Error Budget of LiDAR Systems and Quality Control of the Derived Point Cloud

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Introduction

DPRG
Digital Photogrammetry Research Group

BRITISH COLUMBIA
Ministry of Agriculture and Lands

Integrated Land Management Bureau

UNIVERSITY OF CALGARY
INFORMATION TECHNOLOGIES

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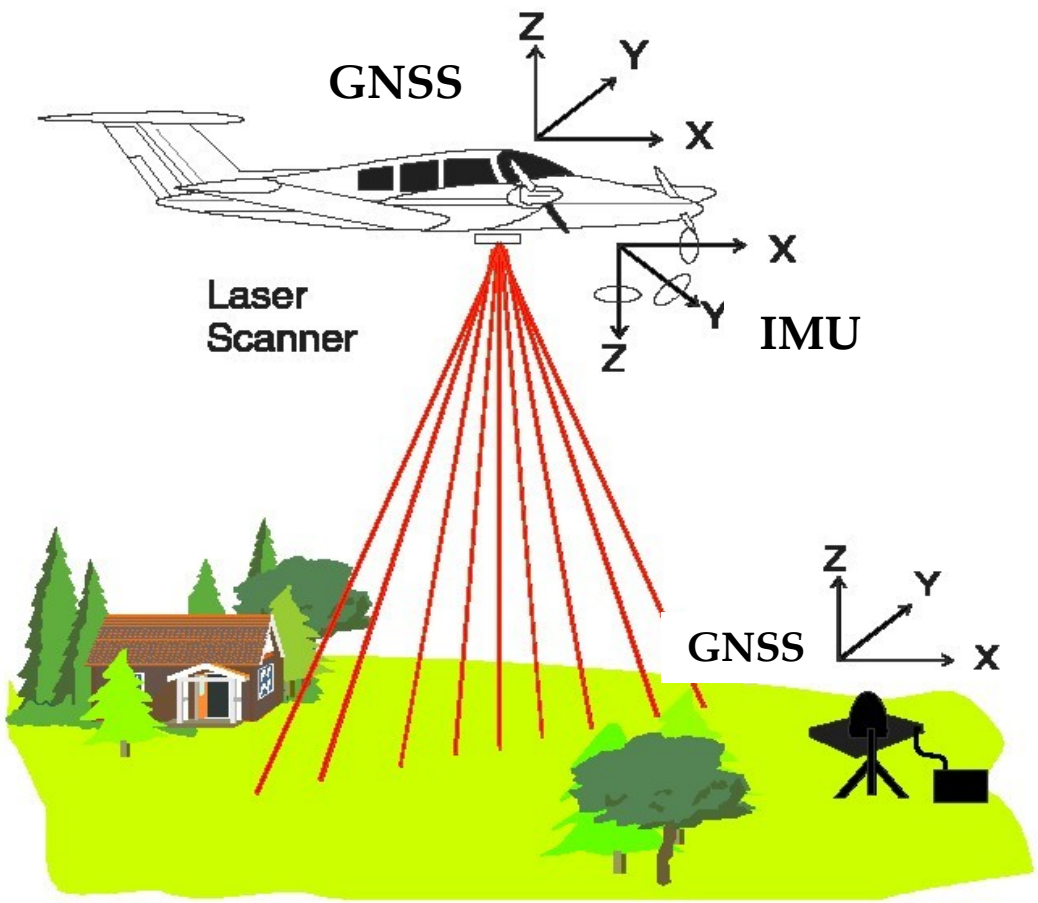
Overview

- LiDAR systems:
  - Introduction
  - Mathematical model
  - Quality Assurance and Quality Control (QA/QC)
  - Error budget
    - Random errors
    - Systematic errors
  - System verification & diagnosis (QC)
- Concluding remarks

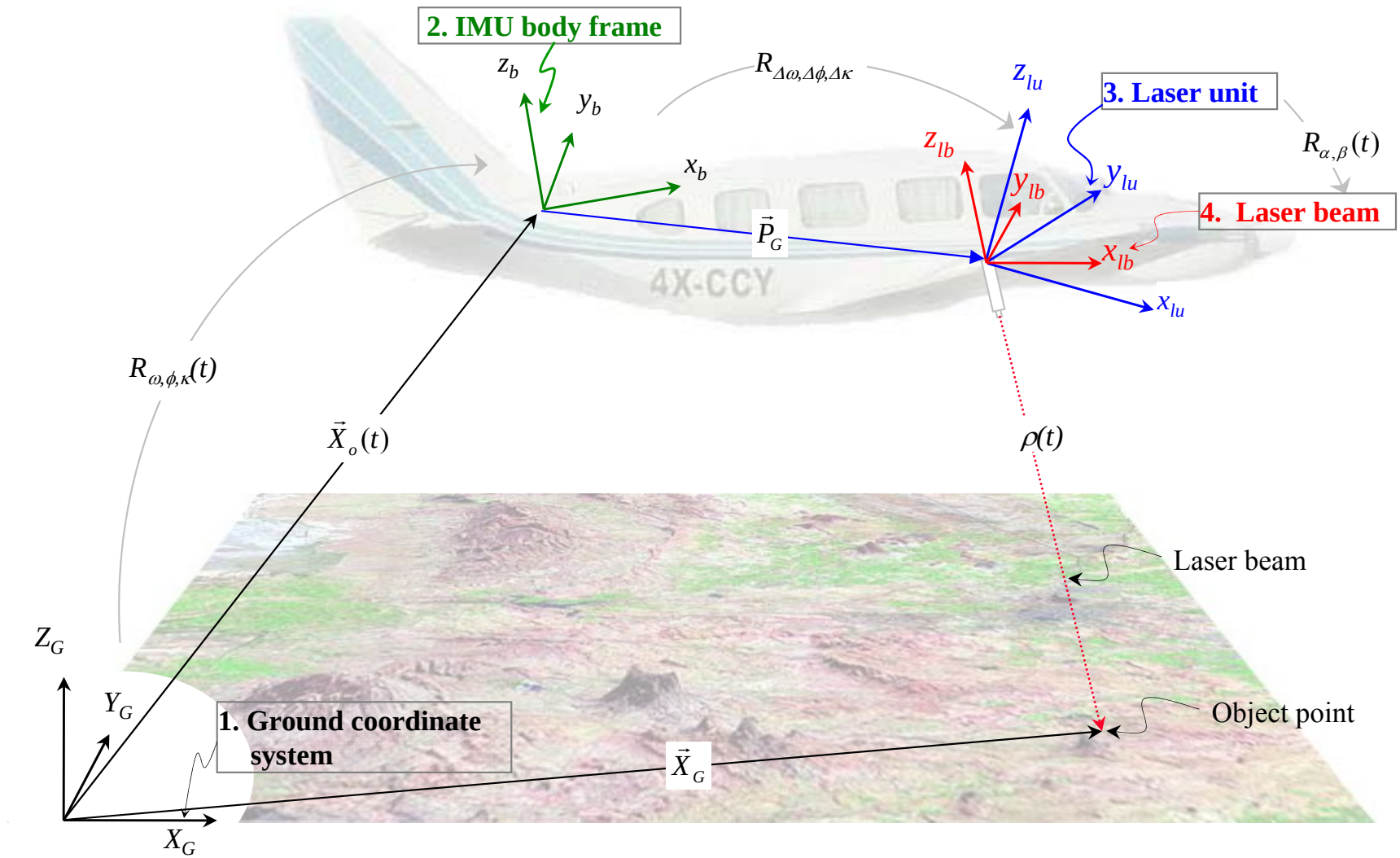
LiDAR Principles

Three Measurement Systems

1. GNSS
2. IMU
3. Laser scanner emits laser beams with high frequency and collects the reflections



LiDAR Equation & Coordinate Systems



- LiDAR equation is a vector summation procedure.

LiDAR Equation

$$\vec{X}_G = \vec{X}_o(t) + R_{\omega,\phi,\kappa}(t)\ \vec{P}_G + R_{\omega,\phi,\kappa}(t)\ R_{\Delta\omega,\Delta\phi,\Delta\kappa}\ R_{\alpha,\beta}(t) \begin{bmatrix} 0 \\ 0 \\ -\rho(t) \end{bmatrix}$$

$\vec{X}_G$ ground coordinates of the object point under consideration

$\vec{X}_o(t)$ ground coordinates of the origin of the IMU coordinate system

$R_{\omega,\phi,\kappa}(t)$ rotation matrix relating the ground and IMU coordinate systems

$\vec{P}_G$ offset between the laser unit and IMU coordinate systems (spatial bore-sighting)

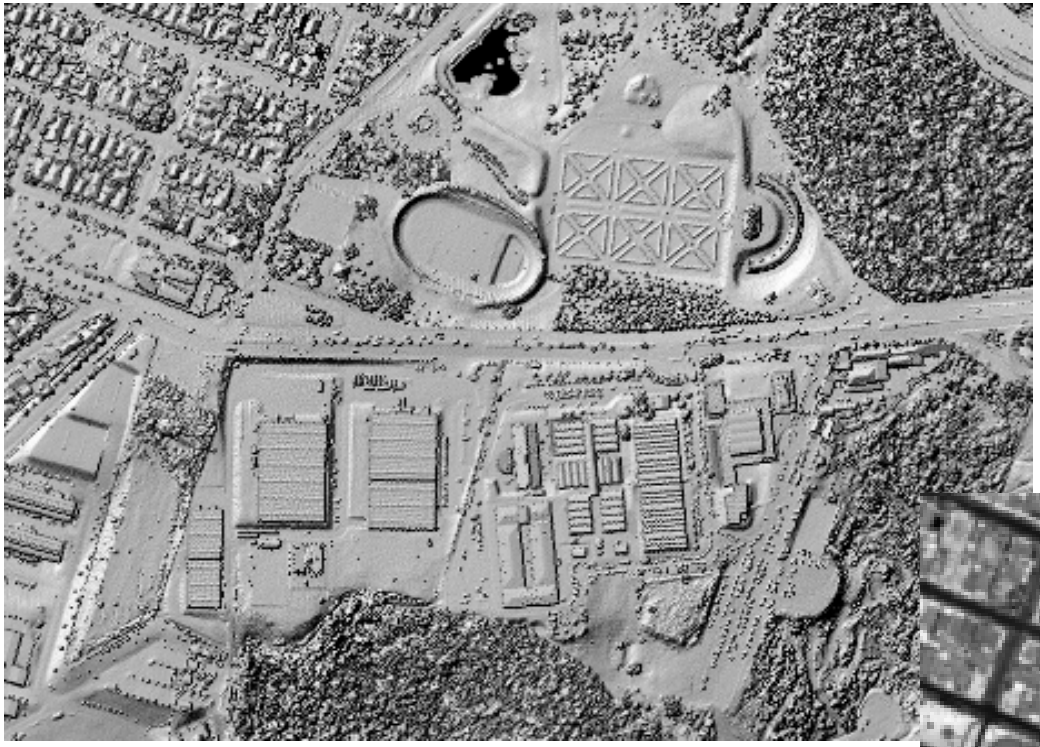
$R_{\Delta\omega,\Delta\phi,\Delta\kappa}$ rotation matrix relating the IMU and laser unit coordinate systems (angular bore-sighting)

$R_{\alpha,\beta}(t)$ rotation matrix relating the laser unit and laser beam coordinate systems

$\rho(t)$ range between the laser beam firing point and its footprint

- Note: There is no redundancy in the surface reconstruction process.

LiDAR Output



Range Data (Shaded Relief)

Intensity Data

Quality Assurance & Quality Control

- Quality assurance (before mission):
  - Management activities to ensure that a process, item, or service is of the quality needed by the user.
  - It deals with creating management controls that cover planning, implementation, and review of data collection activities.
  - Key activity in the quality assurance is the calibration procedure.
- Quality control (after mission):
  - Provide routines and consistent checks to ensure data integrity, correctness, and completeness.
  - Check whether the desired quality has been achieved.
- Error budget analysis is important for QA/QC.

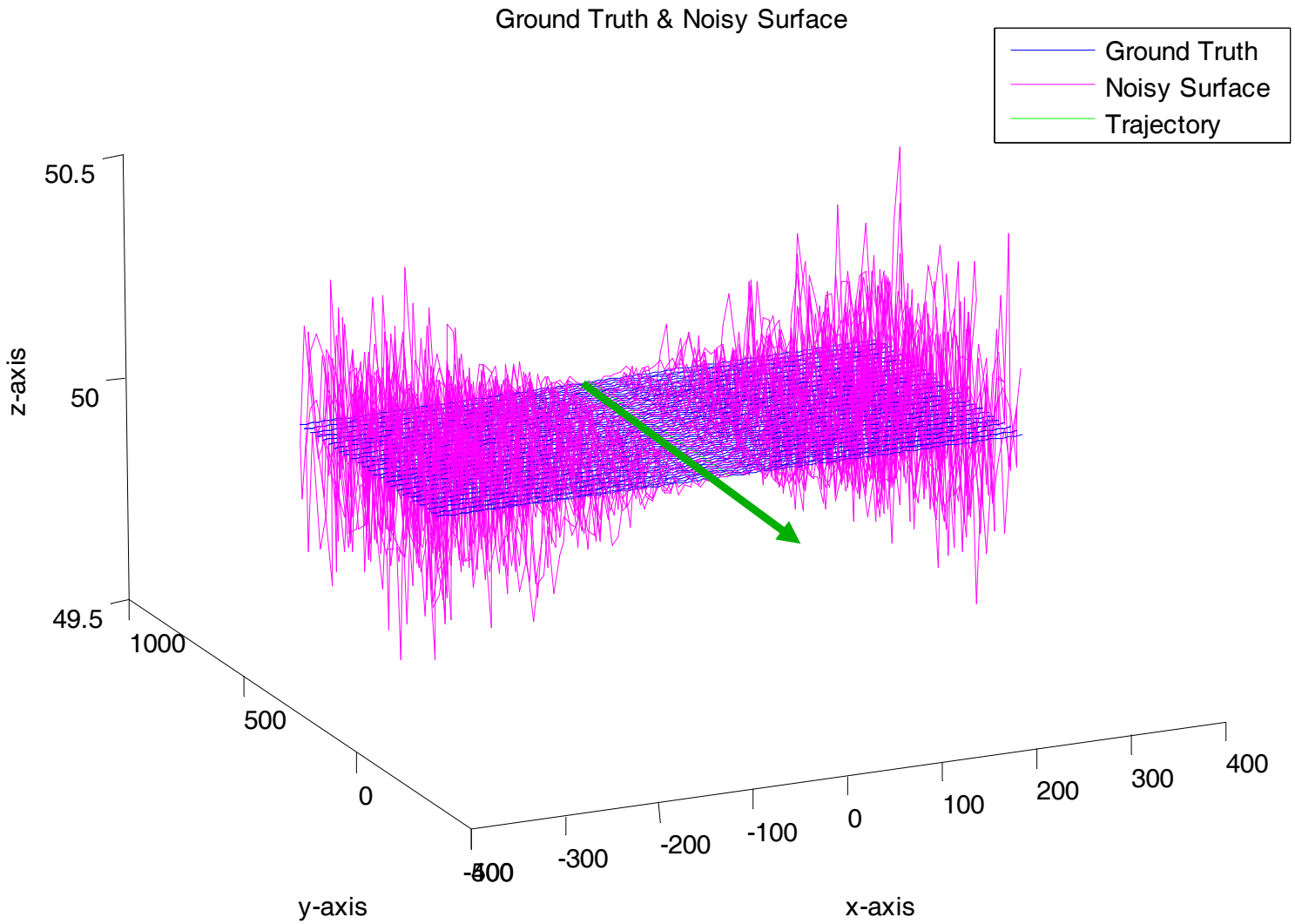
LiDAR Error Budget

- The quality of the derived point cloud from a LiDAR system depends on:
  - **Random errors** in the system measurements.
    - Position and orientation information from the GNSS/INS unit.
    - Ranges between the laser beam firing point and its footprints.
    - Mirror angles.
  - **Systematic errors** in the system parameters:
    - Biases in the spatial bore-sighting parameters ($\delta\Delta X$, $\delta\Delta Y$, $\delta\Delta Z$).
    - Biases in the angular bore-sighting parameters ($\delta\Delta\omega$, $\delta\Delta\phi$, $\delta\Delta\kappa$).
    - Biases in the measured ranges ($\delta\rho$).
    - Scale bias in the mirror angle (δS).
- We would like to investigate the impact of random and systematic errors on the quality of the derived LiDAR surface.

Random Errors

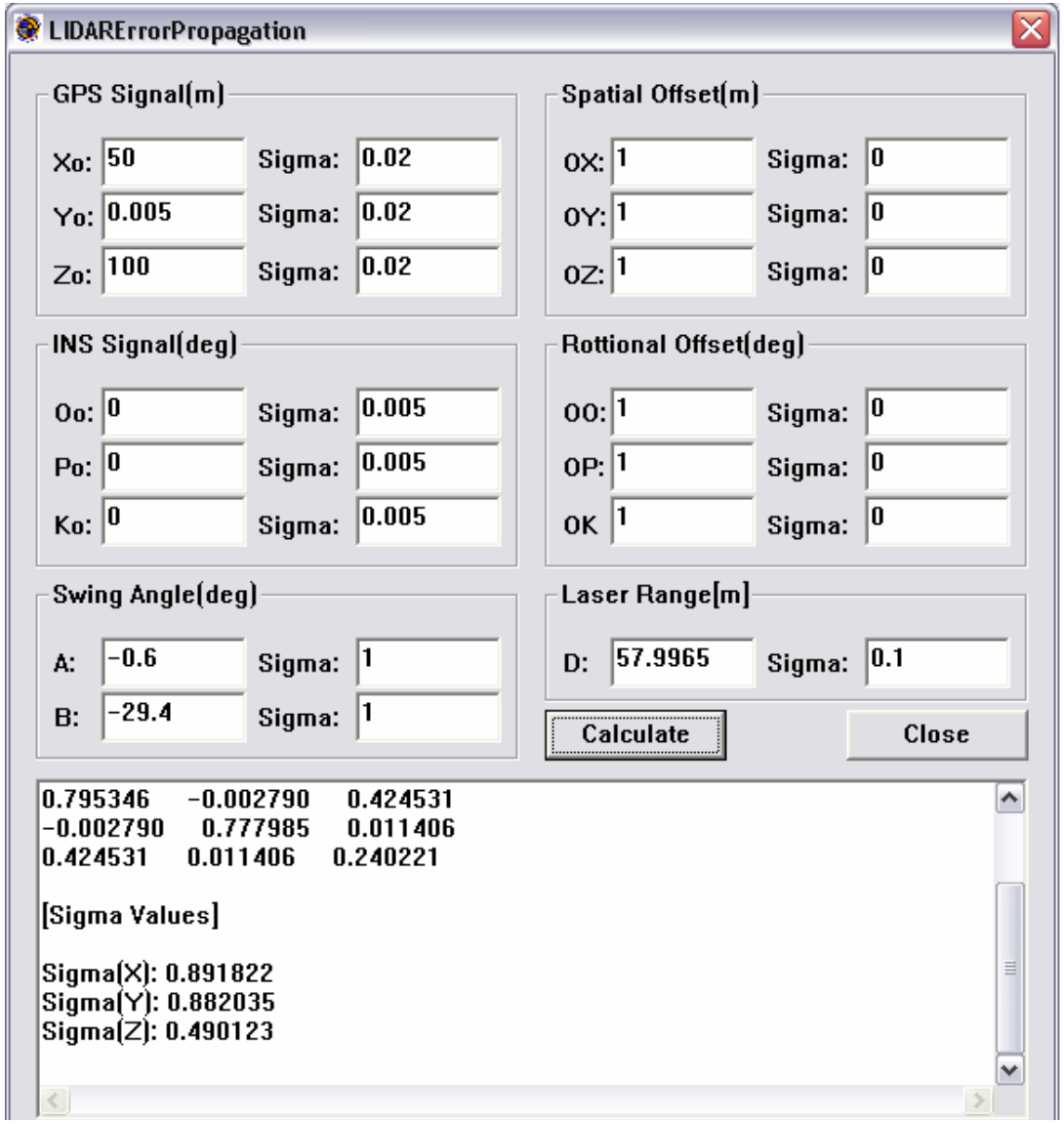
- The effect of random errors can be analyzed using either one of the following approaches:
  - Approach # I:
    - Simulated surface & trajectory → LiDAR measurements → Add noise → Reconstructed surface.
    - Evaluate the differences between the reconstructed footprints and the simulated surface (i.e., ground truth).
  - Approach # II:
    - Law of error propagation to evaluate the accuracy of the derived point cloud using the accuracy of the LiDAR measurements.

Random Errors: Orientation Noise



- Propagates with the flying height
- Depends on the look angle

LiDAR Error Propagation Calculator



http://ilmbwww.gov.bc.ca/bmgs/pba/trim/specs

LiDAR Random Error Budget

- Accuracy of the system components

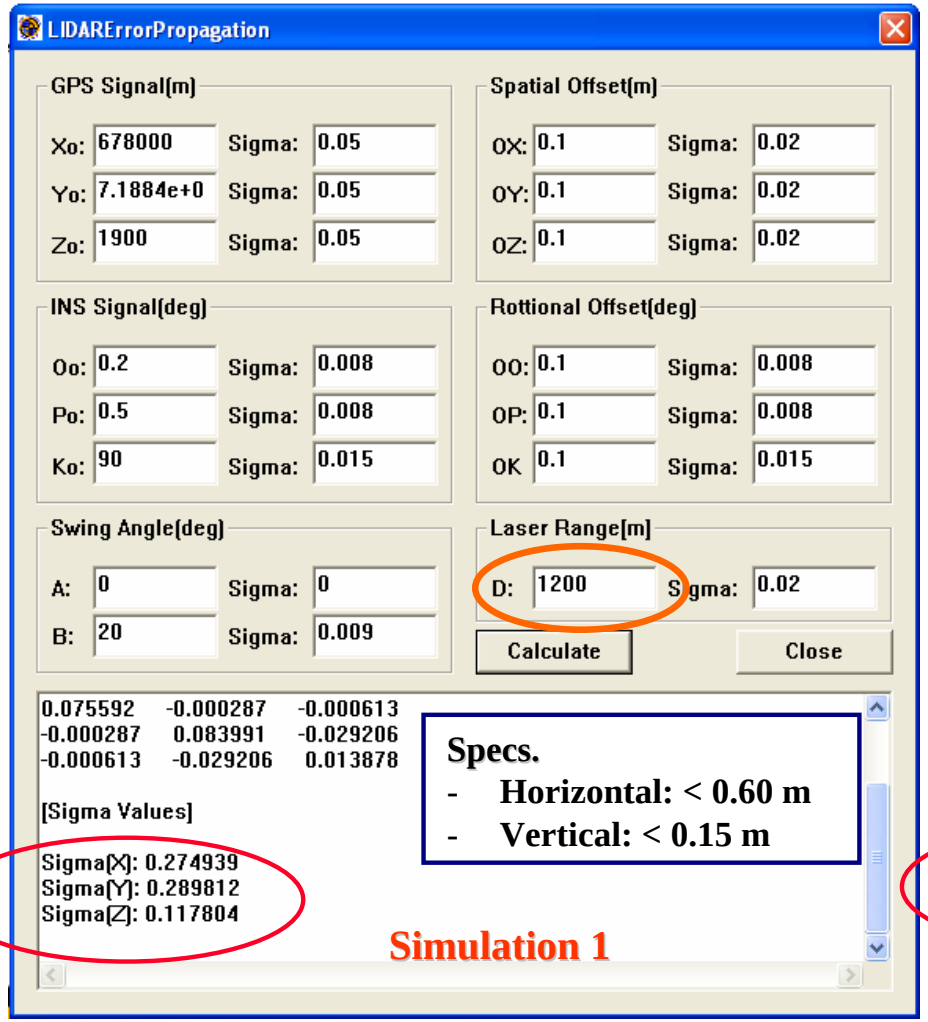
System Model	GPS (m) Post-Processed	IMU (deg) Post-Processed			Scan Angle (deg)	Laser Range (cm)
		Roll	Pitch	Heading		
ALTM 2050	0.05 – 0.3	0.008	0.008	0.015	0.009	~ 2
ALTM 3100	0.05 – 0.3	0.005	0.005	0.008	0.009	~ 2

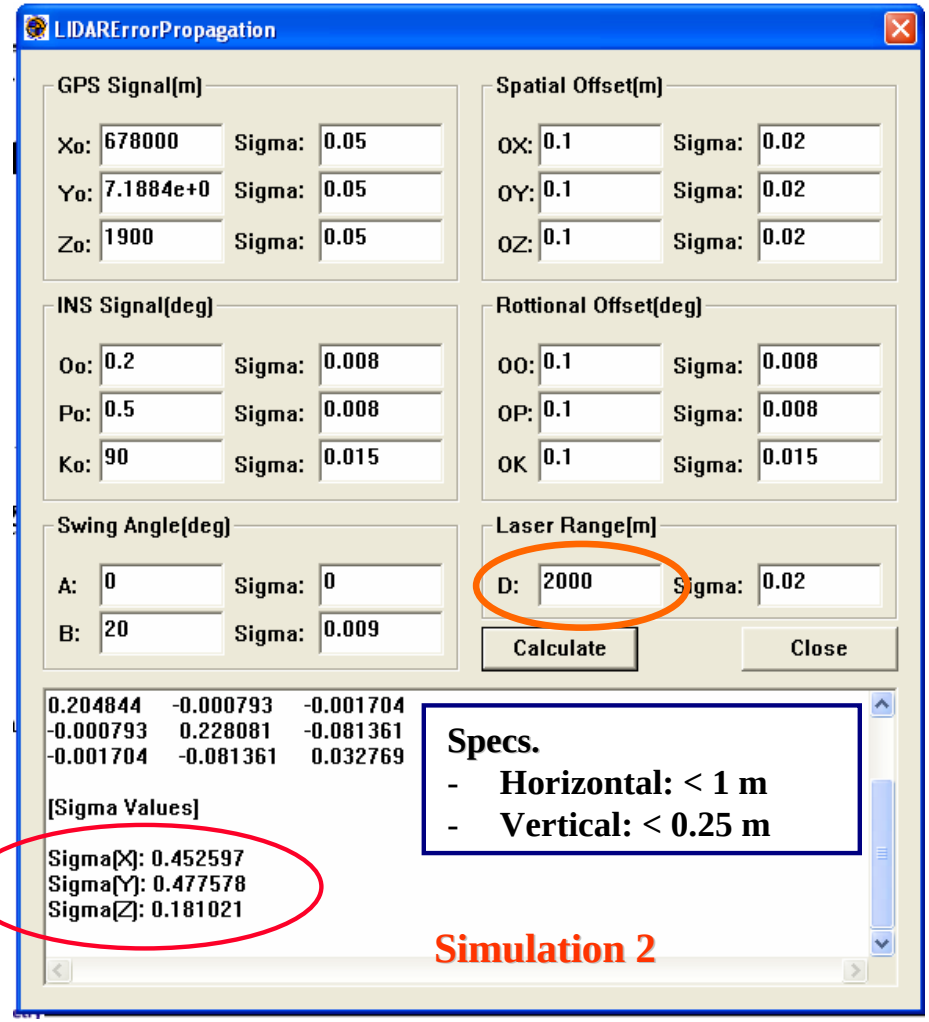
- System Manufacturer Specification (Optech: ALTM 2050 and ALTM 3100)

  - Horizontal accuracy : 1/2000 x altitude
  - Vertical accuracy : <15 cm at 1200 m
    : <25 cm at 2000 m

LiDAR Random Error Budget

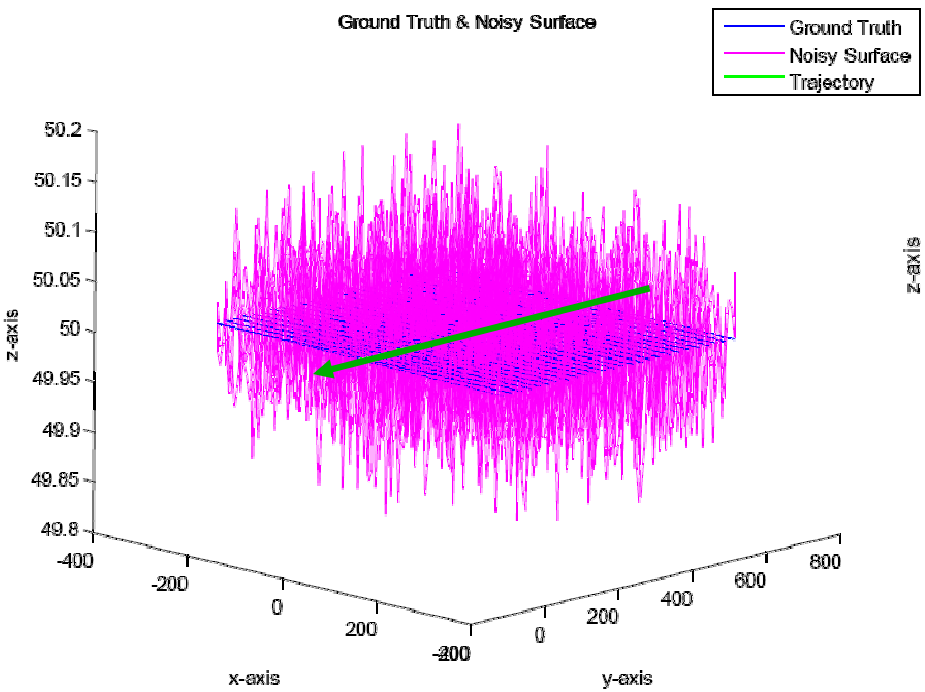
- Expected accuracy (assuming flat solid surface) of the ground coordinates as derived from the error propagation – ALTM 2050





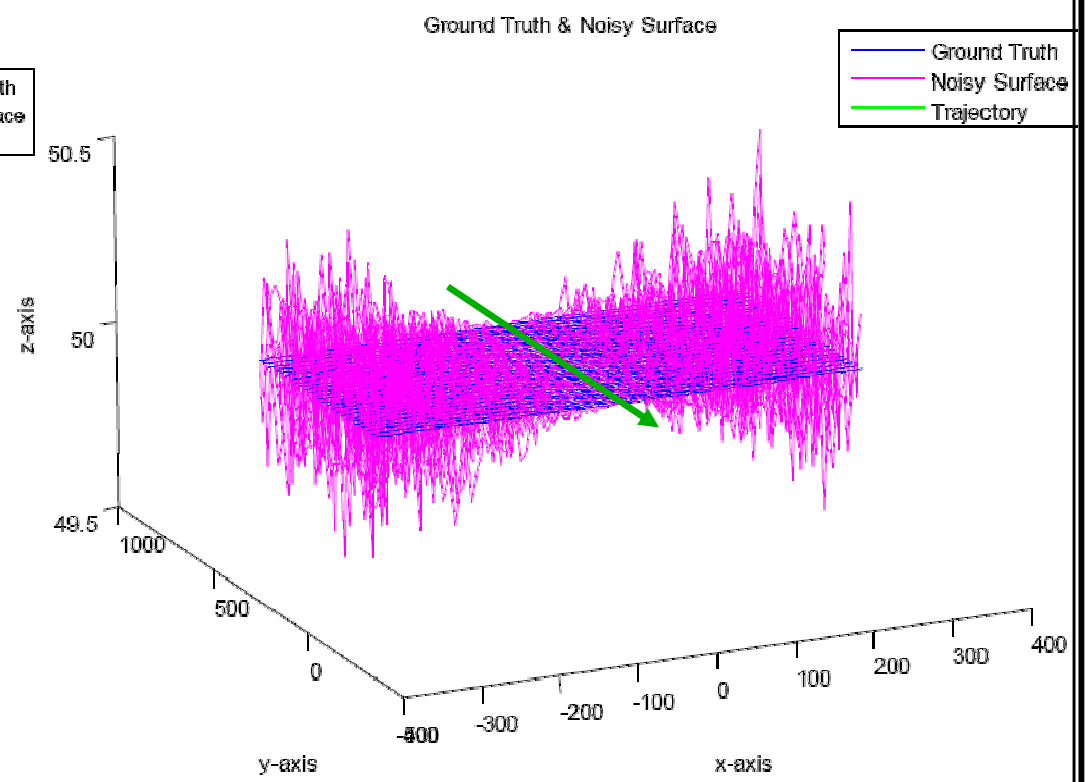
Random Errors and Relative Accuracy

Random Noise added to the Position Measurements



Relative accuracy is not affected

Random Noise added to the Orientation Measurements



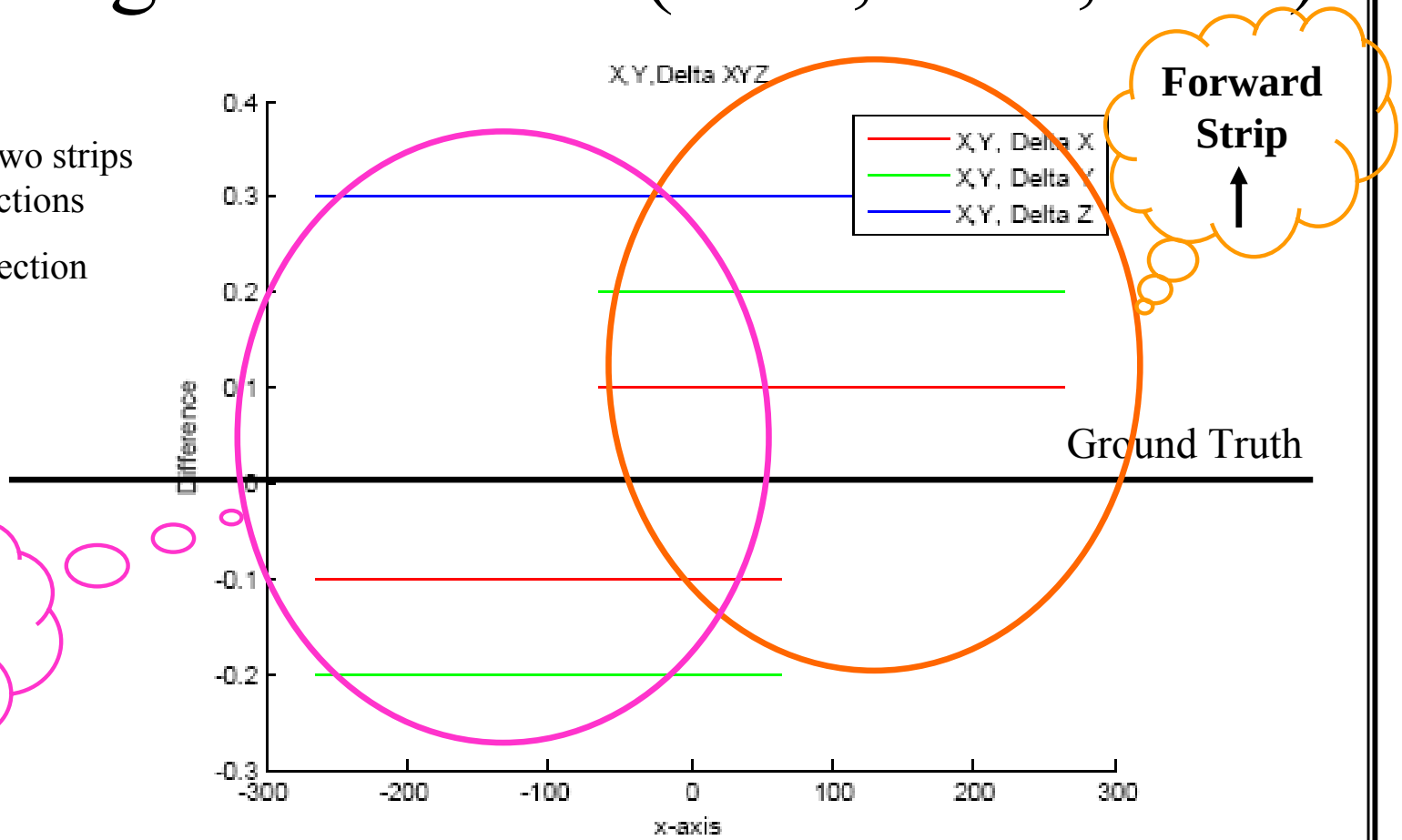
Relative accuracy is affected

Systematic Errors

- We would like to show the effect of systematic errors/biases in the LiDAR parameters on the reconstructed object space.
- The effects will be derived through mathematical analysis of the LiDAR equation.
- The effects will be also analyzed through a simulation process:
  - Simulated surface & trajectory → LiDAR measurements → Add biases → Reconstructed surface.
  - The effects will be shown through the differences between the reconstructed footprints and the simulated surface (i.e., ground truth).
- These effects will be shown for linear LiDAR systems.

Bore-Sighting Offset Bias (δΔX, δΔY, δΔZ)

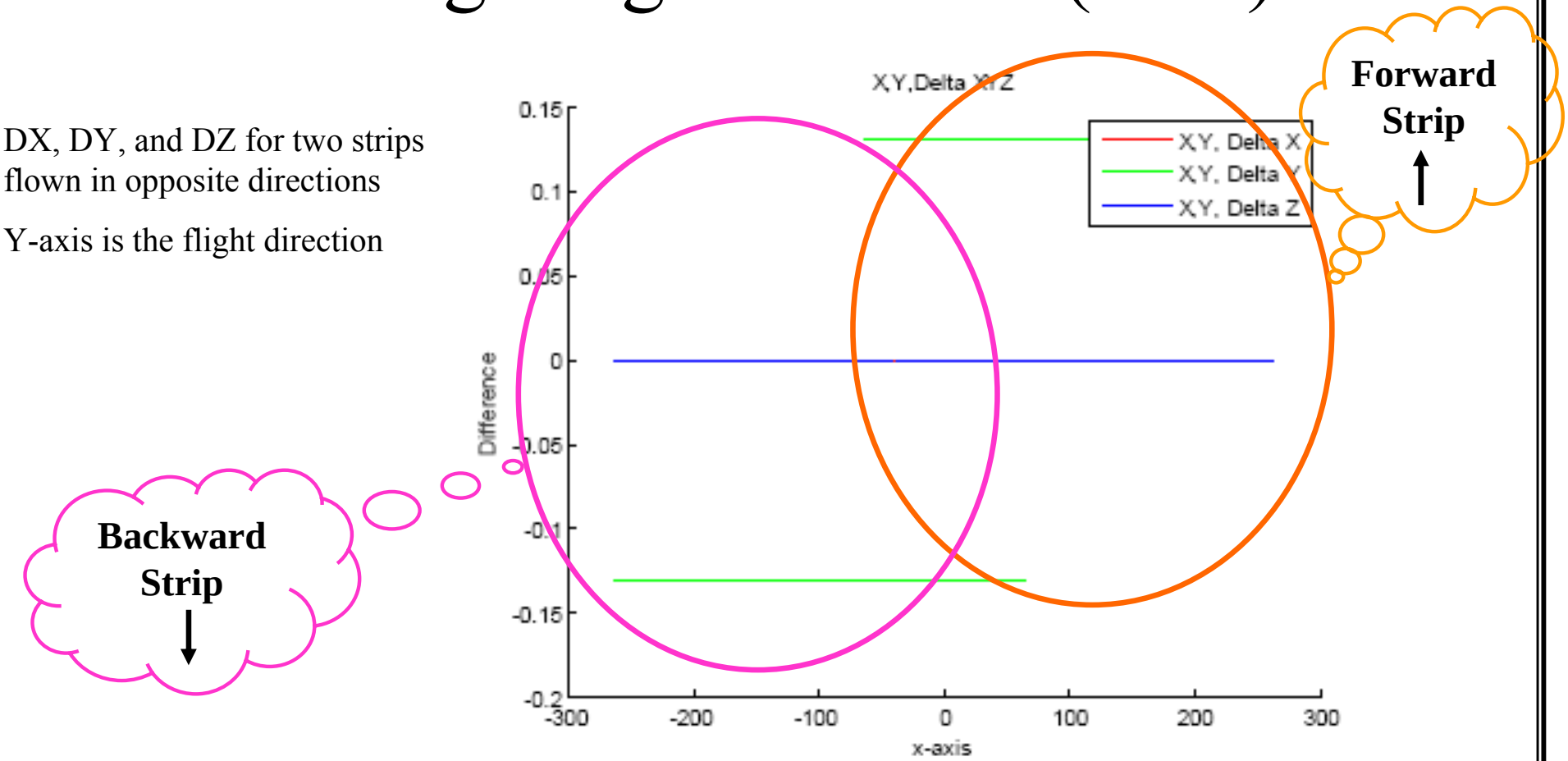
- DX, DY, and DZ for two strips flown in opposite directions
- Y-axis is the flight direction



	Flying Height	Flying Direction	Look Angle
Bore-sighting Offset Bias	• Effect is independent of the flying height	• Planimetric effect is dependent on the flying direction • Vertical effect is independent of the flying direction	• Effect is independent of the look angle

Bore-Sighting Pitch Bias (δΔω)

- DX, DY, and DZ for two strips flown in opposite directions
- Y-axis is the flight direction

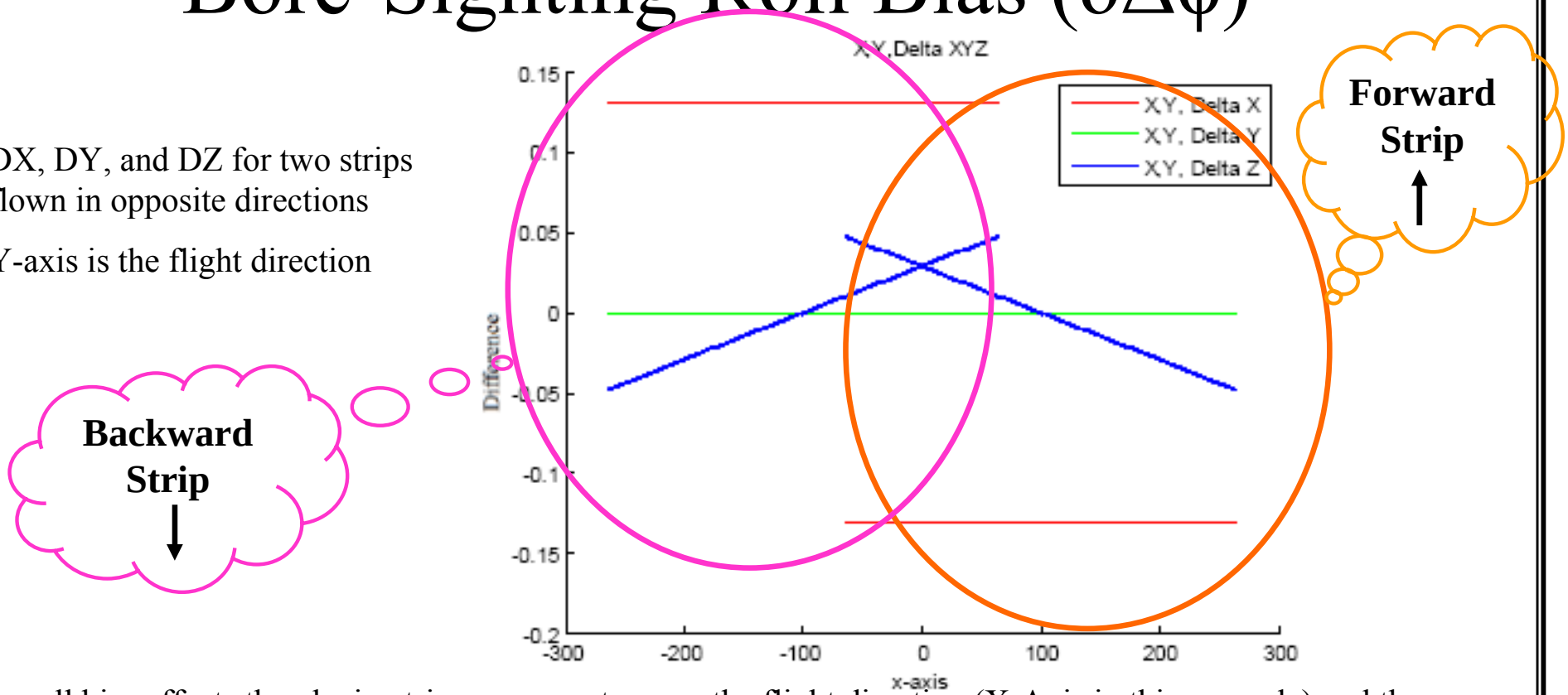


The pitch bias only affects the planimetric component along the flight direction (Y-Axis in this example).

	Flying Height	Flying Direction	Look Angle
Bore-sighting Pitch Bias	• Effect is dependent on the flying height	• Planimetric effect along the flight direction is dependent on the flying direction	• Effect is independent of the look angle

Bore-Sighting Roll Bias ($\delta\Delta\phi$)

- DX, DY, and DZ for two strips flown in opposite directions
- Y-axis is the flight direction

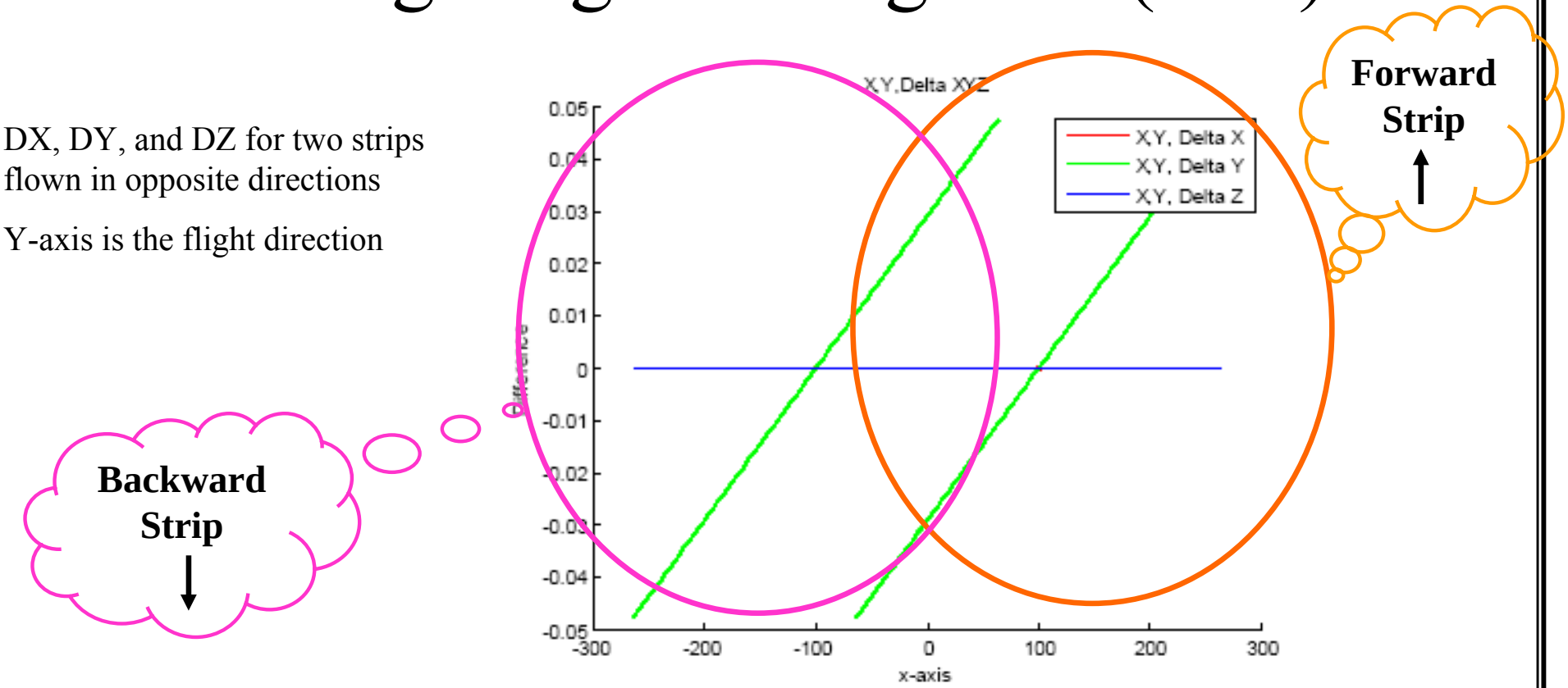


The roll bias affects the planimetric component across the flight direction (X-Axis in this example) and the height component.

	Flying Height	Flying Direction	Look Angle
Bore-sighting Roll Bias	• Planimetric effect across the flight direction is dependent on the flying height • Vertical effect is independent of the flying height	• Planimetric effect across the flight direction and vertical effect are dependent on the flying direction	• Planimetric effect across the flight direction is independent of the look angle • Vertical effect is dependent on the look angle

Bore-Sighting Heading Bias (δΔκ)

- DX, DY, and DZ for two strips flown in opposite directions
- Y-axis is the flight direction

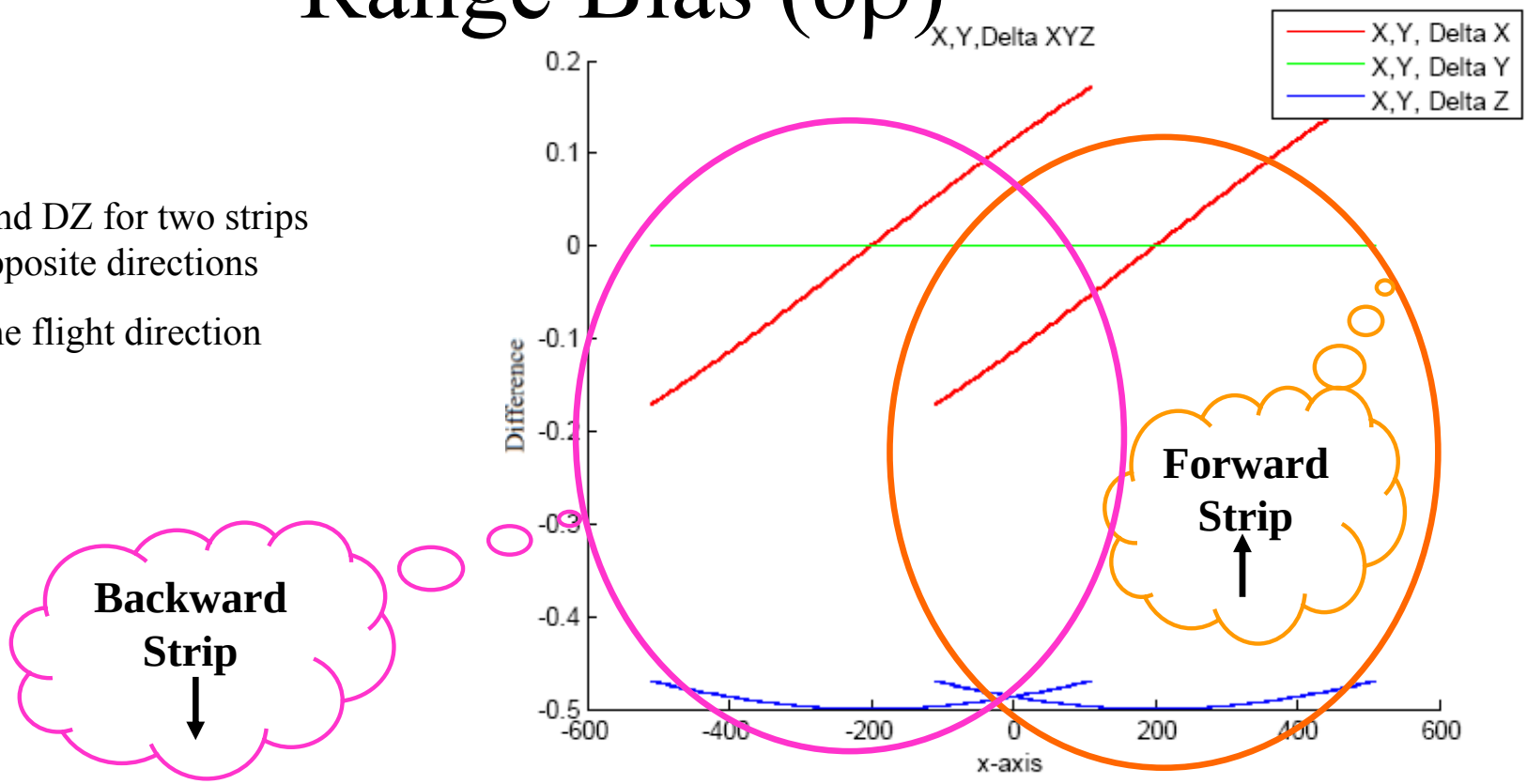


The heading bias only affects the planimetric component along the flight direction (Y-Axis in this example).

	Flying Height	Flying Direction	Look Angle
Bore-sighting Heading Bias	• Effect is independent of the flying height	• Planimetric effect along the flight direction is independent of the flying direction	• Planimetric effect along the flight direction is dependent on the look angle

Range Bias (δρ)

- DX, DY, and DZ for two strips flown in opposite directions
- Y-axis is the flight direction



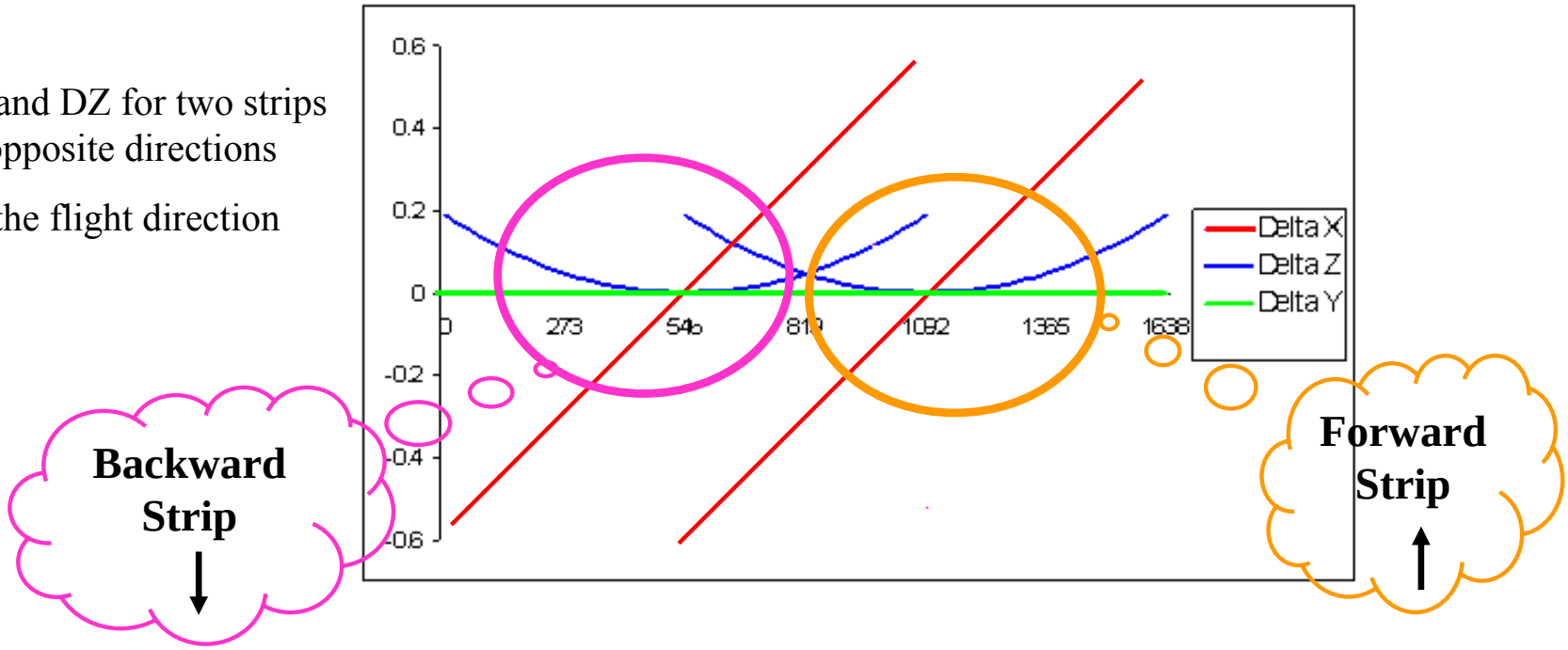
The range bias affects the planimetric component across the flight direction (X-Axis in this example) and the height component.

	Flying Height	Flying Direction	Look Angle
Range Bias	• Effect is dependent on the flying height	• Planimetric effect across the flight direction and vertical effect are independent of the flying direction	• Planimetric effect across the flight direction and vertical effect are dependent on the look angle (DX more than DZ)

Mirror Angle Scale Bias (δS)

$$\beta_{true} = \beta_{meas.} * (1 + \delta S)$$

- DX, DY, and DZ for two strips flown in opposite directions
- Y-axis is the flight direction



The mirror angle scale bias affects the planimetric component across the flight direction (X-Axis in this example) and the height component.

	Flying Height	Flying Direction	Look Angle
Mirror Angle Scale	• Effect is dependent on the flying height	• Planimetric effect across the flight direction and vertical effect are independent of the flying direction	• Planimetric effect across the flight direction and vertical effect are dependent on the look angle.

Bore-sighting, Mirror Angle Scale & Range Biases in Overlapping Strips

- Strips flown in opposite directions

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} 2\ \delta\Delta X\ -\ 2\ H\ \ \delta\Delta\varphi \mp D/H\ \ \delta\rho \mp H\ \ \delta\theta \\ 2\,\delta\Delta Y\ +\ 2\ H\ \ \delta\Delta\omega \mp D\ \delta\Delta\kappa \\ 0 \end{bmatrix} + R_{(2\delta\Delta\varphi \pm 2\delta\theta)} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

- Using two strips flown in opposite directions (100% side lap)

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} 2\ \delta\Delta X\ -\ 2\ H\ \ \delta\Delta\varphi \\ 2\,\delta\Delta Y\ +\ 2\ H\ \ \delta\Delta\omega \\ 0 \end{bmatrix} + R_{2\delta\Delta\varphi} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + R \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

- Strips flown in opposite directions with 100% side lap are good for highlighting:
  - Bore-sighting roll bias ($\delta\Delta\phi$) from $R_{2\delta\Delta\phi}$
  - $\delta\Delta X$ from X_T
  - $(2\delta\Delta Y + 2\ H\ \delta\Delta\omega)$ from Y_T
    - Assuming $\delta\Delta Y$ is very small, $\delta\Delta\omega$ can be derived from Y_T

Bore-sighting, Mirror Angle Scale & Range Biases in Overlapping Strips

- The previous models are derived using the following assumptions:
  - Linear scanner,
  - Vertical laser unit (z-axis coincides with the plumb line),
  - The strips are flown in straight lines with constant attitude,
  - The strips are parallel,
  - Relatively small bore-sighting biases, and
  - Elevation variations are small when compared with the flying height.

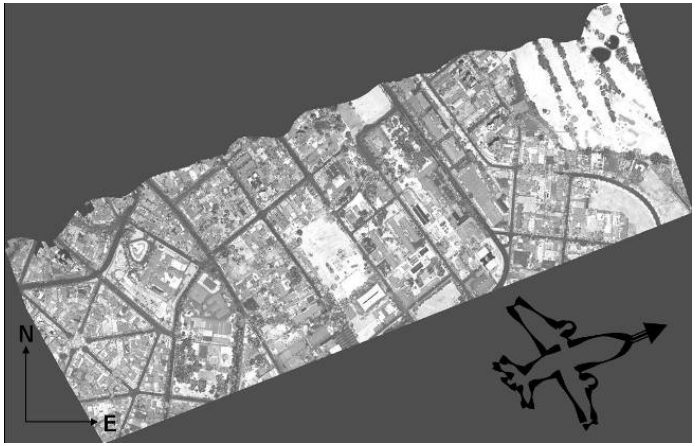
QC of LiDAR Data

System Diagnosis

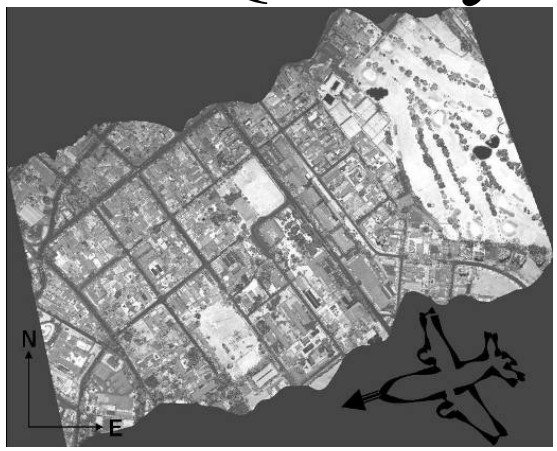
LiDAR Quality Control

- 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.

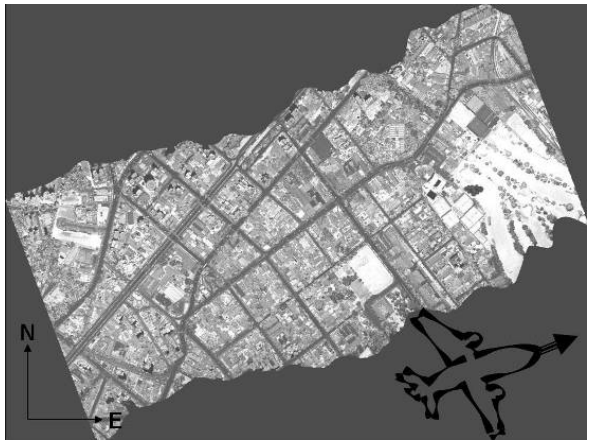
IQC: LIDAR Quality Control



Strip 2



Strip 3



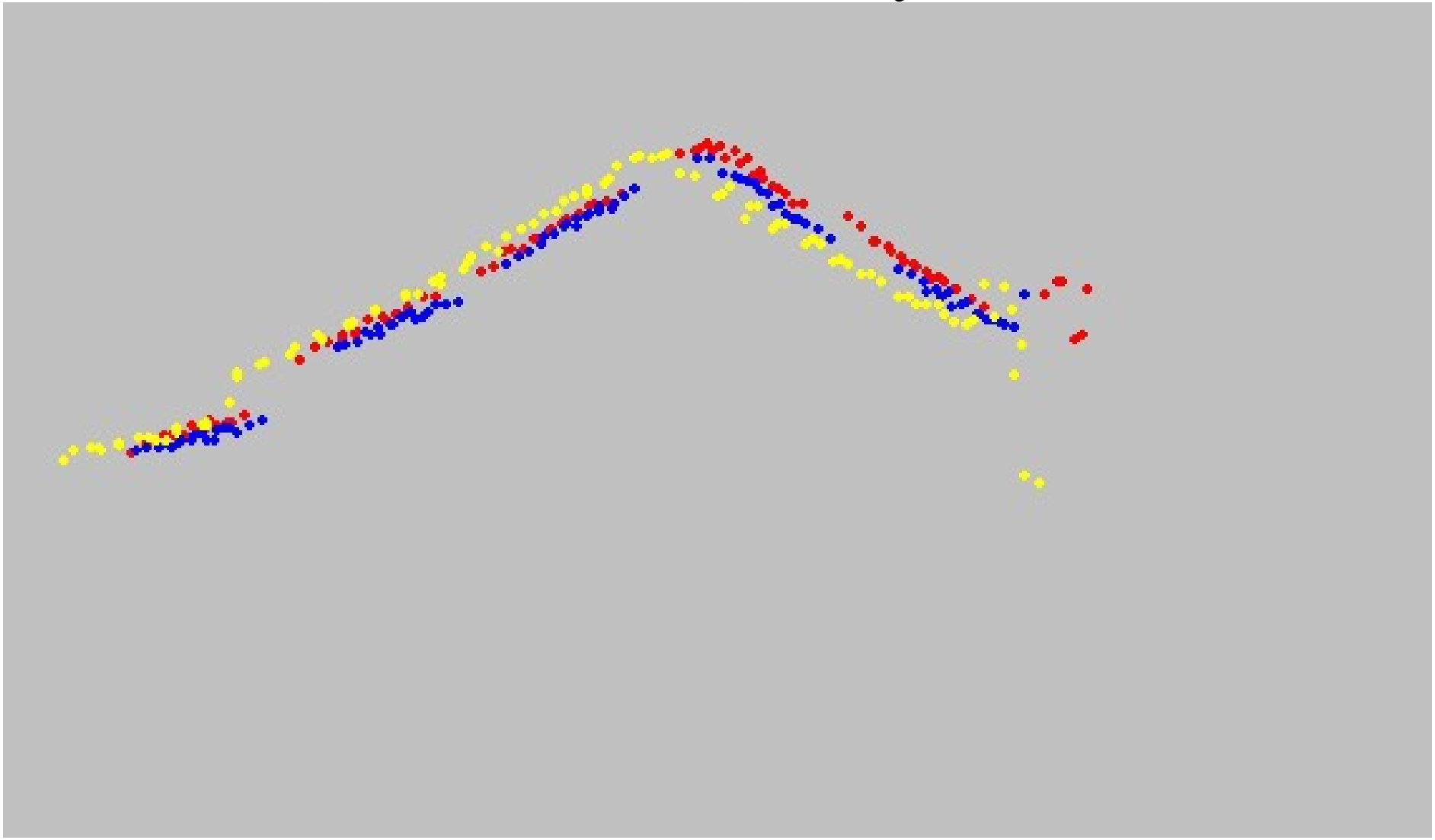
Strip 4

- IQC is used for:
  - Checking for the presence of systematic biases.
    - In the absence of systematic biases, conjugate surface elements in overlapping strips should coincide with each other as well as possible.
  - Checking the noise level in the point cloud.
    - Using the a posteriori variance factor.
    - The quality of fit between conjugate entities after removing existing biases.

IQC: LIDAR Quality Control

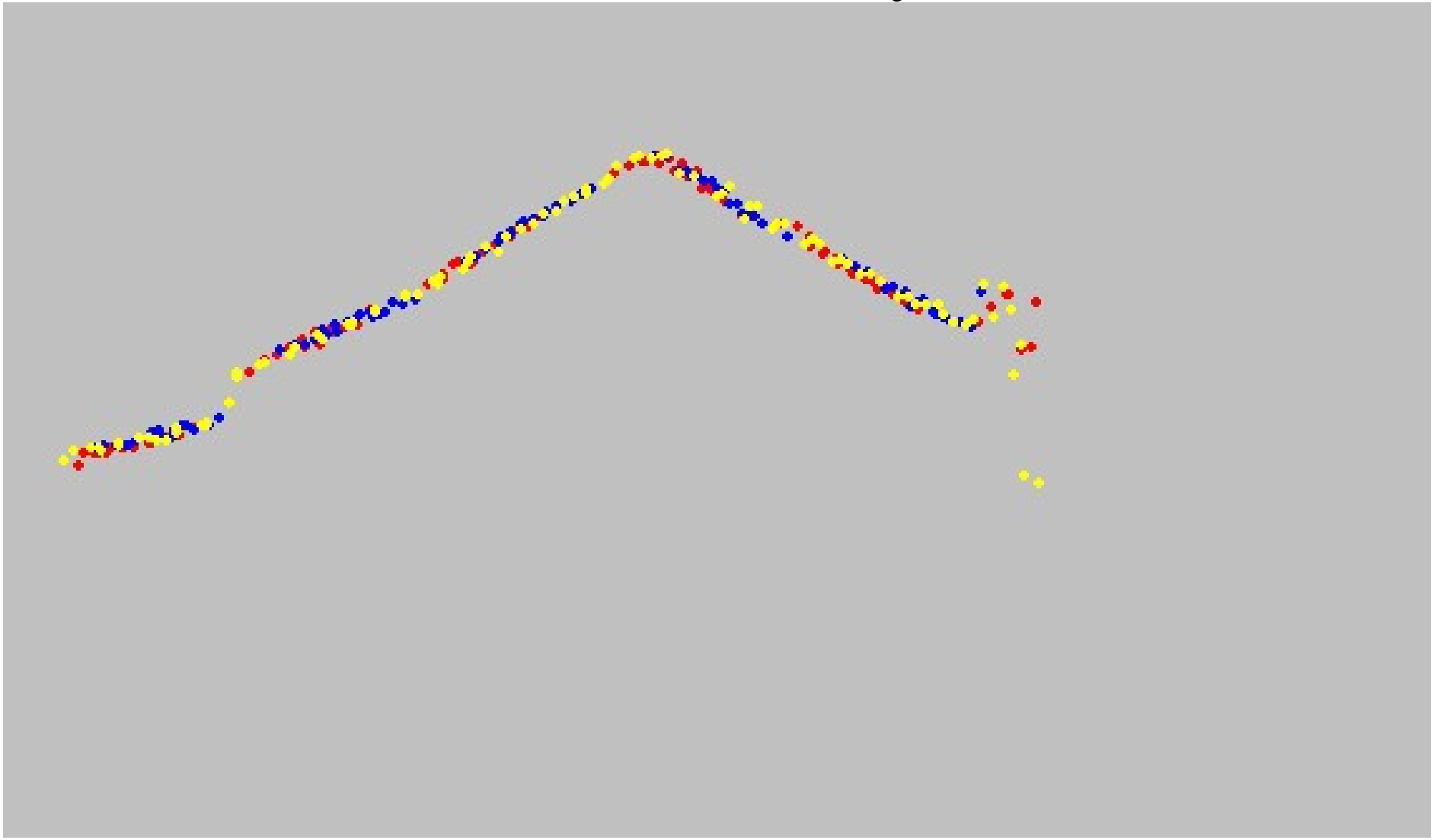
- Check for the presence of biases:
  - In the absence of biases, conjugate surface elements in overlapping strips should coincide with each other as well as possible.
  - Biases will cause shifts and rotation between overlapping strips flown in the same or opposite directions.
    - It should be noted that random noise in the LiDAR data, regardless of its magnitude, will not cause systematic discrepancies between overlapping strips.
  - Using procedures for discrepancy detection between conjugate strips, we can estimate the necessary shifts and rotation, which are needed for the best alignment of overlapping strips.
  - Significant deviations from the optimum values (zero translations and rotations) indicate the presence of biases in the system parameters.

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

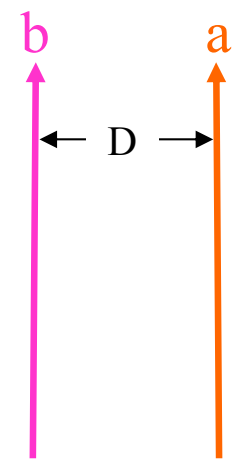
IQC: LIDAR Quality Control

- 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.

System Diagnosis using Overlapping Strips

- Using two strips flown in the same direction

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} -D/H\ \delta\rho - H\ \delta\theta \\ -D\ \delta\Delta\kappa \\ D\ \delta\Delta\varphi \end{bmatrix} + R_{2\,\delta\theta} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$



- D is the lateral distance between the strips
- When D is maximum, parallel strips are good for detecting:
  - Mirror angle scale ($\delta\theta$ from $R_{2\delta\theta}$)
  - Range bias ($\delta\rho$ from X_T)
  - Bore-sighting heading bias ($\delta\Delta\kappa$ from Y_T)
  - Bore-sighting roll bias ($\delta\Delta\phi$ from Z_T)

- Question: How can we determine the shift and rotation parameters (X_T, Y_T, Z_T, $2\delta\theta$) from overlapping strips without having point-to-point correspondence?

System Diagnosis using Overlapping Strips

- Strips flown in opposite directions

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} 2\,\delta\Delta X - 2\,H\,\delta\Delta\varphi \mp D/H\,\delta\rho \mp H\,\delta\theta \\ 2\,\delta\Delta Y + 2\,H\,\delta\Delta\omega \mp D\,\delta\Delta\kappa \\ 0 \end{bmatrix} + R_{(2\delta\Delta\varphi \pm 2\delta\theta)} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

- Using two strips flown in opposite directions (100% side lap)

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} 2\,\delta\Delta X - 2\,H\,\delta\Delta\varphi \\ 2\,\delta\Delta Y + 2\,H\,\delta\Delta\omega \\ 0 \end{bmatrix} + R_{2\delta\Delta\varphi} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + R \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

- Confirm bore-sighting roll bias ($\delta\Delta\phi$ from $R_{2\delta\Delta\phi}$)
- Derive $\delta\Delta X$ from X_T
- Derive ($2\delta\Delta Y$ - $2\,z\,\delta\Delta\omega$) from Y_T
  - Assuming $\delta\Delta Y$ is very small, $\delta\Delta\omega$ can be derived from Y_T
- $\delta\Delta Z$ cannot be recovered
  - Question: How can we determine the shift and rotation parameters (X_T, Y_T, Z_T, $2\delta\Delta\phi$) from overlapping strips without having point-to-point correspondence?

System Diagnosis using Overlapping Strips

- Using four strips flown in opposite directions with 100% side lap at two different flying heights:

$$\begin{bmatrix} X_{A_1} \\ Y_{A_1} \\ Z_{A_1} \end{bmatrix} = \begin{bmatrix} 2\,\delta\Delta X - 2\,H_1\,\delta\Delta\varphi \\ 2\,\delta\Delta Y + 2\,H_1\,\delta\Delta\omega \\ 0 \end{bmatrix} + R_{2\delta\Delta\varphi} \begin{bmatrix} X_{B_1} \\ Y_{B_1} \\ Z_{B_1} \end{bmatrix} = \begin{bmatrix} X_{T_1} \\ Y_{T_1} \\ Z_T \end{bmatrix} + R \begin{bmatrix} X_{B_1} \\ Y_{B_1} \\ Z_{B_1} \end{bmatrix}$$

$$\begin{bmatrix} X_{A_2} \\ Y_{A_2} \\ Z_{A_2} \end{bmatrix} = \begin{bmatrix} 2\,\delta\Delta X - 2\,H_2\,\delta\Delta\varphi \\ 2\,\delta\Delta Y + 2\,H_2\,\delta\Delta\omega \\ 0 \end{bmatrix} + R_{2\delta\Delta\varphi} \begin{bmatrix} X_{B_2} \\ Y_{B_2} \\ Z_{B_2} \end{bmatrix} = \begin{bmatrix} X_{T_2} \\ Y_{T_2} \\ Z_T \end{bmatrix} + R \begin{bmatrix} X_{B_2} \\ Y_{B_2} \\ Z_{B_2} \end{bmatrix}$$

- Confirm bore-sighting roll bias ($\delta\Delta\phi$ from $R_{2\delta\Delta\phi}$)
- Derive $\delta\Delta X$ from X_{T_1} and confirm it using X_{T_2}.
- Derive $(2\delta\Delta Y - 2\,H_1\,\delta\Delta\omega)$ from Y_{T_1}.
- Derive $(2\delta\Delta Y - 2\,H_2\,\delta\Delta\omega)$ from Y_{T_2}.

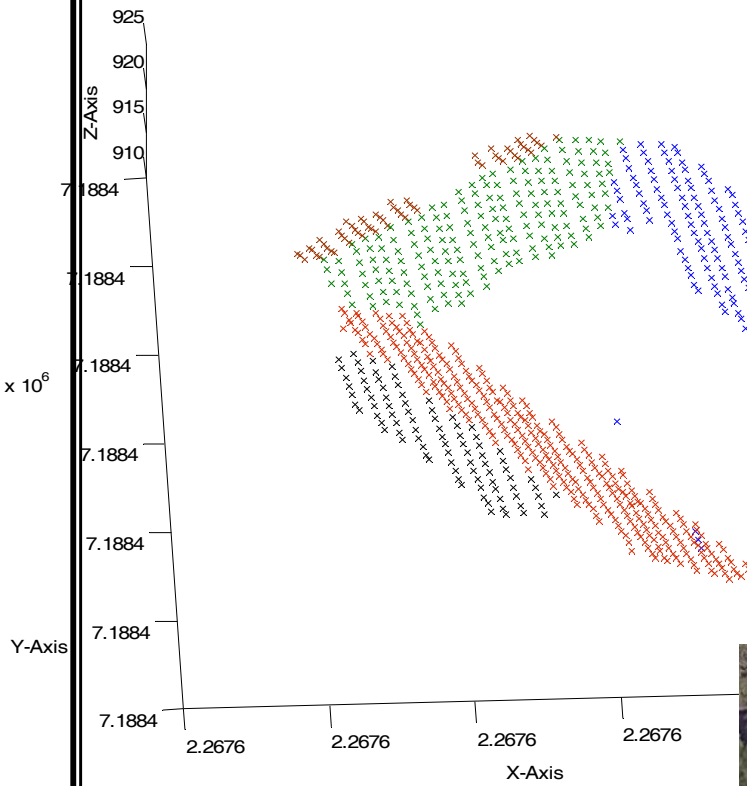
$\Rightarrow$ • Derive $\delta\Delta Y$ and $\delta\Delta\omega$

- $\delta\Delta Z$ cannot be recovered
- Question: How can we determine the shift and rotation parameters (X_T, Y_T, Z_T, $2\delta\Delta\phi$) from overlapping strips without having point-to-point correspondence?

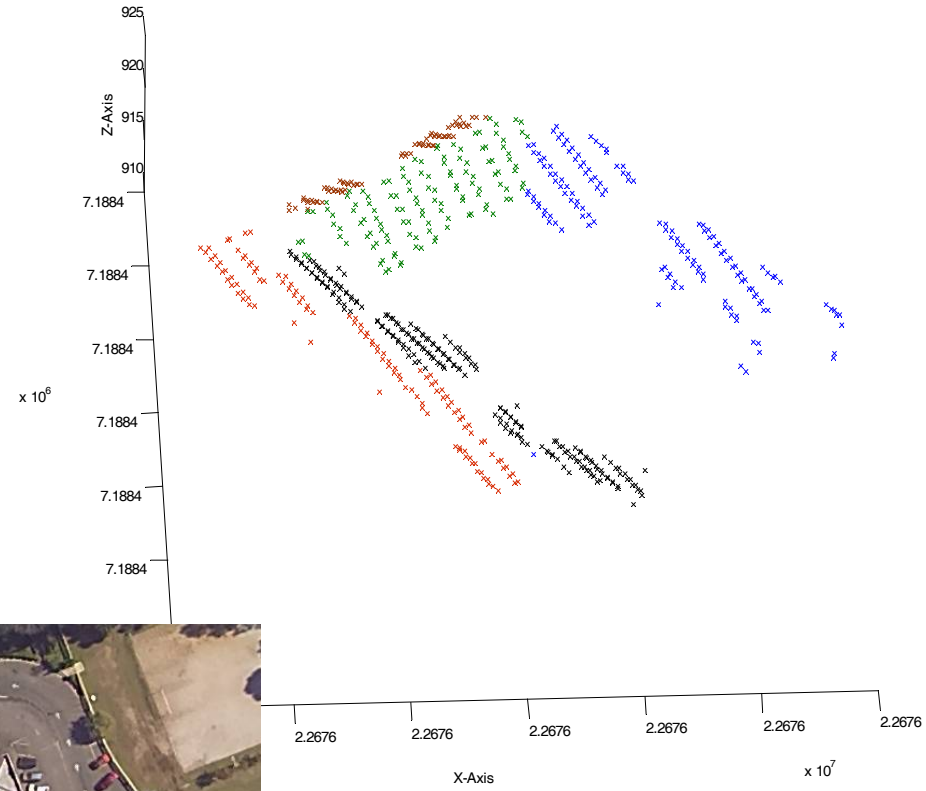
System Diagnosis using Overlapping Strips

- Conceptual basis:
  - Detect discrepancies between overlapping strips.
  - Relate the detected discrepancies to systematic errors in the system parameters.
- For detecting existing discrepancies, we need to identify conjugate surface elements (primitives) in overlapping LiDAR strips.
- What are the most appropriate primitives?
  - Points (not recommended).
  - Areal features.
  - Linear features.

Discrepancy Detection using Planar Patches



Strip # 3



Strip # 4

Discrepancy Detection using Planar Patches

- Extraction Procedure:

ROI* selection

↓

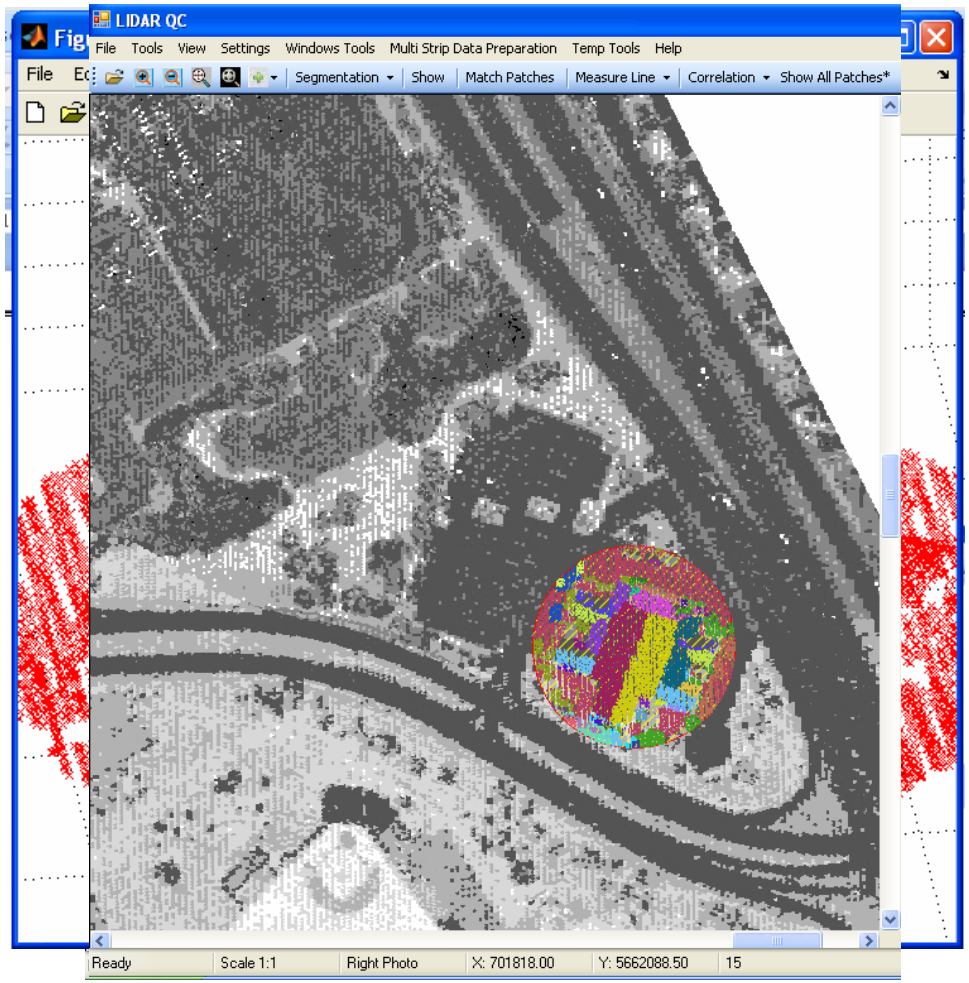
Data extraction in overlapping Strips

↓

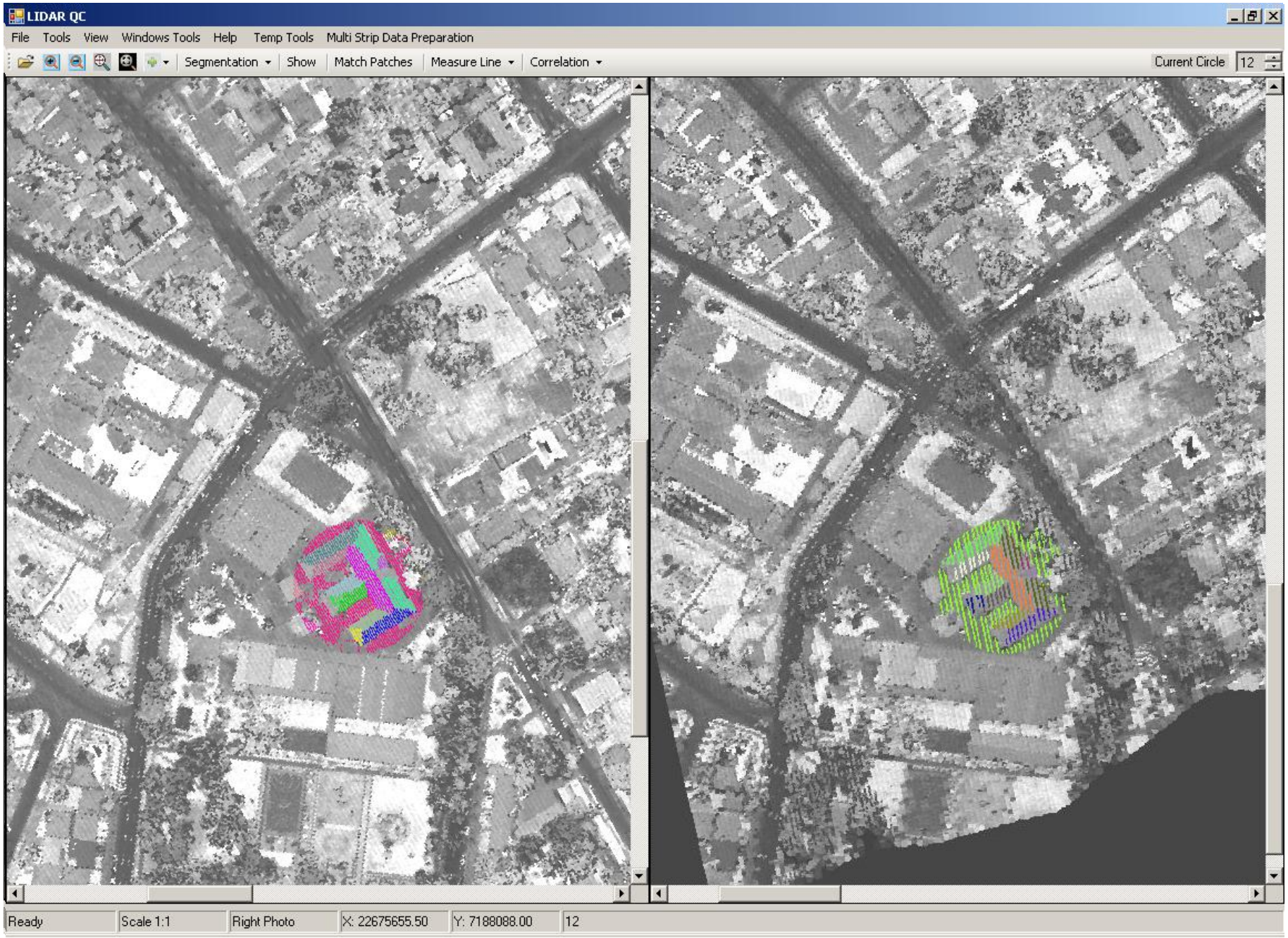
Segmentation

↓

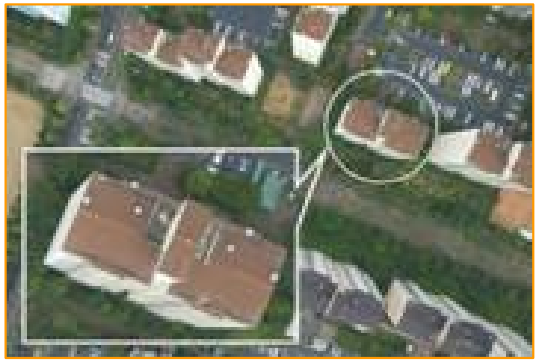
Patch matching

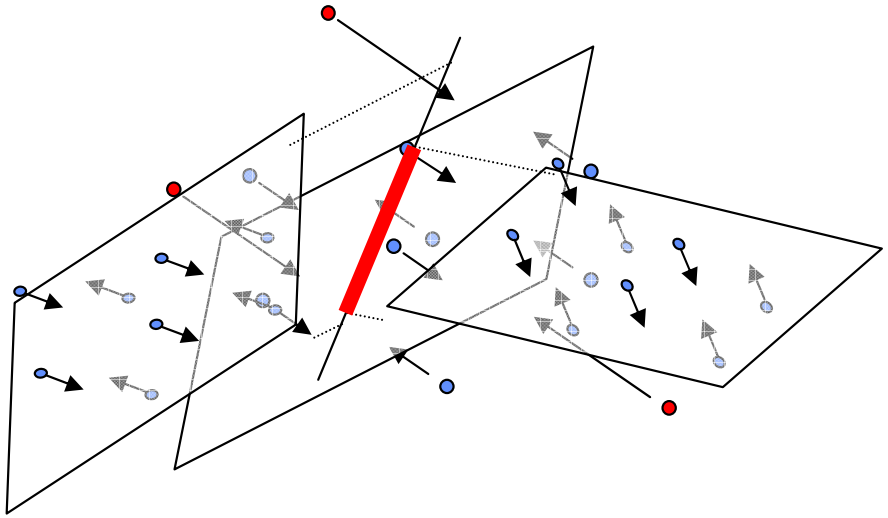


* Region of Interest

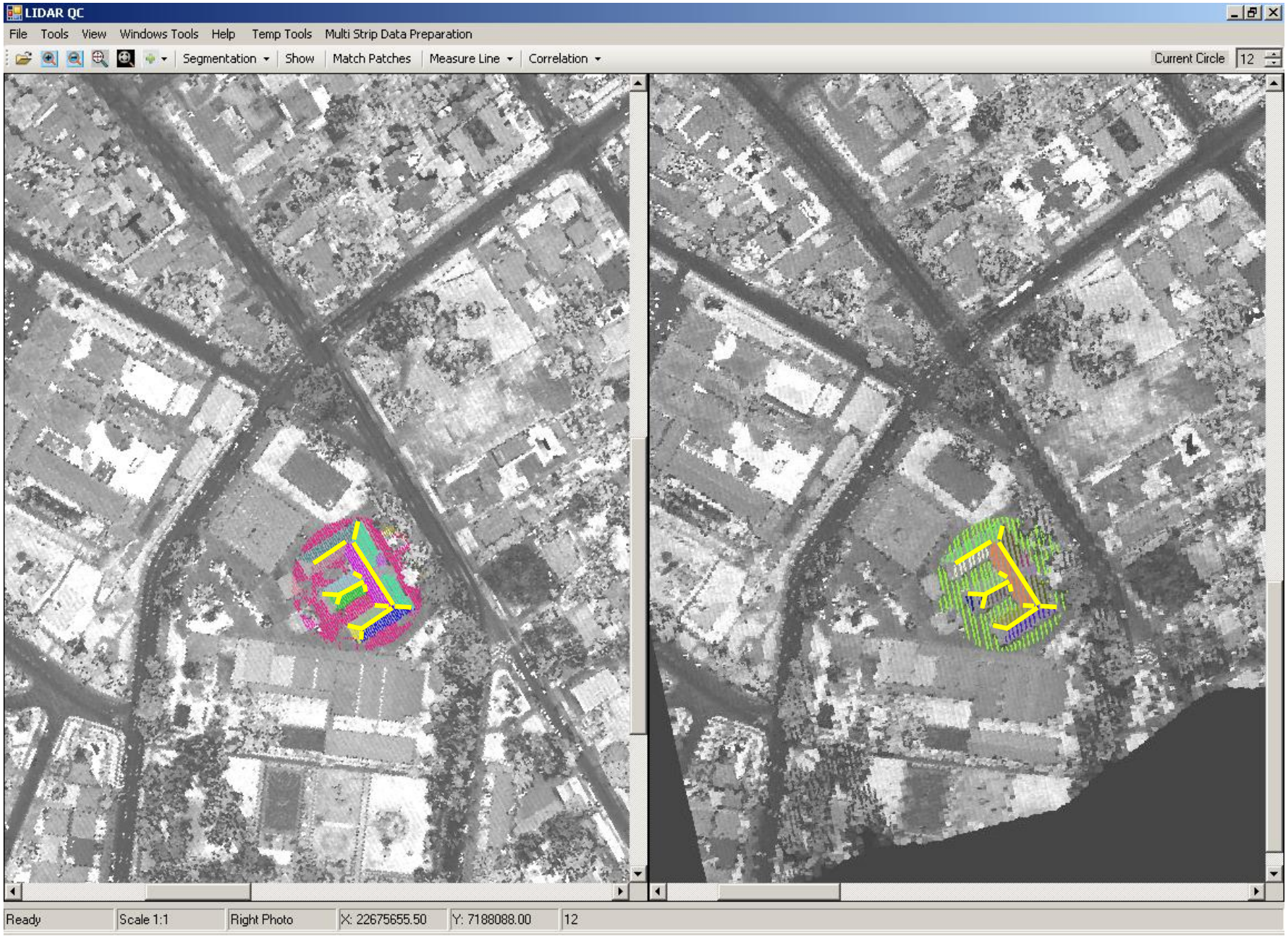

LIDAR QC
File Tools View Windows Tools Help Temp Tools Multi Strip Data Preparation
Segmentation
Show
Match Patches
Measure Line
Correlation
Current Circle
12
Ready
Scale 1:1
Right Photo
X: 22675655.50
Y: 7188088.00
12

Discrepancy Detection using Linear Features





Linear Feature Extraction


LIDAR QC
File Tools View Windows Tools Help Temp Tools Multi Strip Data Preparation
Segmentation
Show
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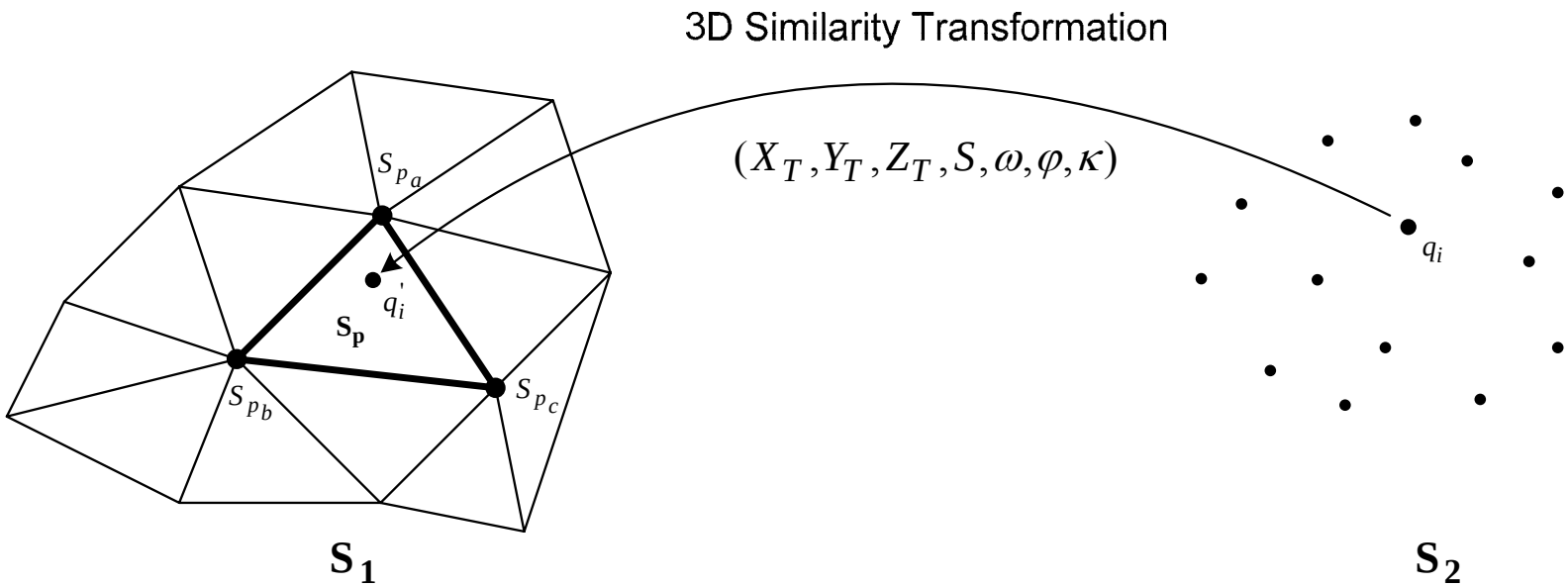
Measure Line
Correlation
Current Circle
12
Ready
Scale 1:1
Right Photo
X: 22675655.50
Y: 7188088.00
12

Discrepancy Detection using Non-Conjugate Points

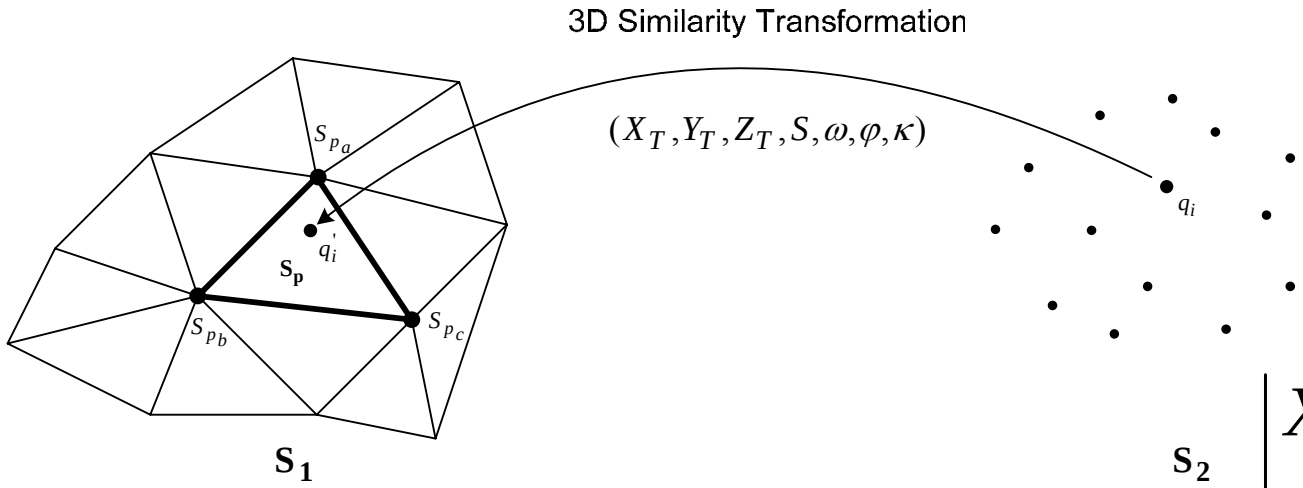
- The previous procedures for detecting discrepancies between overlapping strips require preprocessing of the LiDAR point cloud:
  - Interpolation, planar patch segmentation, plane fitting, and/or intersection.
- Another approach can be devised while using the original point cloud.
  - One strip is represented by a set of irregularly distributed points (LiDAR point cloud).
  - Second strip is represented by a TIN generated from the LiDAR point cloud.
  - Iterative Closest Patch (ICPatch).

Discrepancy Detection using Non-Conjugate Points

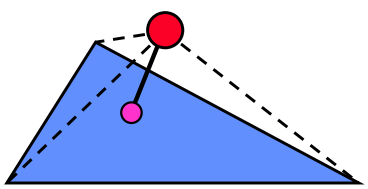


- Starting from a given set of approximate parameters, we determine conjugate point-patch pairs in overlapping strips.
- Conjugate primitives are used to estimate an updated set of parameters, which are then used to determine new correspondences.
- The approach is repeated until convergence.

Discrepancy Detection using Non-Conjugate Points



$$\begin{vmatrix} X_{q_1'} & Y_{q_1'} & Z_{q_1'} & 1 \\ X_{p_a} & Y_{p_a} & Z_{p_a} & 1 \\ X_{p_b} & Y_{p_b} & Z_{p_b} & 1 \\ X_{p_c} & Y_{p_c} & Z_{p_c} & 1 \end{vmatrix} = 0$$



Where:

$$\begin{bmatrix} X_{q_1'} \\ Y_{q_1'} \\ Z_{q_1'} \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + S\ R_{\omega,\phi,\kappa} \begin{bmatrix} X_{q_1} \\ Y_{q_1} \\ Z_{q_1} \end{bmatrix}$$

Conditions:

- Closest patch
- Point located within the patch

IQC & EQC: LIDAR Quality Control

- The proposed strategies for IQC can be used for EQC as well.
  - Instead of evaluating the consistency of two over lapping strips, we can evaluate the consistency between the LiDAR point cloud and an independently acquired control surface.
  - The control surface can be derived from photogrammetric reconstruction or RTK GPS survey.

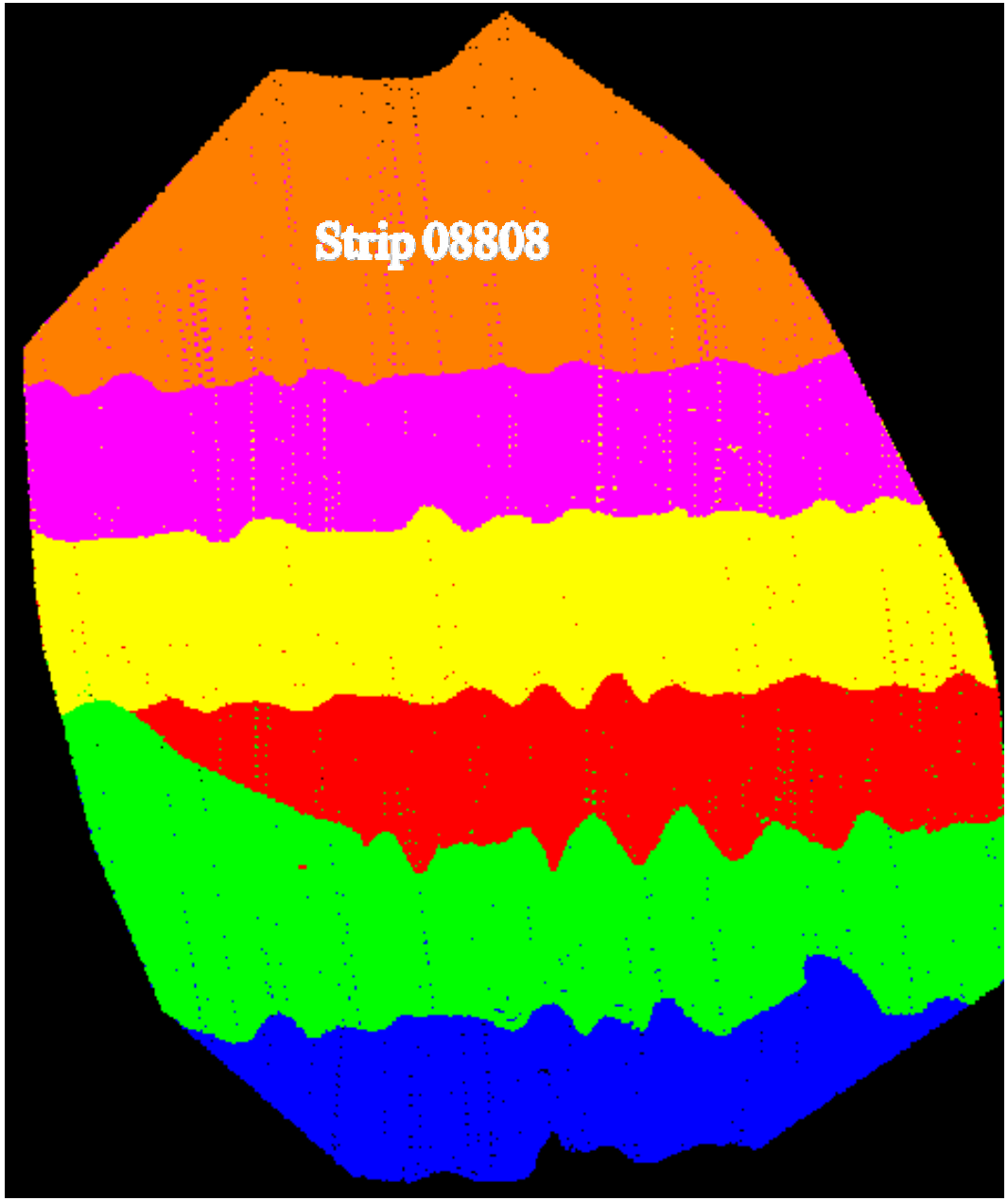
Experimental Results

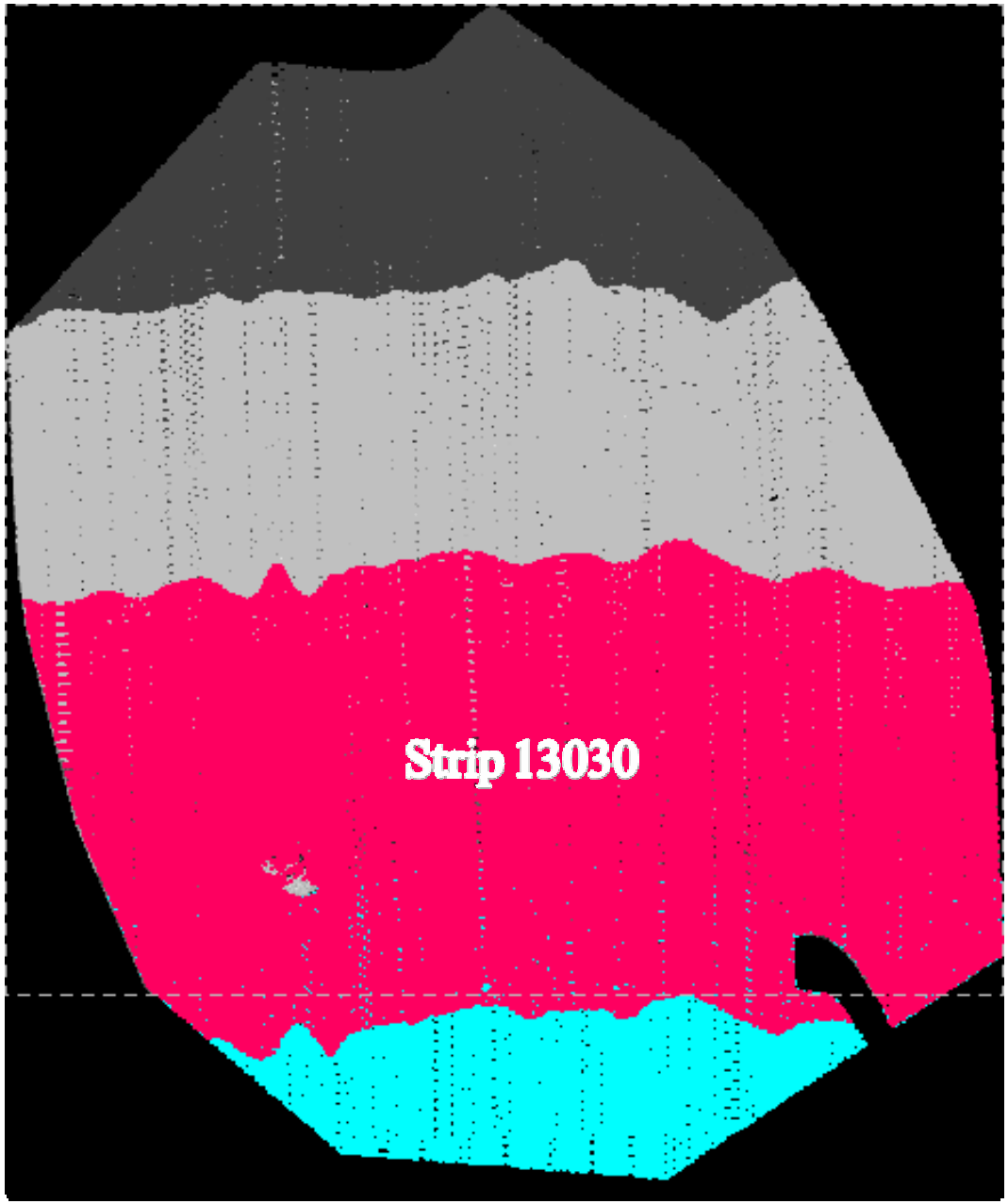
University of Calgary Data

Study Area

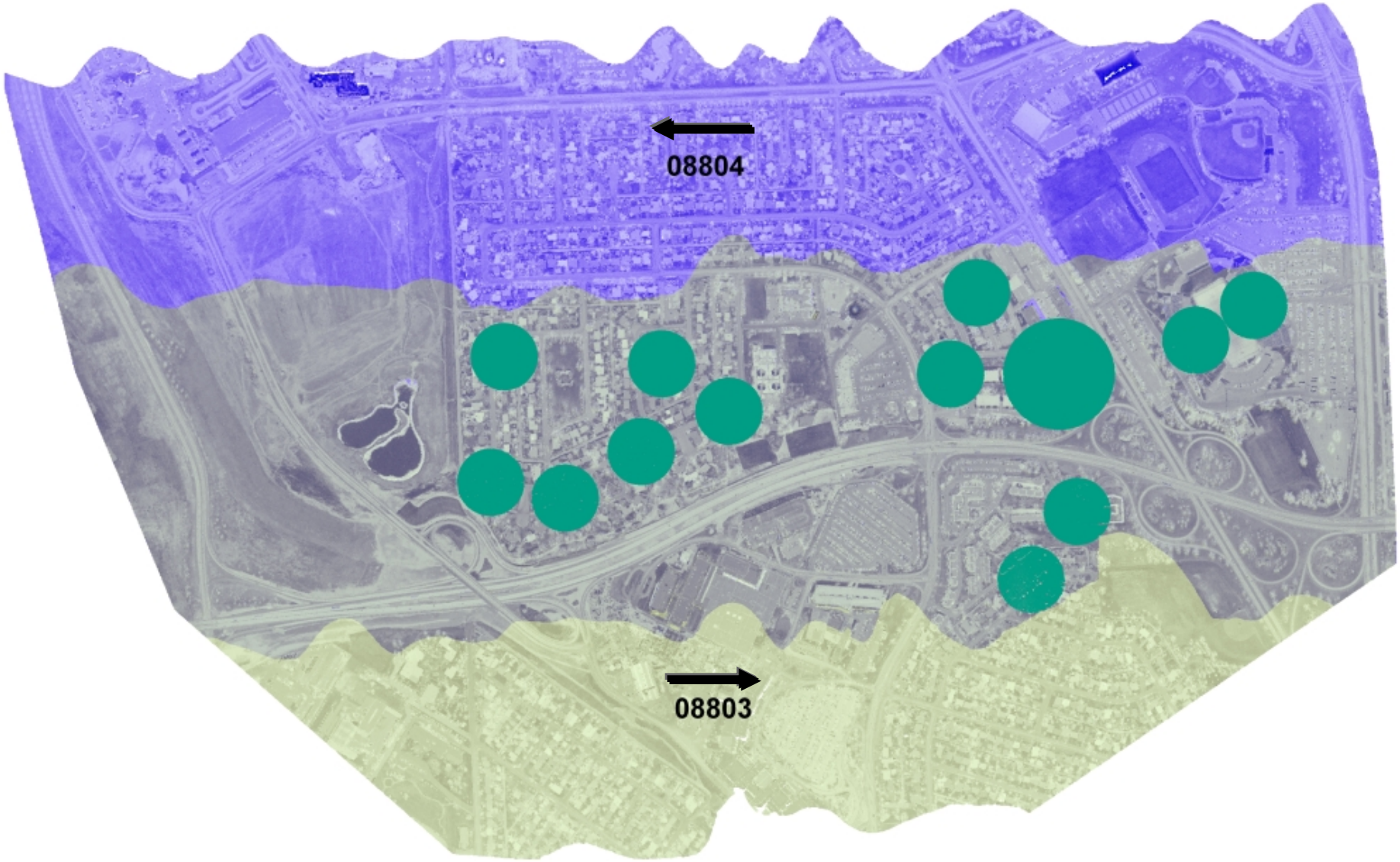
- Surveyed area – UofC Campus

Sensor Model	Optech 3100
Flying Height	~1000 & 1400m
Ground Point Spacing	~0.75m
2 Surveying Days	
– 1st Day: 088	6 strips @1000m
– 2nd Day: 130	4 strips @1400m

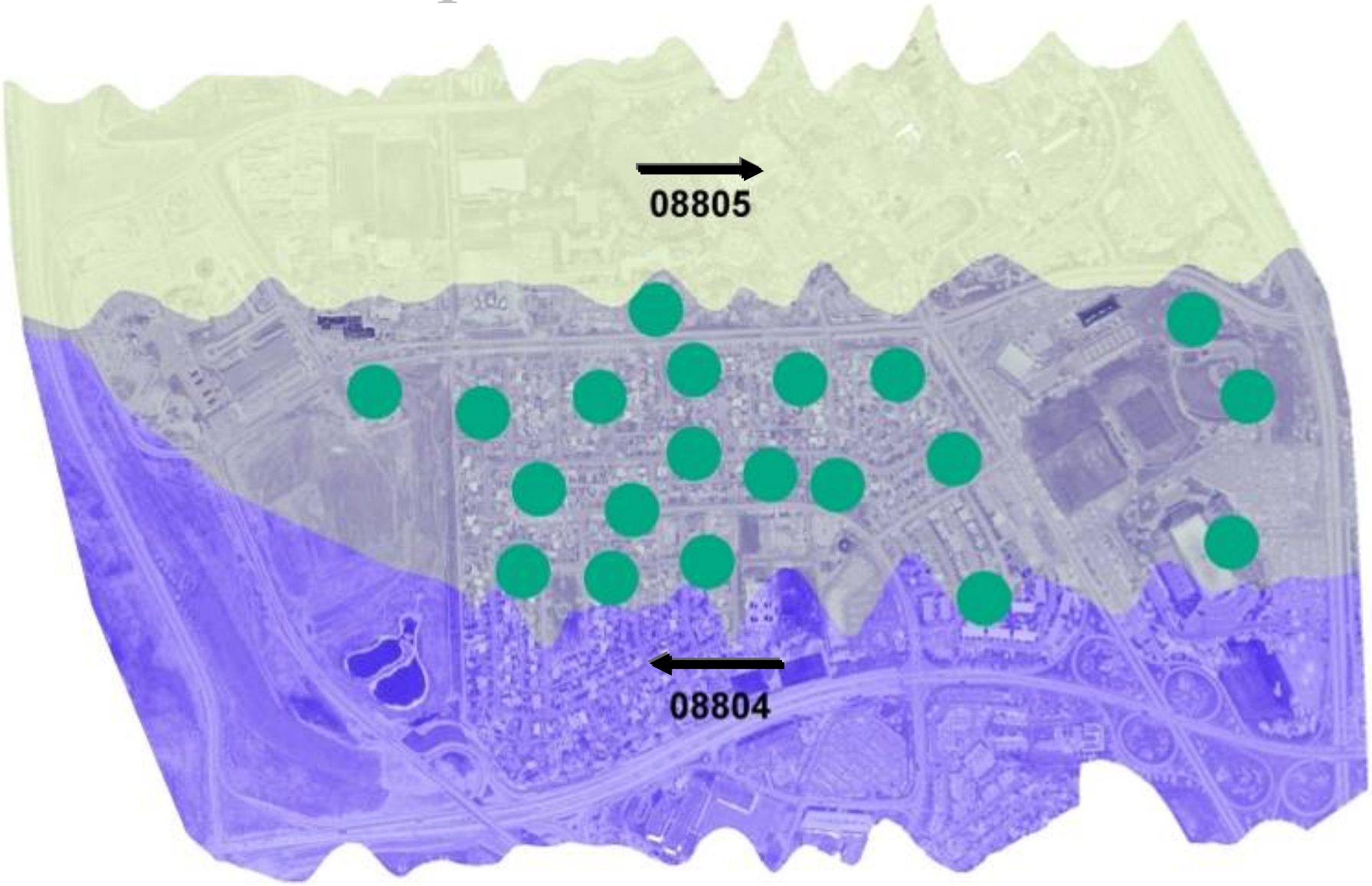

Strip 08808


Strip 13030

Strips 08803 & 08804



Strips 08804 & 08805



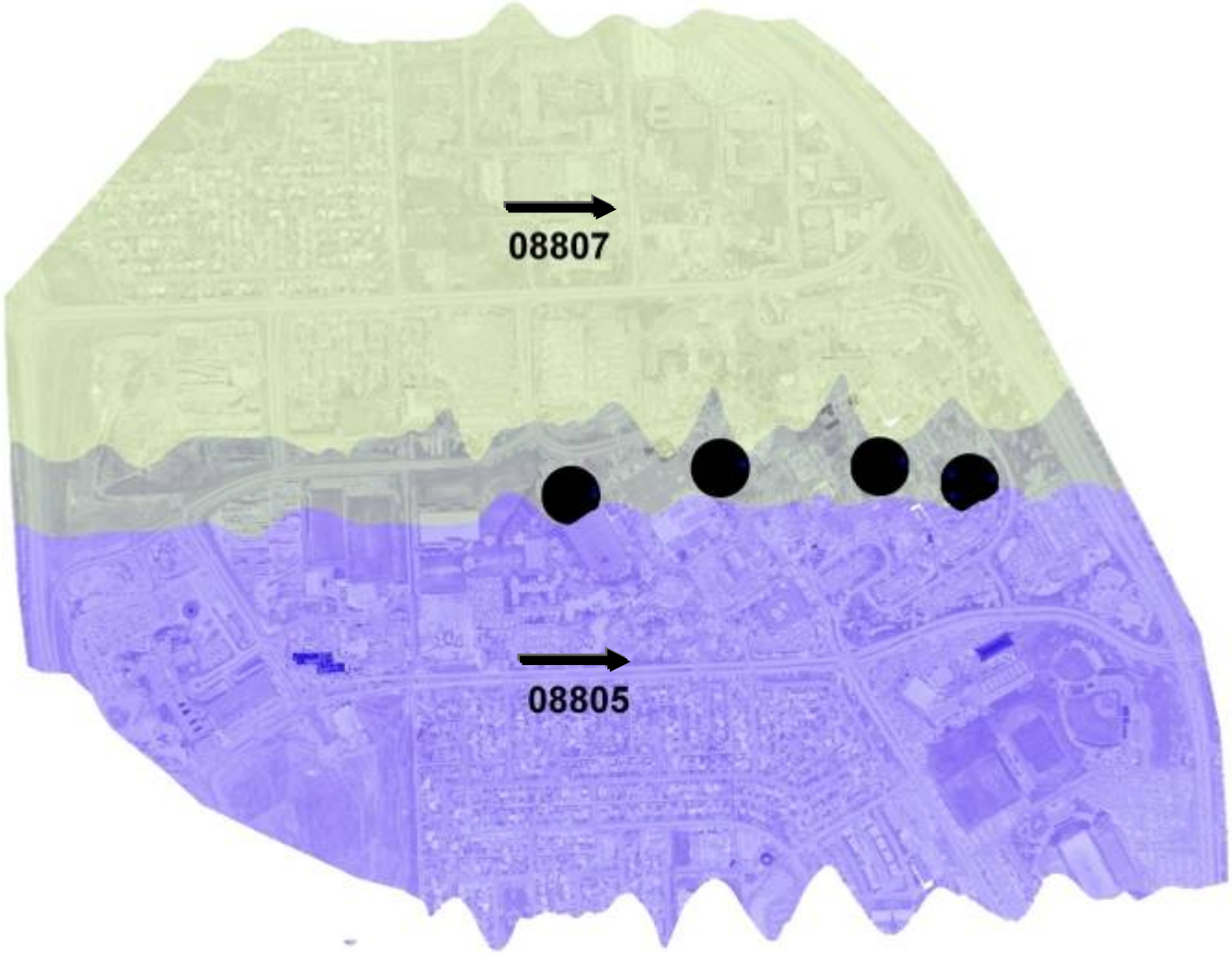
Strips 08805 & 08806

Strips 08806 & 08807

Strips 08807 & 08808

Strips 08803 & 08805

Strips 08805 & 08807



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

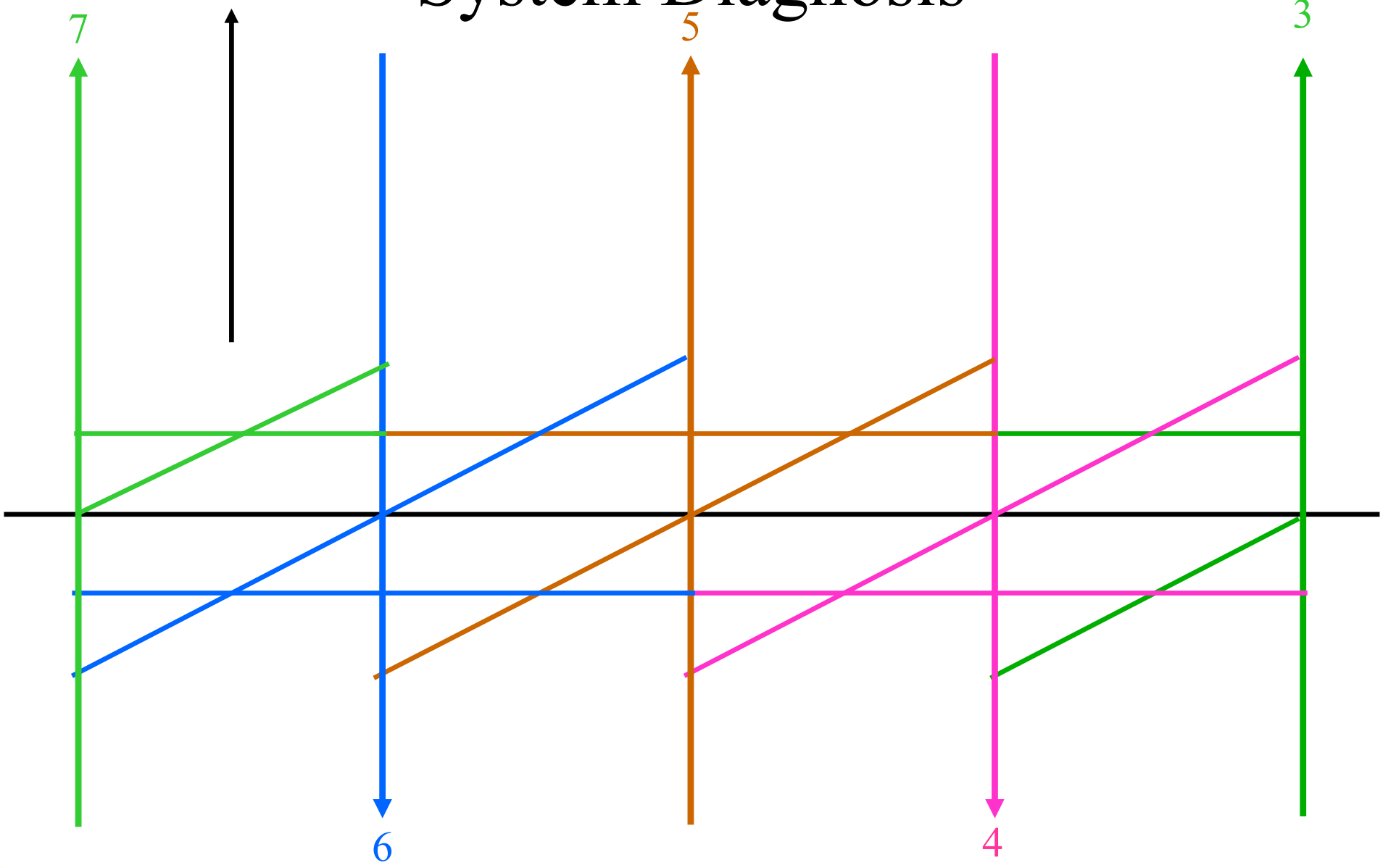
$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} 2\,\delta\Delta X - 2\,H\,\delta\Delta\varphi \mp D/H\,\delta\rho \mp H\,\delta\theta \\ 2\,\delta\Delta Y + 2\,H\,\delta\Delta\omega \mp D\,\delta\Delta\kappa \\ 0 \end{bmatrix} + R_{(2\delta\Delta\varphi \pm 2\delta\theta)} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

System Diagnosis

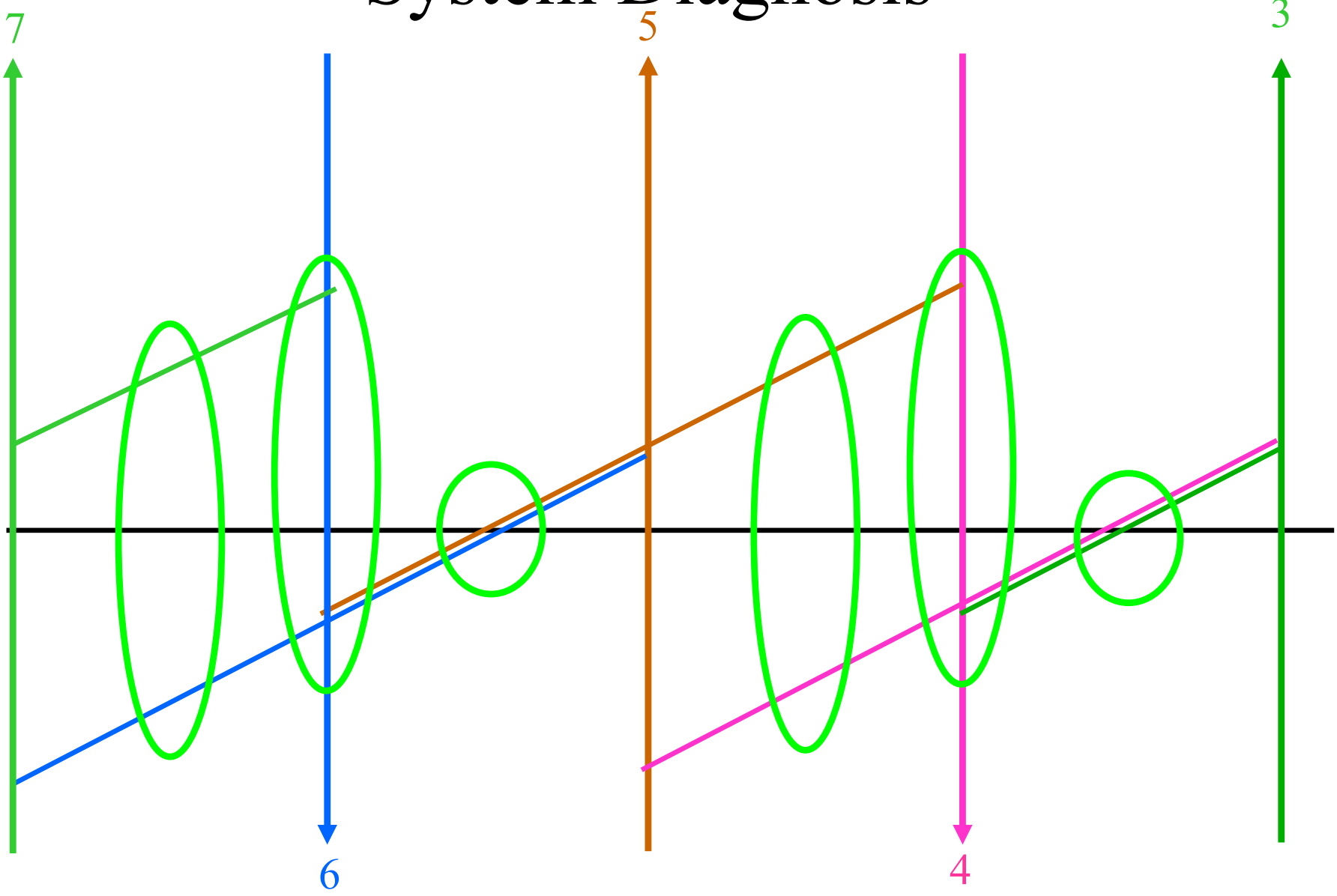
	X_T (m)	Y_T (m)	Z_T (m)	Φ (°)
3 – 5	-0.04	-0.81	0.07	-0.0030
5 – 7	0.04	-0.89	0.02	0.0034

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} -D/H\ \delta\rho - H\ \delta\theta \\ -D\ \delta\Delta\kappa \\ D\ \delta\Delta\varphi \end{bmatrix} + R_{2\,\delta\theta} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

System Diagnosis



System Diagnosis



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

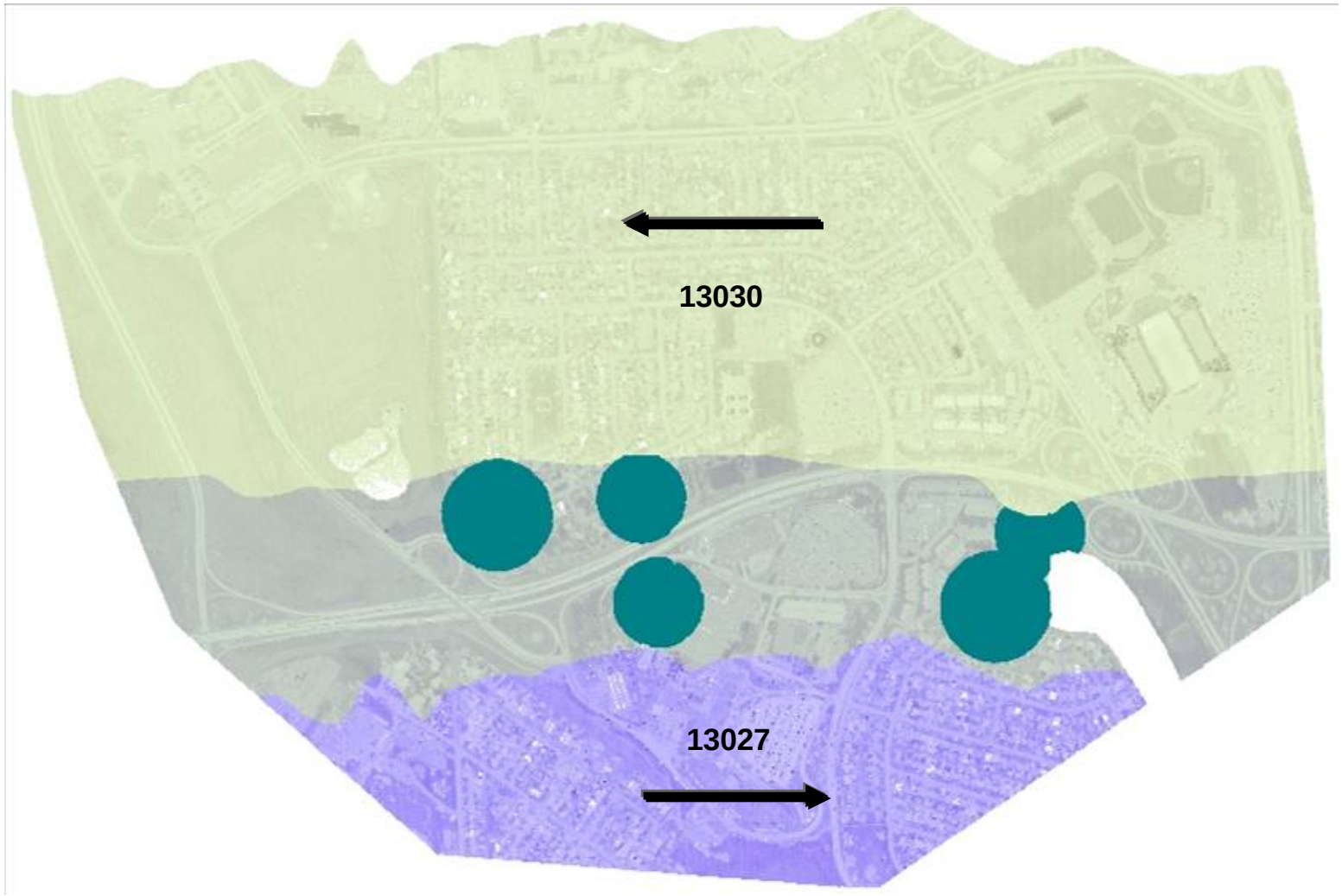
$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} 2\,\delta\Delta X - 2\,H\,\delta\Delta\varphi \mp D/H\,\delta\rho \mp H\,\delta\theta \\ 2\,\delta\Delta Y + 2\,H\,\delta\Delta\omega \mp D\,\delta\Delta\kappa \\ 0 \end{bmatrix} + R_{(2\delta\Delta\varphi \pm 2\delta\theta)} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

System Diagnosis

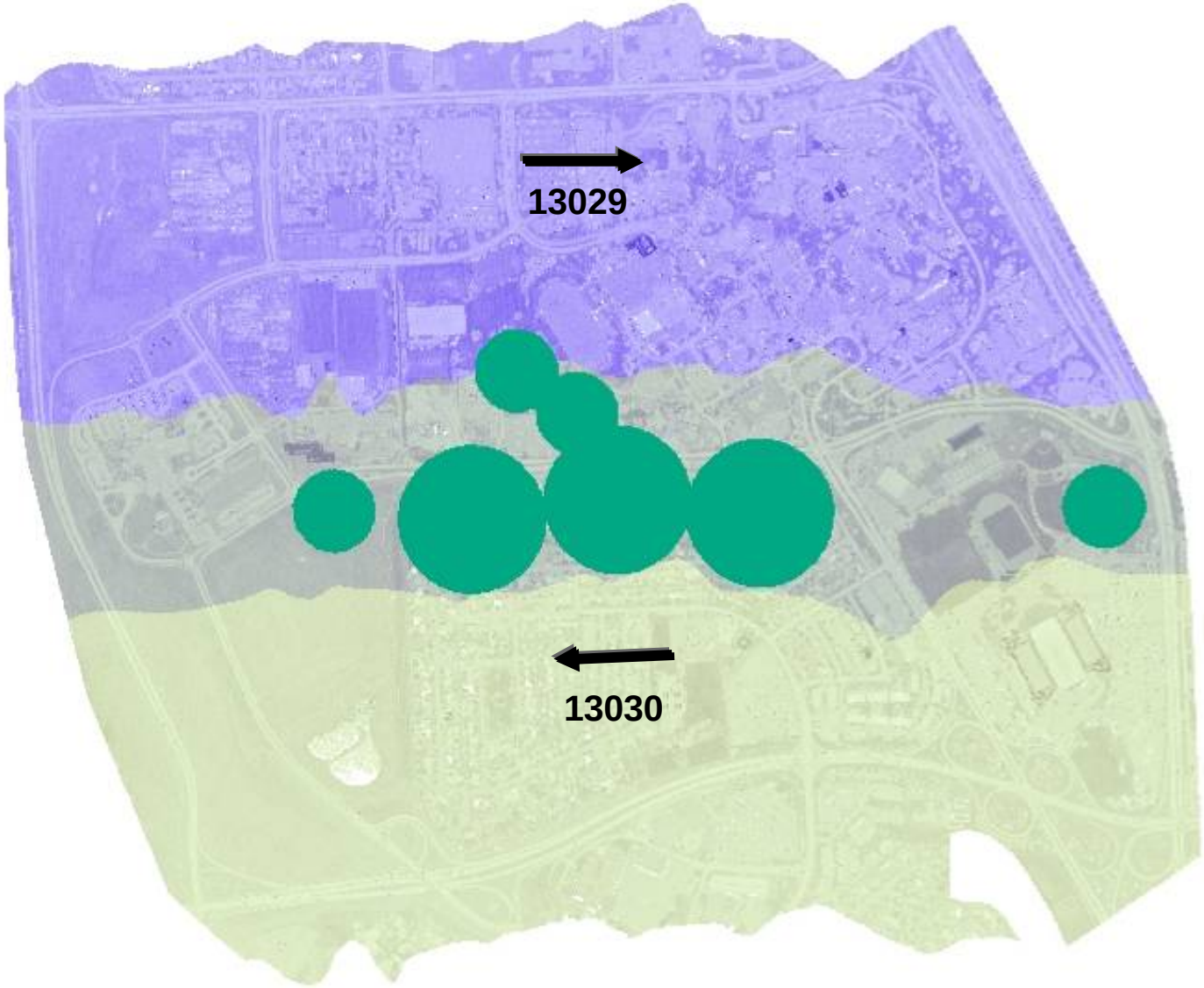
	X_T (m)	Y_T (m)	Z_T (m)	Φ (°)
3 – 5	-0.04	-0.81	0.07	-0.0030
5 – 7	0.04	-0.89	0.02	0.0034

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} -D/H\ \delta\rho - H\ \delta\theta \\ -D\ \delta\Delta\kappa \\ D\ \delta\Delta\varphi \end{bmatrix} + R_{2\,\delta\theta} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

Strips 13027 & 13030



Strips 13029 & 13030



Strips 13029 & 13028

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

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} 2\ \delta\Delta X\ -\ 2\ H\ \ \delta\Delta\varphi \mp D/H\ \ \delta\rho \mp H\ \ \delta\theta \\ 2\,\delta\Delta Y\ +\ 2\ H\ \ \delta\Delta\omega \mp D\ \delta\Delta\kappa \\ 0 \end{bmatrix} + R_{(2\delta\Delta\varphi \pm 2\delta\theta)} \begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix}$$

System Diagnosis

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

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

Concluding Remarks

- QA and QC procedures are essential for any spatial data acquisition system.
- Approximate calibration of a LiDAR system is possible by detecting the nature of discrepancies between overlapping strips.
- Rigorous calibration of a LiDAR system is only possible for a transparent system.
  - Availability of the raw data.
- Quality control of LiDAR data can be conducted by the end user.
  - LiDAR derived data is not based on adjustment procedure.
  - Quality control measures, which are typically used in photogrammetry, are not applicable.
  - Alternative procedures are needed to check for systematic biases and evaluate the noise level in the point cloud.

Concluding Remarks

- We developed procedures for detecting discrepancies between overlapping strips while having non-conjugate points.
  - Linear and areal features.
  - Iterative Closest Patch (ICPatch).
- We introduced the appropriate mathematical model relating conjugate elements in overlapping strips.
- We need to verify the detected biases by recalculating the point cloud (only possible if we have access to the processing SW).
- Pursue rigorous calibration of LiDAR systems (only possible if the raw data is available).
- Strip adjustment: is it a good idea?
- Promote commonly accepted standards for QA/QC of LiDAR systems and derived data.