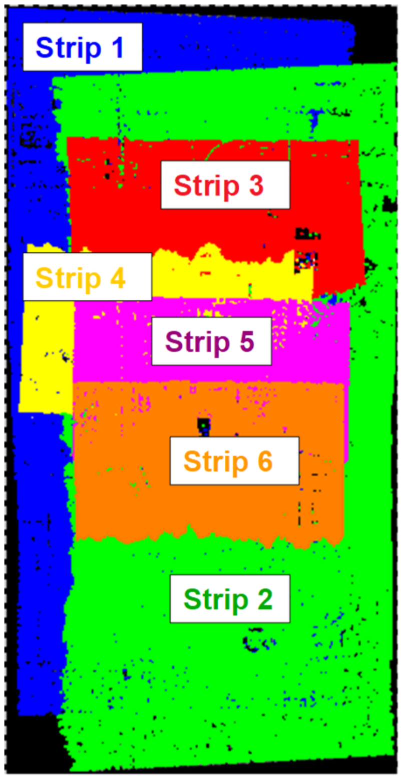
LiDAR QA/QC: Experimental Results (III)



After QA/QC

LiDAR QA/QC: Experimental Results (IV)

Dataset Description



Strip Number	Flying Height	Direction
1	1150 m	N-S
2	1150 m	S-N
3	539 m	E-W
4	539 m	W-E
5	539 m	E-W
6	539 m	E-W

Overlapping Strips Cases	% of Overlap	Direction
Strips 1&2	80%	Opposite directions
Strips 3&4	25%	Opposite directions
Strips 4&5	75%	Opposite directions
Strips 5&6	50%	Same direction

LiDAR QA/QC: Experimental Results (IV)

Estimated system biases using the Simplified and the Quasi-rigorous methods

Method	δΔX(m)	δΔY(m)	δΔω(°)	δΔφ(°)	δΔκ(°)	Δρ(m)	δS
Simplified	0.03	-0.01	-26	-91	-19	0.18	0.000046
Quasi-rigorous	-0.01	0.02	-40.2	-90.9	-4.58	0.26	-0.000096

LiDAR QA/QC: Experimental Results (IV)

Before Calibration		
Strips 1&2		
X_T (m)	Y_T (m)	Z_T (m)
1.10	-0.32	-0.01
ω (deg)	φ (deg)	κ (deg)
0.0001	-0.052	-0.002
Strips 3&4		
X_T (m)	Y_T (m)	Z_T (m)
0.18	0.41	-0.01
ω (deg)	φ (deg)	κ (deg)
0.0484	-0.0005	-0.0011

Compatibility between overlapping strips before and after the calibration procedure

Relative Accuracy (IQC) Evaluation

LiDAR QA/QC: Experimental Results (IV)

	Before Calibration	*After Calibration*
Mean ΔX (m)	**-0.36**	**-0.10**
Mean ΔY (m)	**0.67**	**0.24**
Mean ΔZ (m)	**-0.05**	**-0.015**
σ_X (m)	**0.40**	**0.11**
σ_Y (m)	**0.29**	**0.06**
σ_Z (m)	**0.24**	**0.13**
$RMSE_X$ (m)	**0.53**	**0.14**
$RMSE_Y$ (m)	**0.72**	**0.24**
$RMSE_Z$ (m)	**0.25**	**0.20**
$RMSE_{TOTAL}$ (m)	**0.93**	**0.35**

RMSE analysis of the photogrammetric check points using extracted control planar features from the LiDAR data before and after the calibration procedure

Absolute Accuracy (EQC) Evaluation

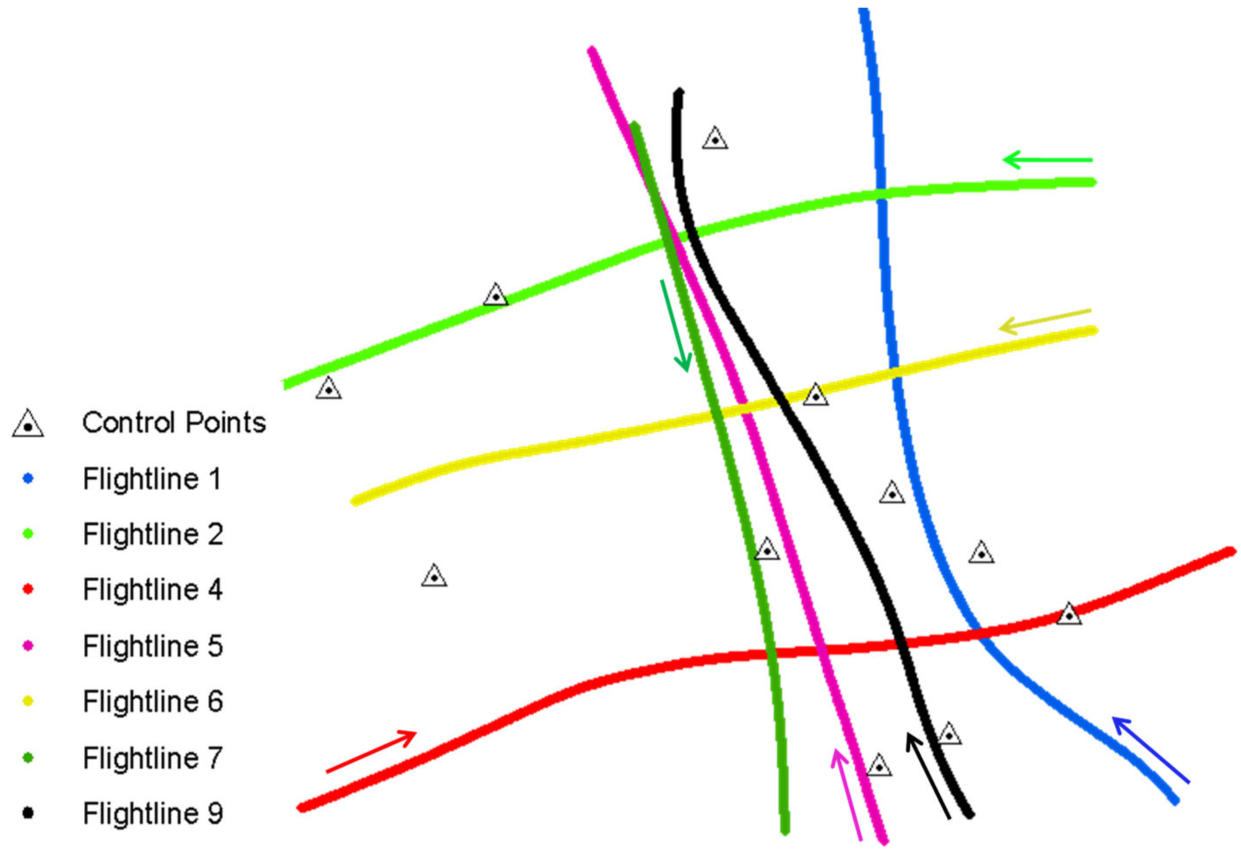
LiDAR QA/QC: Experimental Results (V)

Dataset Description

Source: http://www.isprs.org/publications/related/semana_geomatica05/front/abstracts/Dimecres9/F01.pdf

LiDAR QA/QC: Experimental Results (V)

Dataset Description



Dataset captured by a compact LiDAR system built at EPFL operated from the side of a helicopter

LiDAR QA/QC: Experimental Results (V)

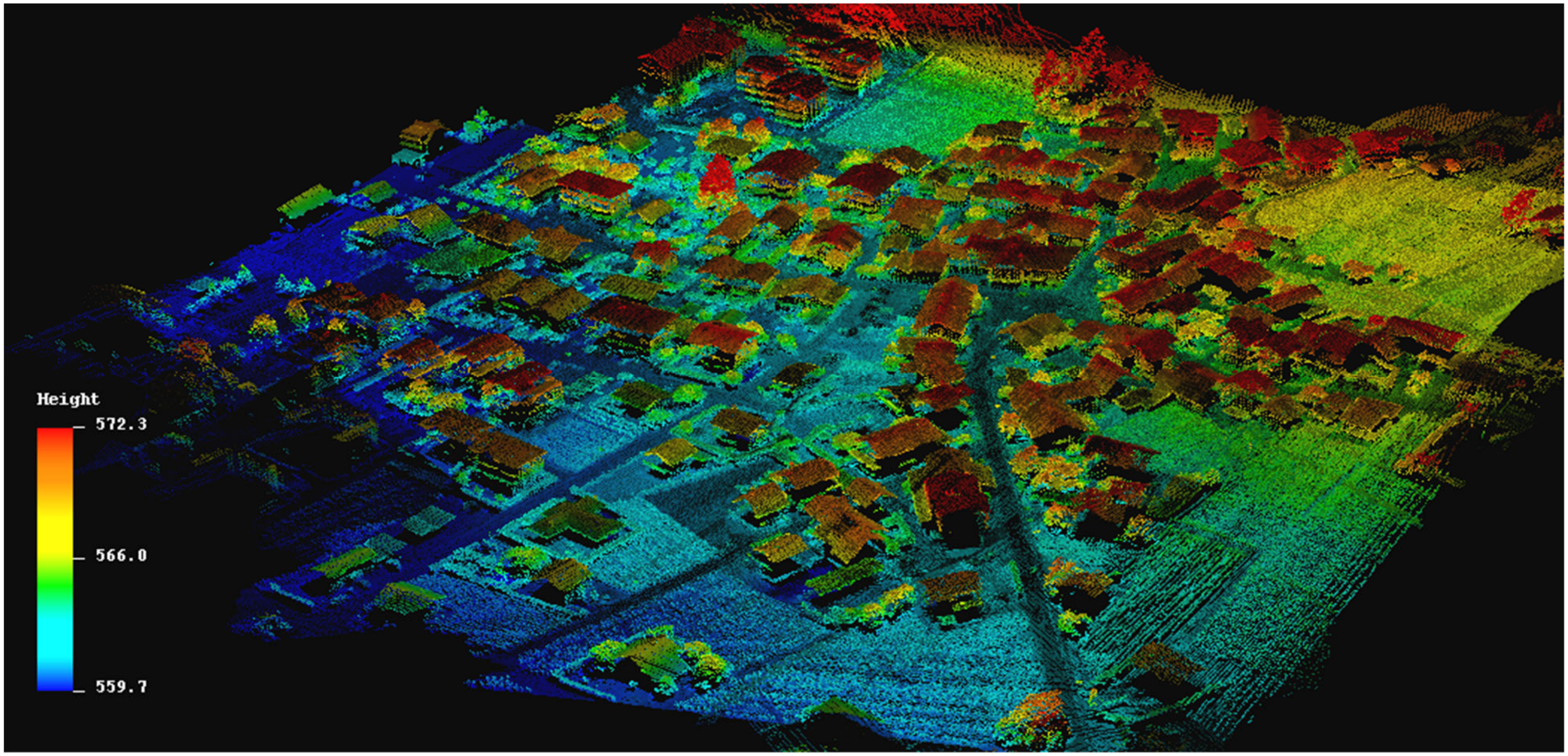
Dataset Description

Platform attitude variation

Flight line	ω (º) min/max	φ (º) min/max
1	-3.0 / 4.2	6.4 / 9.1
2	-9.4 / -3.0	-4.0 / 1.6
4	6.8 / 8.7	0.6 / 1.4
5	0.0 / 7.5	4.7 / 10.7
6	-11.4 / -3.0	0.4 / 5.0
7	-4.2 / 8.8	-12.9 / -7.4
9	-9.9 / -2.2	1.6 / 23.2

LiDAR QA/QC: Experimental Results (V)

Dataset Description



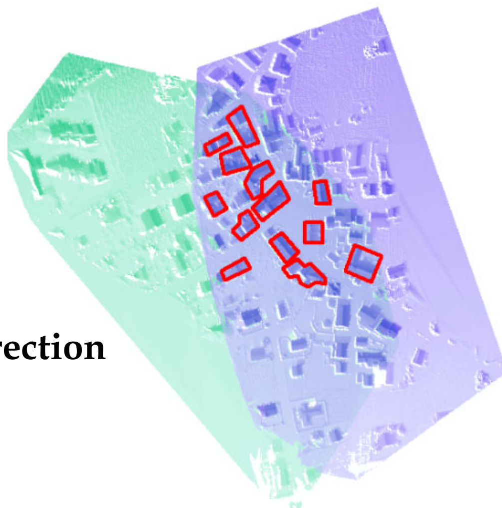
LiDAR QA/QC: Experimental Results (V)

Strip pairs	Flying Direction
Rigorous	1&9; 2&4; 5&6; 5&7
Quasi-rigorous	1&9; 2&4; 5&6; 5&7
Simplified	1&9; 2&4; 5&7

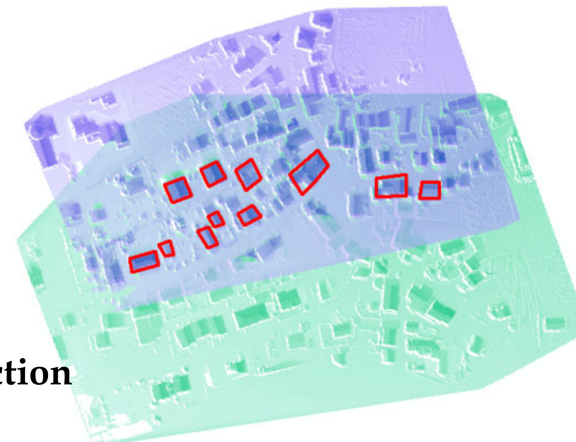
Strip pairs	Flying Direction	% Overlap	Average Lateral Distance D (m)	Average Flying Height H (m)
1&9	approx. parallel	75	66	130
2&4	approx. opposite	70	160	130
5&6	cross	-	-	230
5&7	approx. opposite	75	10	230

LiDAR QA/QC: Experimental Results (V)

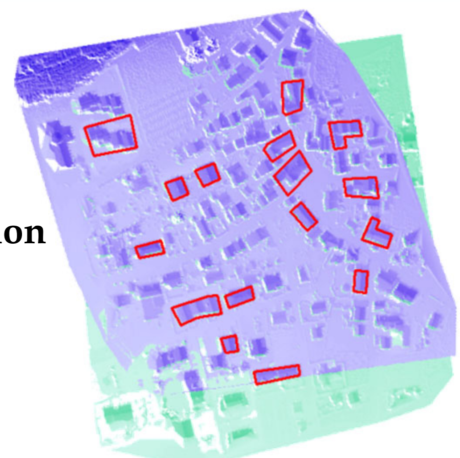
Dataset Description



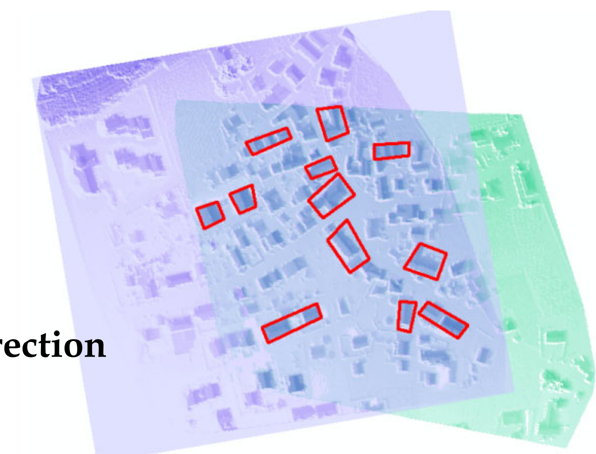
1&9
~Parallel Direction



2&4
~Opposite Direction



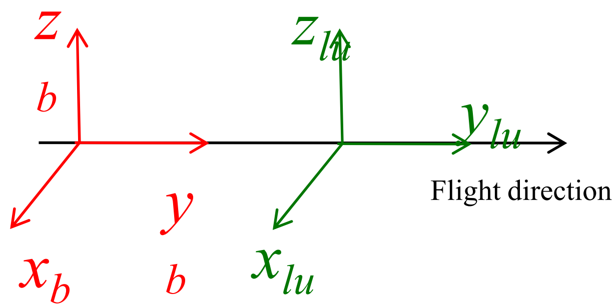
5&6
~Cross Direction



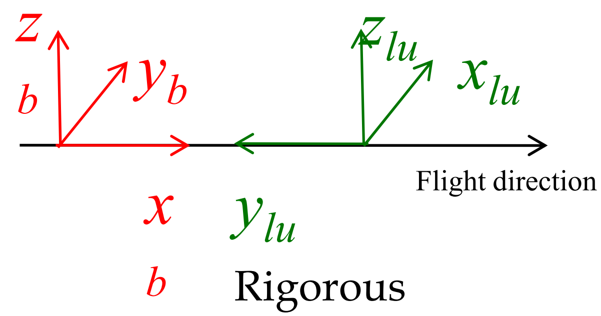
5&7
~Opposite Direction

LiDAR QA/QC: Experimental Results (V)

Method	δΔω(°)	δΔφ(°)	δΔκ(°)	S/δS
Simplified	0.039	0.092	-0.029	-0.00028204
Quasi-rigorous	0.038	0.093	-0.044	-0.00000514
Rigorous	-0.094	0.032	90.064	1.00017



Simplified/Quasi-Rigorous



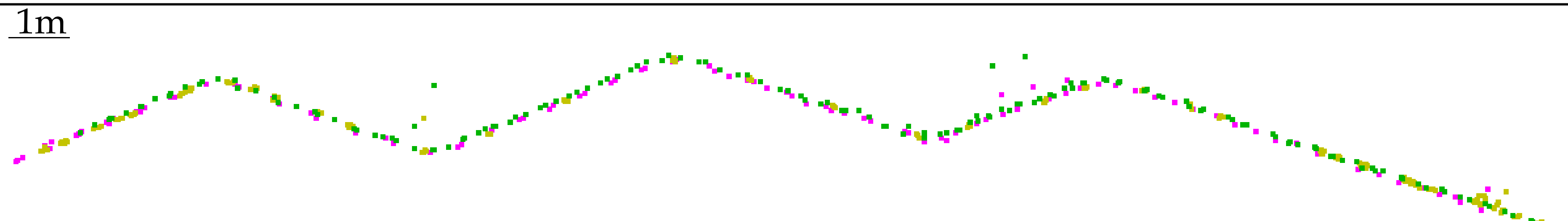
Rigorous

Please, note that the estimated parameters are not compatible since different coordinate systems definition are utilized in the two calibration approaches.

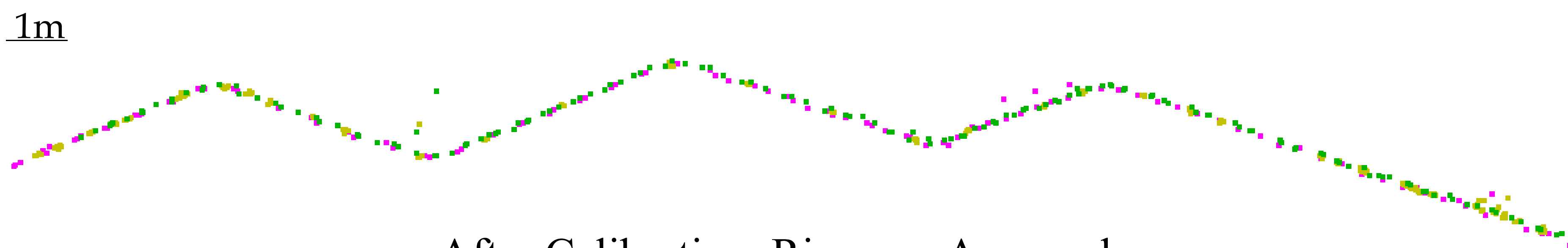
LiDAR QA/QC: Experimental Results (V)

Qualitative QC

Before Calibration



After Calibration: Quasi-Rigorous Approach



After Calibration: Rigorous Approach

LiDAR QA/QC: Experimental Results (V)

Quantitative QC

Before Calibration			After Calibration								
			Rigorous			Quasi-Rigorous			Simplified		
1&9											
X_T'(m)	Y_T'(m)	Z_T'(m)	X_T'(m)	Y_T'(m)	Z_T'(m)	X_T'(m)	Y_T'(m)	Z_T'(m)	X_T'(m)	Y_T'(m)	Z_T'(m)
0.00	-0.21	-0.07	0.01	-0.01	0.01	0.03	-0.11	0.01	0.04	-0.13	0.00
Ω'(°)	Φ' (°)	K'(°)	Ω'(°)	Φ' (°)	K'(°)	Ω'(°)	Φ' (°)	K'(°)	Ω'(°)	Φ' (°)	K'(°)
-0.0177	0.0169	0.0432	0.0178	0.0114	0.0178	0.0178	0.0178	0.0147	0.0128	0.0098	0.0155
2&4											
X_T'(m)	Y_T'(m)	Z_T'(m)	X_T'(m)	Y_T'(m)	Z_T'(m)	X_T'(m)	Y_T'(m)	Z_T'(m)	X_T'(m)	Y_T'(m)	Z_T'(m)
-0.53	0.19	0.06	-0.06	-0.02	0.00	-0.11	-0.11	0.00	-0.11	0.13	0.01
Ω'(°)	Φ' (°)	K'(°)	Ω'(°)	Φ' (°)	K'(°)	Ω'(°)	Φ' (°)	K'(°)	Ω'(°)	Φ' (°)	K'(°)
-0.0217	0.1505	0.0009	-0.0241	-0.0109	-0.0077	-0.0245	-0.0073	0.0032	0.0113	0.0275	0.0031
5&6											
X_T(m)	Y_T(m)	Z_T(m)	X_T(m)	Y_T(m)	Z_T(m)	X_T(m)	Y_T(m)	Z_T(m)	X_T(m)	Y_T(m)	Z_T(m)
0.33	-0.46	0.01	0.00	-0.02	0.02	0.02	-0.02	0.02	0.02	-0.02	0.02
Ω (°)	Φ (°)	K (°)	Ω (°)	Φ (°)	K (°)	Ω (°)	Φ (°)	K (°)	Ω (°)	Φ (°)	K (°)
-0.0626	-0.1021	-0.0083	0.0013	0.0070	0.0017	-0.0021	0.0001	0.0007	-0.0049	-0.0014	-0.0026
5&7											
X_T'(m)	Y_T'(m)	Z_T'(m)	X_T'(m)	Y_T'(m)	Z_T'(m)	X_T'(m)	Y_T'(m)	Z_T'(m)	X_T'(m)	Y_T'(m)	Z_T'(m)
-0.68	0.36	0.10	-0.02	0.00	0.03	0.04	0.05	0.01	0.04	0.05	0.01
Ω'(°)	Φ' (°)	K'(°)	Ω'(°)	Φ' (°)	K'(°)	Ω'(°)	Φ' (°)	K'(°)	Ω'(°)	Φ' (°)	K'(°)
-0.0311	0.1847	0.0032	-0.0069	-0.0102	0.0231	-0.0292	-0.0008	0.0209	-0.0288	0.0014	0.0196

Concluding Remarks

- QA/QC of LiDAR mapping is not as mature as those for photogrammetric mapping.
  - There are several challenges when compared with photogrammetric mapping.
- Challenges with QA/QC of LiDAR mapping:
  - Raw measurements might not be always available.
  - Sophisticated procedures are needed to relate the LiDAR data to distinct points (e.g., GCPs).
  - LiDAR-derived coordinates is not based on an adjustment procedure.
  - Quality control measures, which are typically used in photogrammetry, are not applicable.

Concluding Remarks

- Alternative procedures are needed to check for systematic biases and evaluate the noise level in the point cloud.
- LiDAR system calibration is possible by identifying the nature of discrepancies between overlapping strips.
  - Models that can be conducted in the absence of the system's raw measurements
  - Models that can be conducted in the absence of control information
- Quality control of LiDAR data can be conducted by the end user.
- Standards and procedures are needed for QA/QC activities.

Concluding Remarks

- Quality Assurance and Quality Control should not be viewed as two independent processes.
  - The potential of using the outcome from the quality control to improve the system parameters
- The QC should evaluate the following:
  - The consistency of derived surfaces from overlapping strips (precision)
  - The consistency of the derived surface and ground truth (accuracy)
  - Point density and its utilization in subsequent data processing
  - Quality of derived products (e.g., DTM generation, classification & segmentation outcome)