A Unified Conceptual Methodology for LiDAR and Camera System Calibration

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Integrated Land Management Bureau

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McElhanney

Overview

- Data acquisition systems: Introduction
- System calibration: Conceptual basis
- Photogrammetric system calibration
  - Camera calibration
  - Mounting parameters calibration
  - Experimental results
- LiDAR system calibration
  - Simplified/quasi-rigorous calibration procedures
  - Experimental results
- Concluding remarks

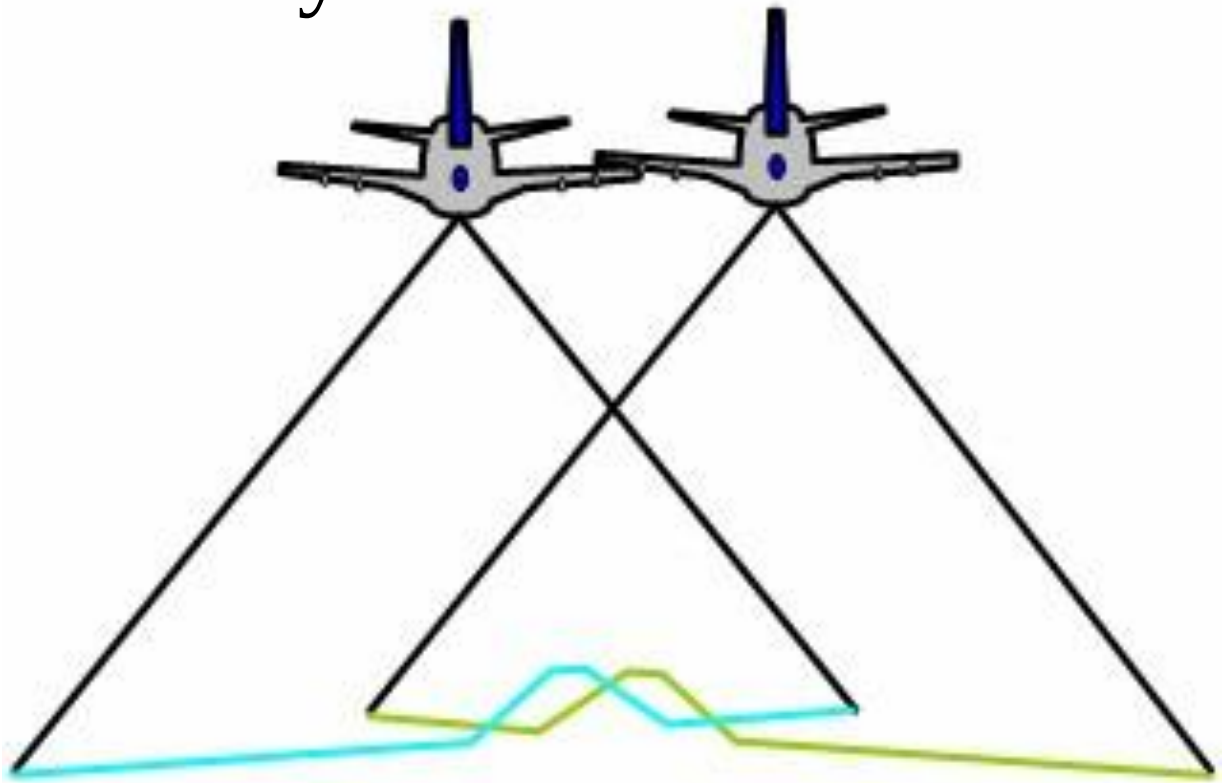
Data Acquisition Systems

- Three dimensional data is essential for several applications in the industrial, agricultural, environmental, hazard assessment, and military fields .
- Current advances in data acquisition systems facilitate the delivery of data that meets the needs of these applications.
  - Direct geo-referencing, digital camera, and LiDAR systems
- Ensuring the quality of collected data mandates the development of reliable, practical, and standardized procedures for the calibration of the utilized systems.

System Calibration

- System calibration has two components:
  - Calibration of the individual sensors comprising the system, and
  - Estimation of the mounting parameters relating the involved sensors (e.g., lever arm and boresight angles).
- Conceptual basis of the developed procedure:
  - Estimate the system parameters that minimize discrepancies between derived surfaces from multiple flight lines while reducing the ground control requirements
  - This requires establishing the optimal flight configuration that maximizes the impact of biases in the system parameters.

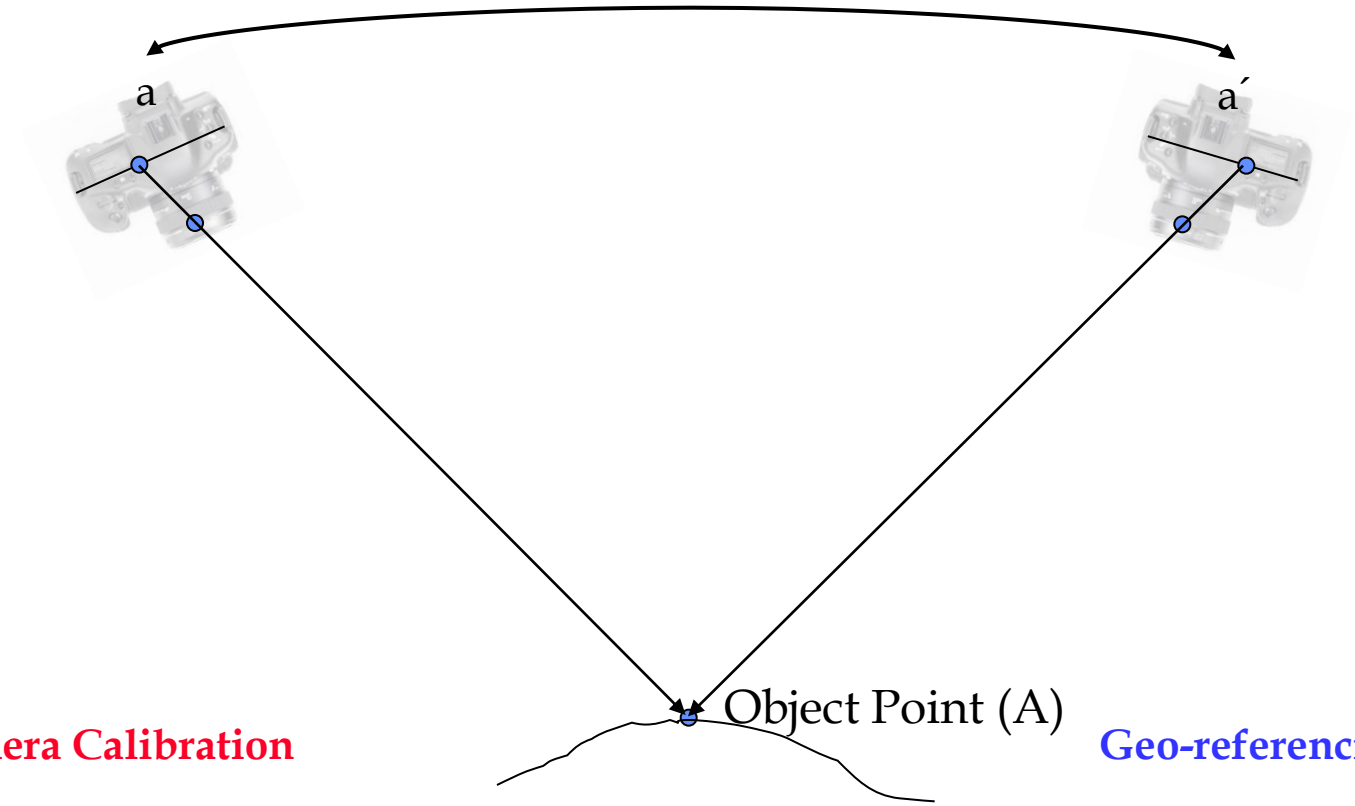
System Calibration



- **<u>Target function:</u>** Estimate the system parameters that minimize discrepancies between derived surfaces from multiple flight lines while reducing ground control requirements

Photogrammetric Principles

Conjugate Points



Camera Calibration

Geo-referencing

- **The interior orientation parameters of the involved cameras have to be known.**
- **The position and the orientation of the camera stations have to be known.**

Operational Photogrammetric Systems

Frame Cameras

RC30

DMC

Applanix DSS 439

Kodak 14n

Canon EOS 1D

SONY 717

Line Camera

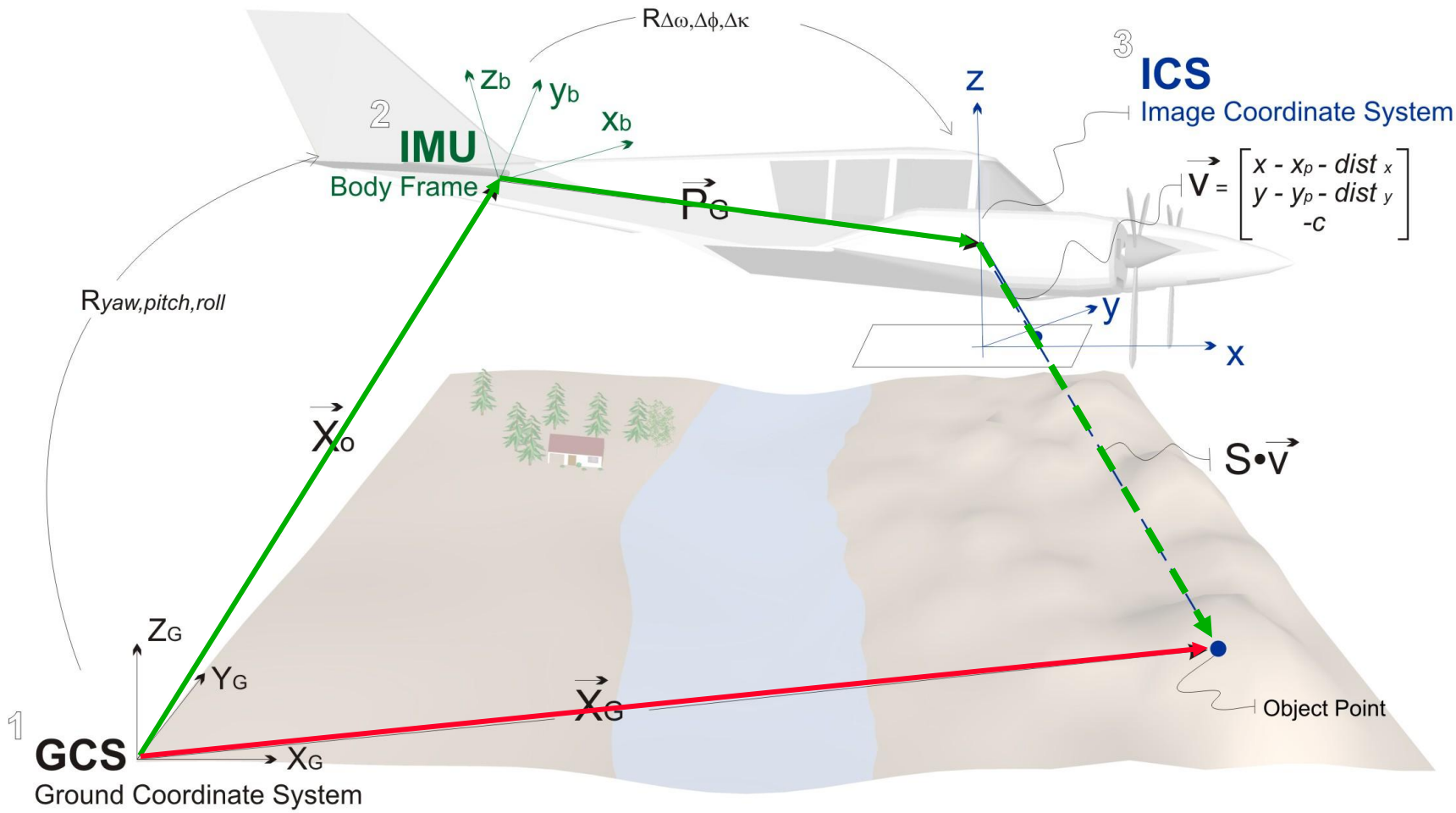
ADS 80

IKONOS/GeoEye

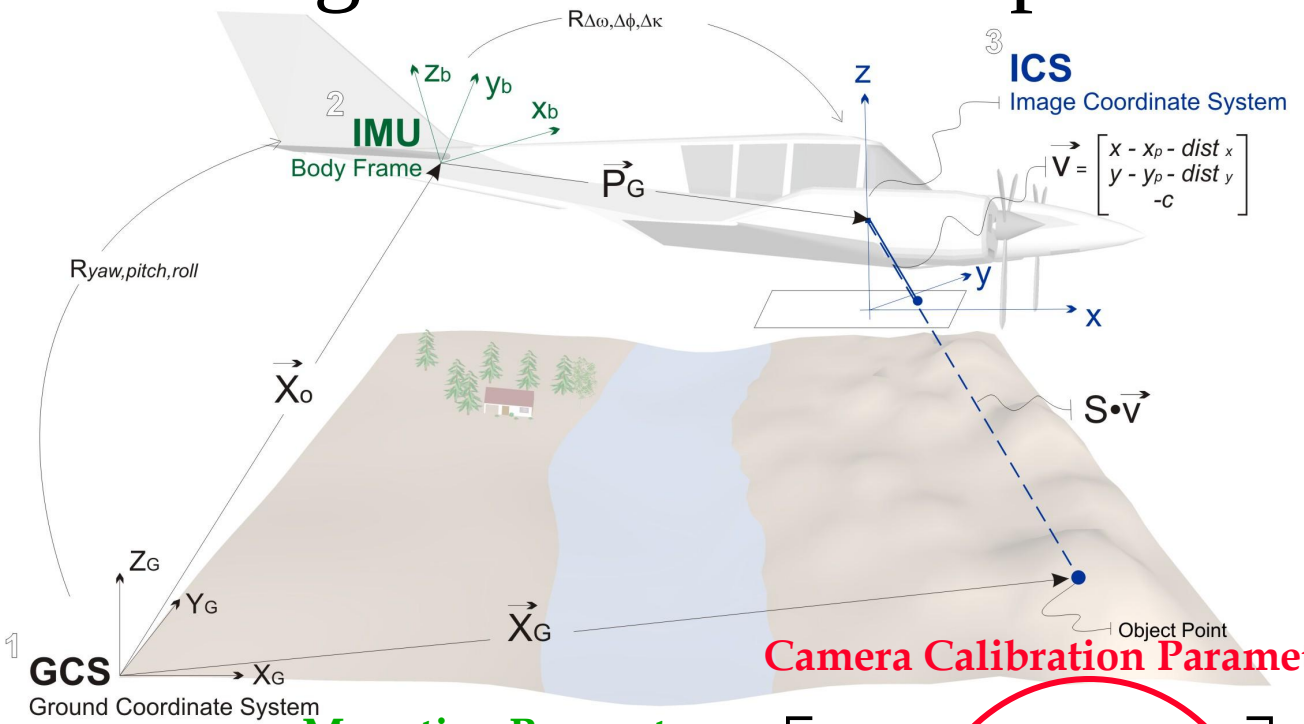
Operational Photogrammetric Systems

- **DAC 101: Camera assembled by Selkirk Remote Sensing**
  - **The camera utilizes a 60mm Rollei lens with a Rodenstock Apo-Sironar shutter and a 22 megapixel digital back (5440x4080 Imacon Ixpress 132 Digital Back with 9µm pixel size)**

Photogrammetric Principles



Photogrammetric Principles



Camera Calibration Parameters – IOP

Mounting Parameters

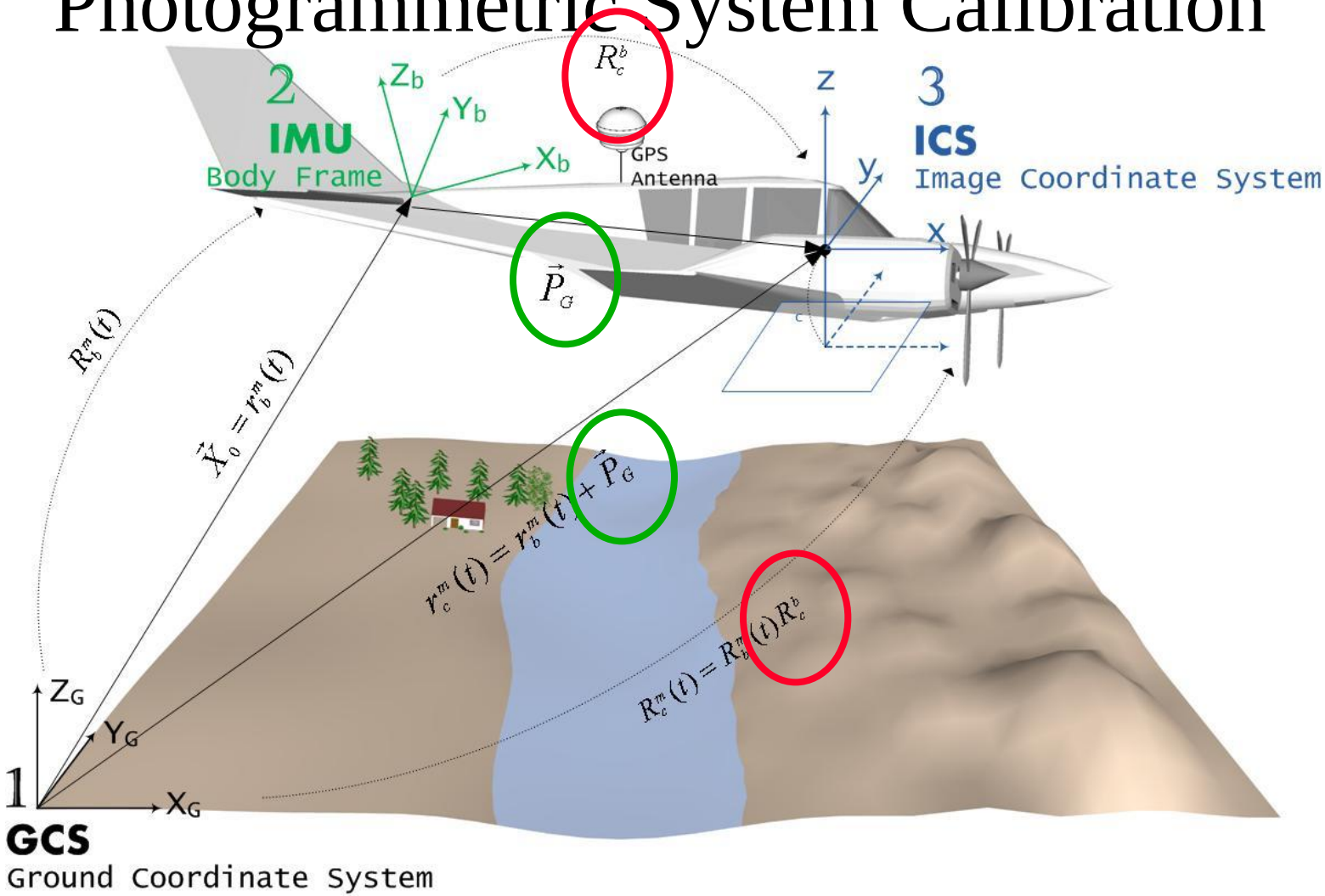
$$\vec{X}_G = \vec{X}_o + R_b^m \vec{P}_G + S_i R_b^m R_c^b \begin{bmatrix} x_i - x_p - dist_{x_i} \\ y_i - y_p - dist_{y_i} \\ -c \end{bmatrix}$$

System Calibration: IOP + Mounting Parameters

Photogrammetric Camera Calibration

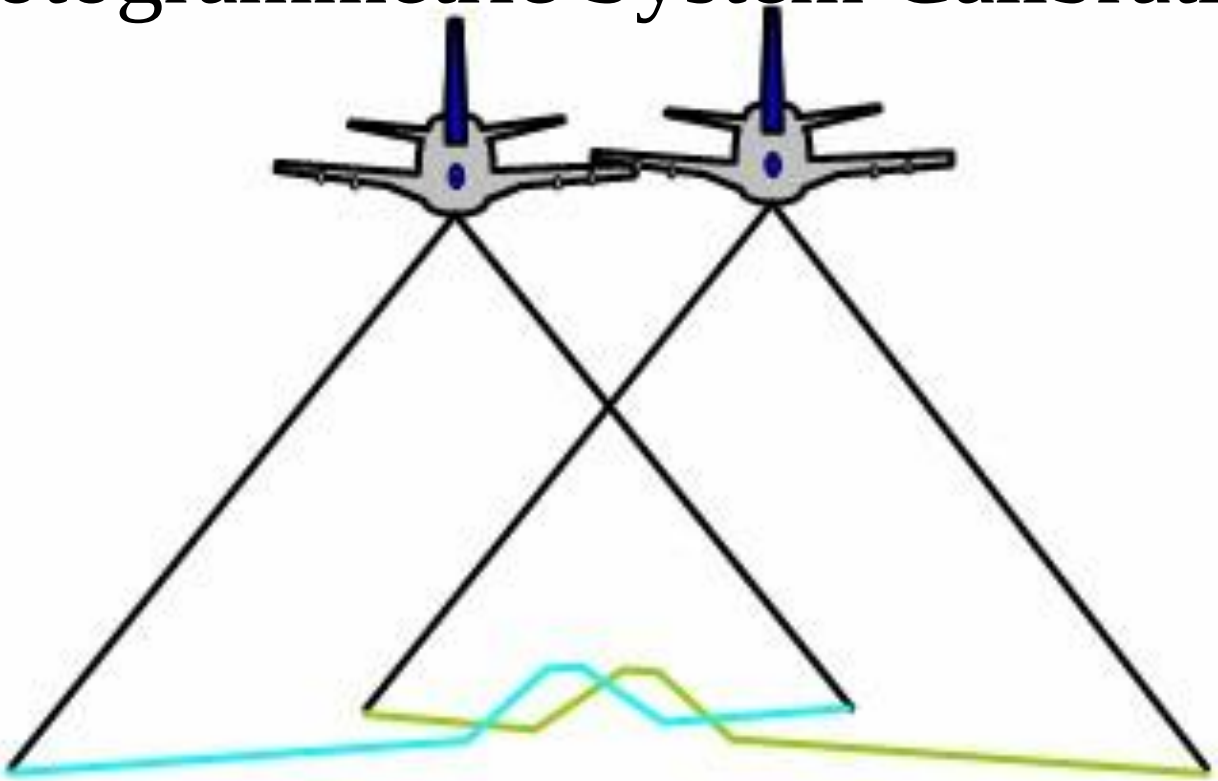
- Alternative procedures for camera calibration are well established.
  - Laboratory camera calibration (Multi-collimators)
  - Indoor camera calibration
  - In-situ camera calibration

Photogrammetric System Calibration



System Calibration: Mounting Parameters

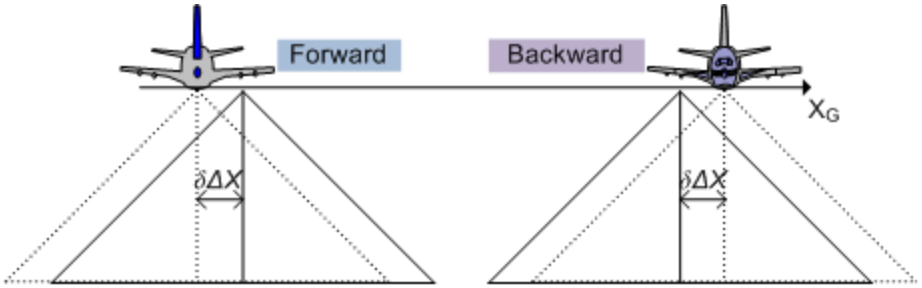
Photogrammetric System Calibration



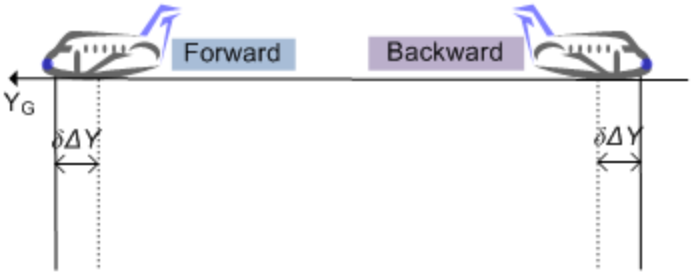
- **<u>Target function:</u>** Estimate the system parameters that
  - Minimize y-parallax between conjugate light rays from overlapping imagery, and
  - Minimize discrepancies between derived surfaces from multiple flight lines while reducing ground control requirements

Photogrammetric System Calibration

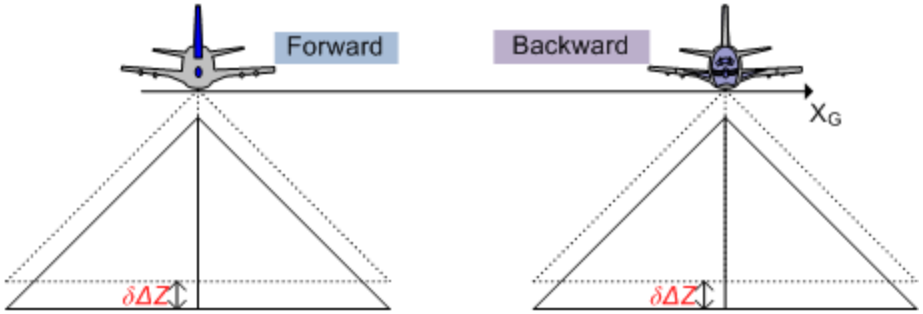
Lever-Arm Offset Bias (δΔX)



Lever-Arm Offset Bias (δΔY)

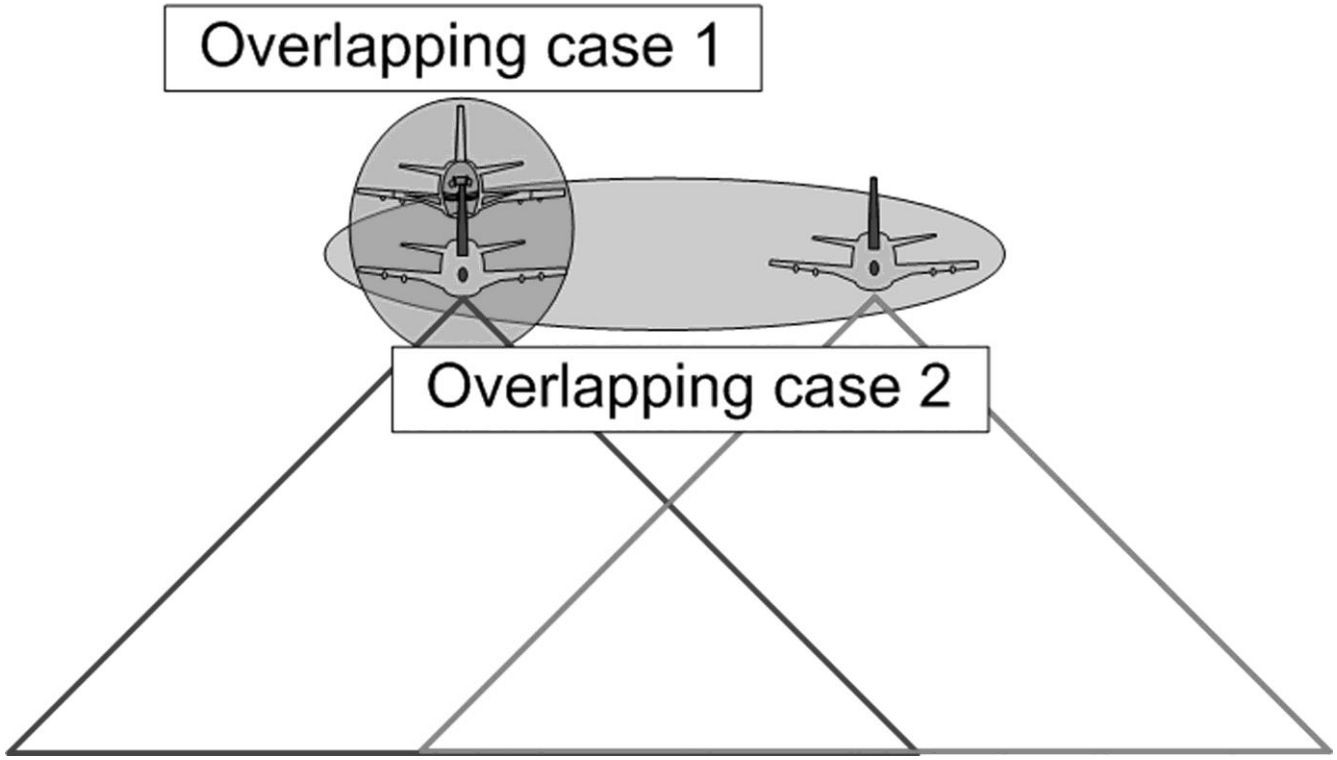


Lever-Arm Offset Bias (δΔZ)



Photogrammetric System Calibration

Optimum Flight Configuration for the Estimation of the Mounting Parameters

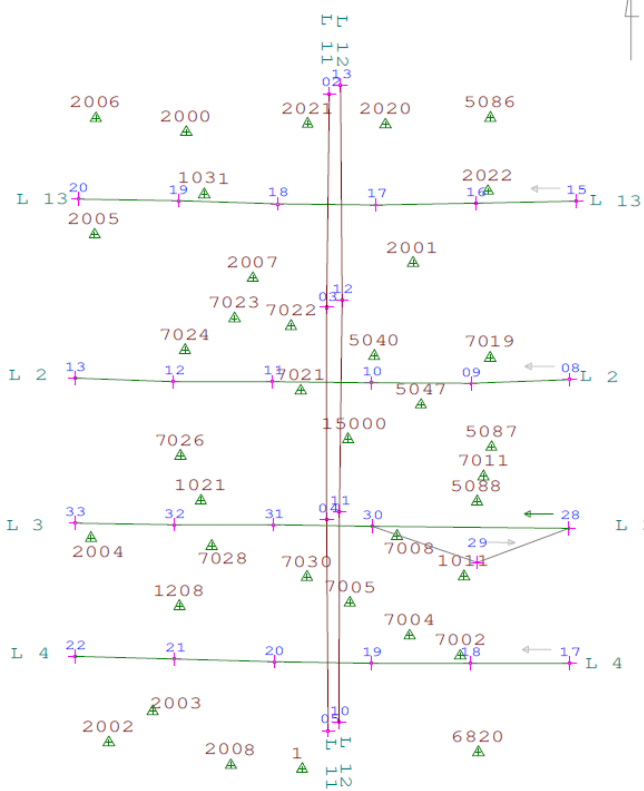


A minimum of one vertical control point is needed.

Experimental Results

Camera Specifications

Camera model	**Rollei P-65**
Array dimension	**8984x6732 pixels**
Pixel size	**6µm**
Nominal focal length	**60mm**
Camera classification	**Normal Angle Camera (AFOV = 58.6°)**



- **Six flight lines:**
  - **Four parallel flight lines @ 500m (60% side lap)**
  - **Two opposite flight lines @ 1000m (100% side lap)**

Camera System Calibration: Results

GPS/INS-Assisted integrated Sensor Orientation

	$(\sigma_o)^2$ $(mm)^2$	dx (m)	dy (m)	dz (m)	dω (º)	dφ (º)	dκ (º)
1 vertical GCP	$(0.0027)^2$	-0.039	-0.110	1.146	-0.1225	0.8418	179.5522
37 vertical GCP	$(0.0026)^2$	-0.033	-0.128	1.123	-0.1186	0.8454	179.5511
37 full GCP	$(0.0026)^2$	-0.007	-0.144	1.232	-0.1203	0.8436	179.5449

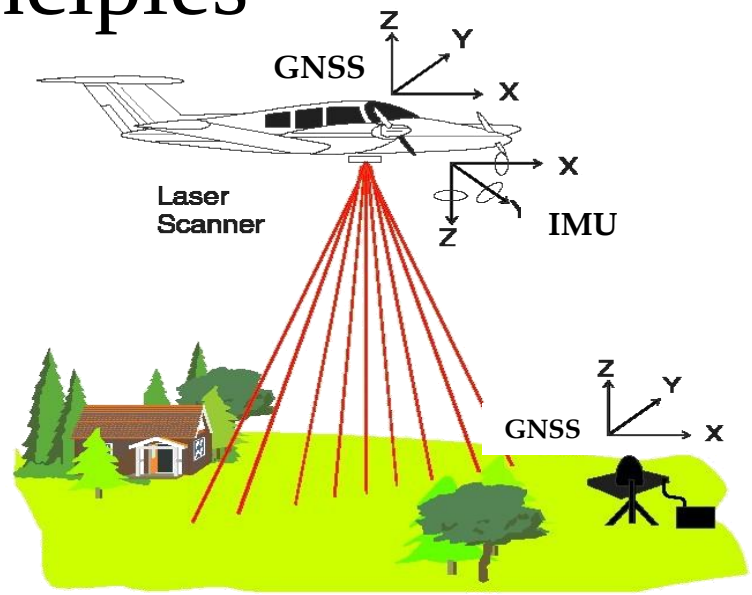
- Estimated lever arm and boresight parameters are not sensitive to the number of utilized control points.

Check point analysis (37 check points)

$RMSE_X$ (m)	$RMSE_Y$ (m)	$RMSE_Z$ (m)
0.078	0.096	0.121

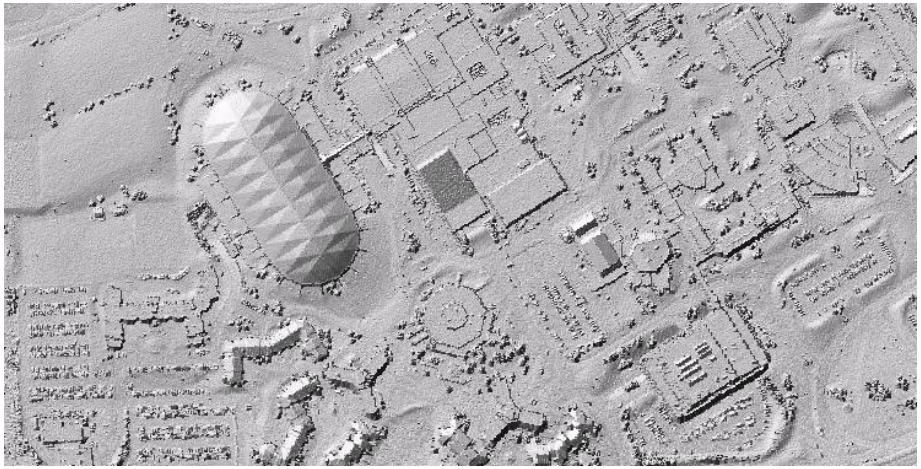
- Achieved accuracy is almost equivalent to the GSD of the utilized sensor.

LiDAR Principles



Three Measurement Systems

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



Direct acquisition of high density and accurate topographic data

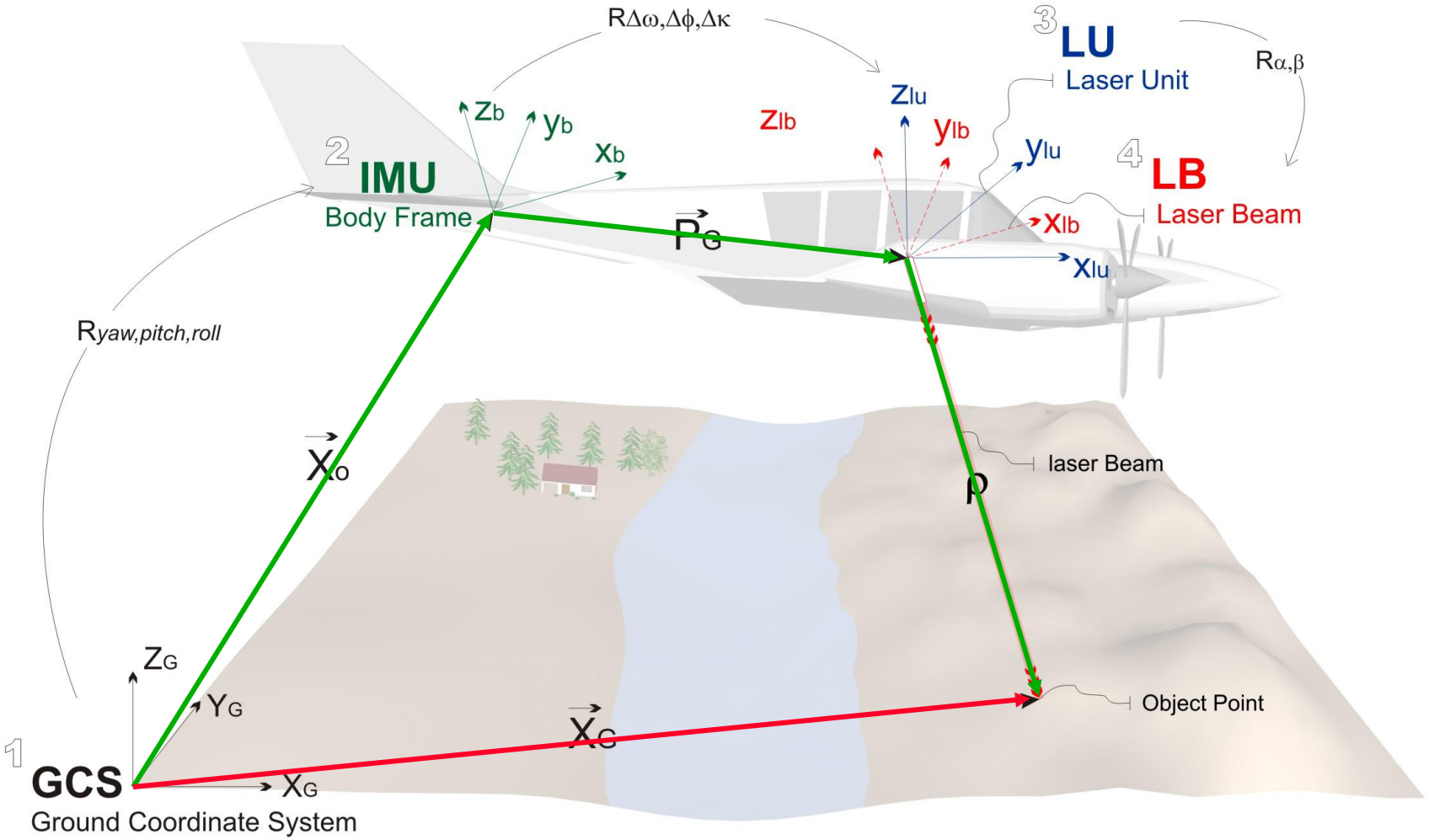
Operational LiDAR Systems

ALS 60 (Leica Geosystems)

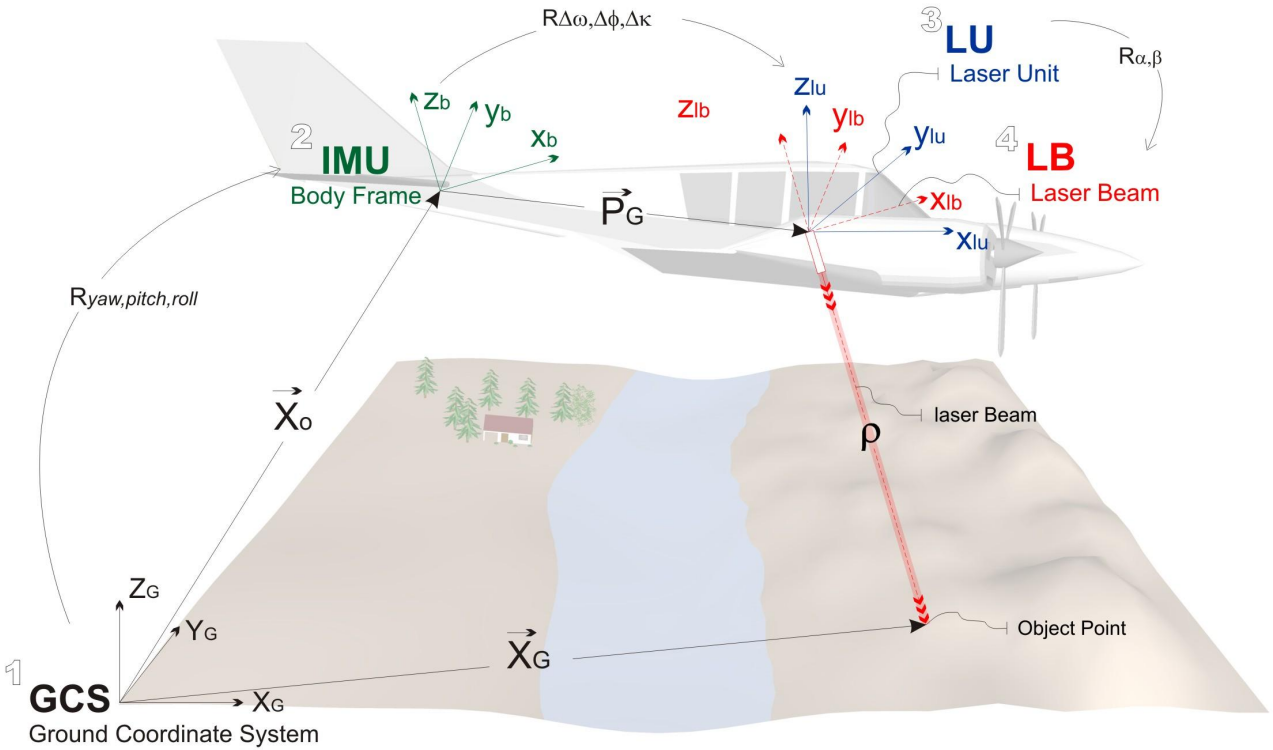
OPTECH ALTM GEMINI

TerraPoint USA

LiDAR Principles



LiDAR Principles



System Calibration

$$\vec{X}_G = \vec{X}_o + R_b^m \vec{P}_G + R_b^m R_{lu}^b R_{lb}^{lu} \begin{bmatrix} 0 \\ 0 \\ -\rho \end{bmatrix}$$

LiDAR System Calibration

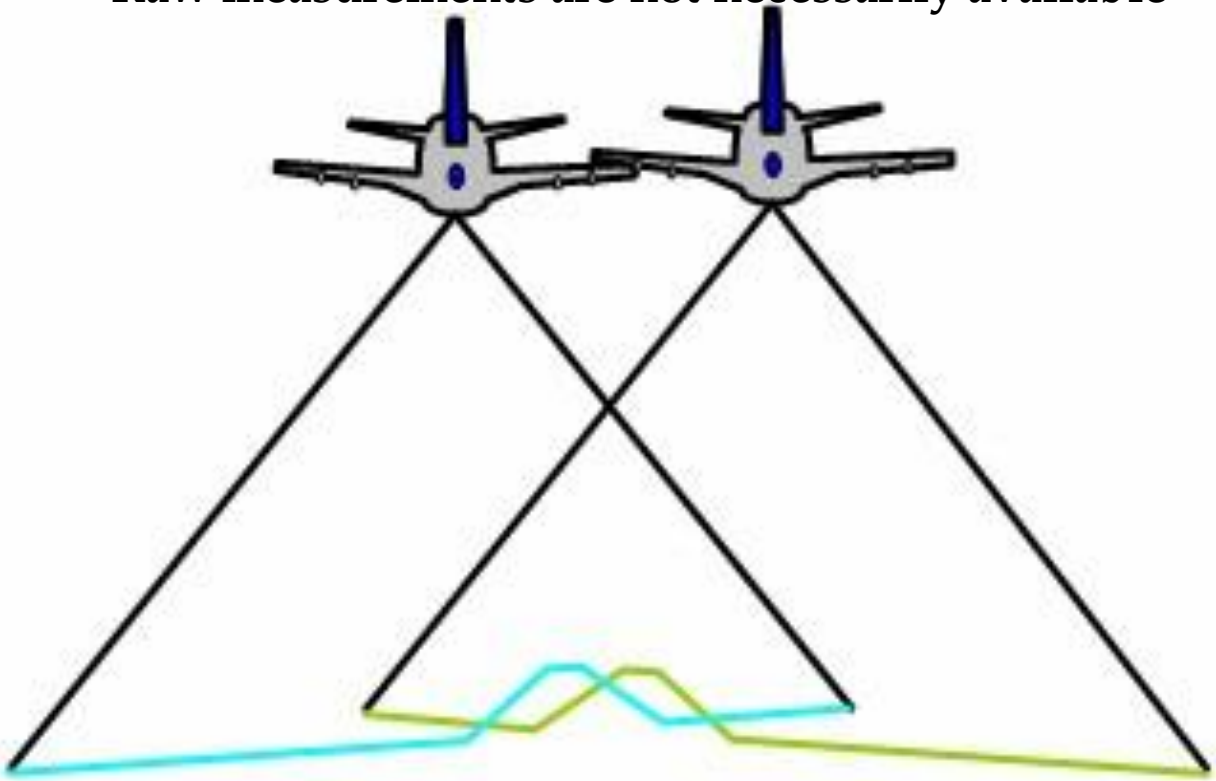
- The calibration of a LiDAR system aims at the estimation of systematic errors in the system parameters.
  - One can assume that the derived point cloud after system calibration is only contaminated by random errors.
- Usually accomplished in several steps:
  - Laboratory calibration,
  - Platform calibration, and
  - In-flight calibration

LiDAR System Calibration

- Drawbacks of current in-flight calibration methods:
  - Some techniques require the raw data, which is not always available.
  - Time consuming and expensive
  - Generally based on complicated and sequential calibration procedures
  - Require some effort in ground surveying of the control points/surfaces
  - Some of these calibration procedures involve manual and empirical procedures.
  - Lack of a commonly accepted methodology

LiDAR System Calibration

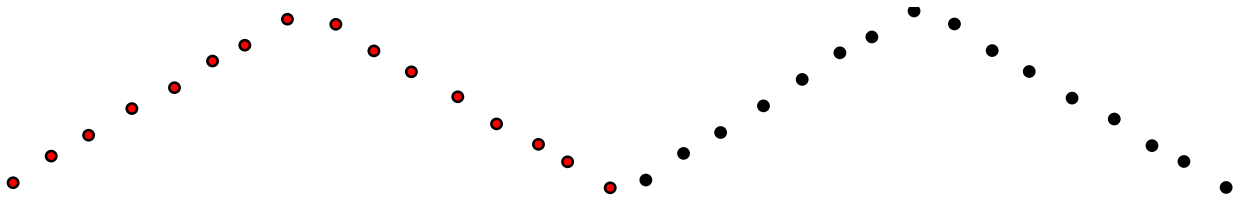
- **LiDAR Data in Overlapping Parallel Strips**
  - ✓ **Point cloud coordinates**
  - ✓ **Raw measurements are not necessarily available**

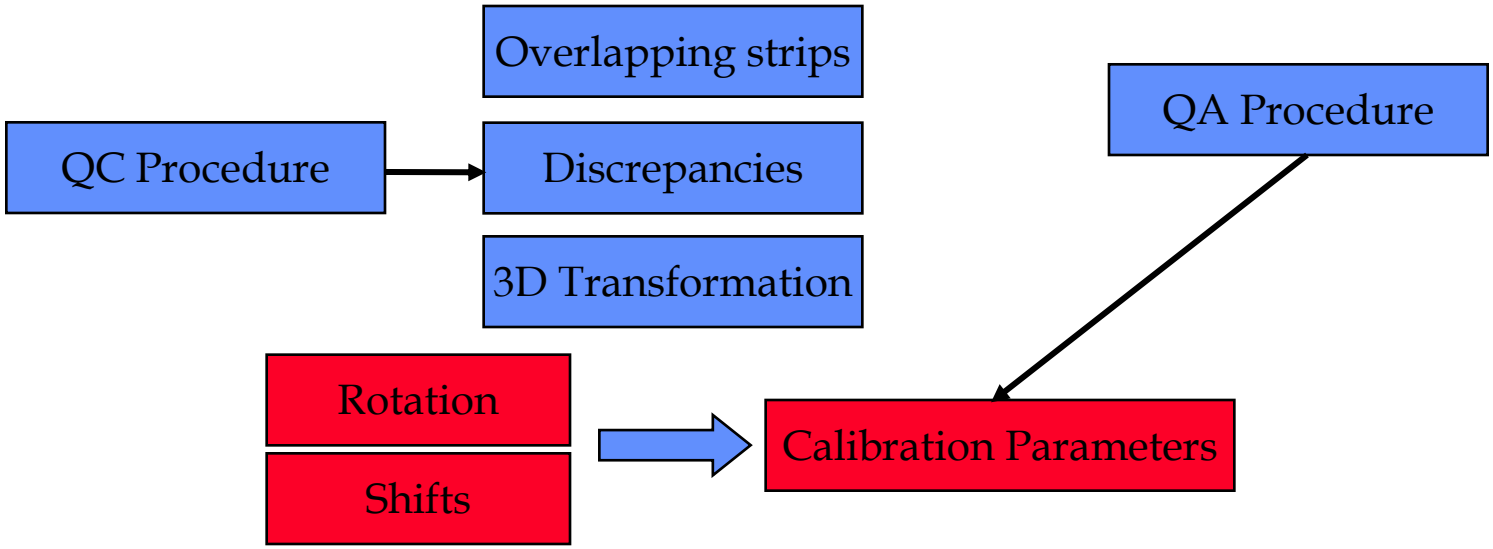


LiDAR System Calibration

Simplified Calibration

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

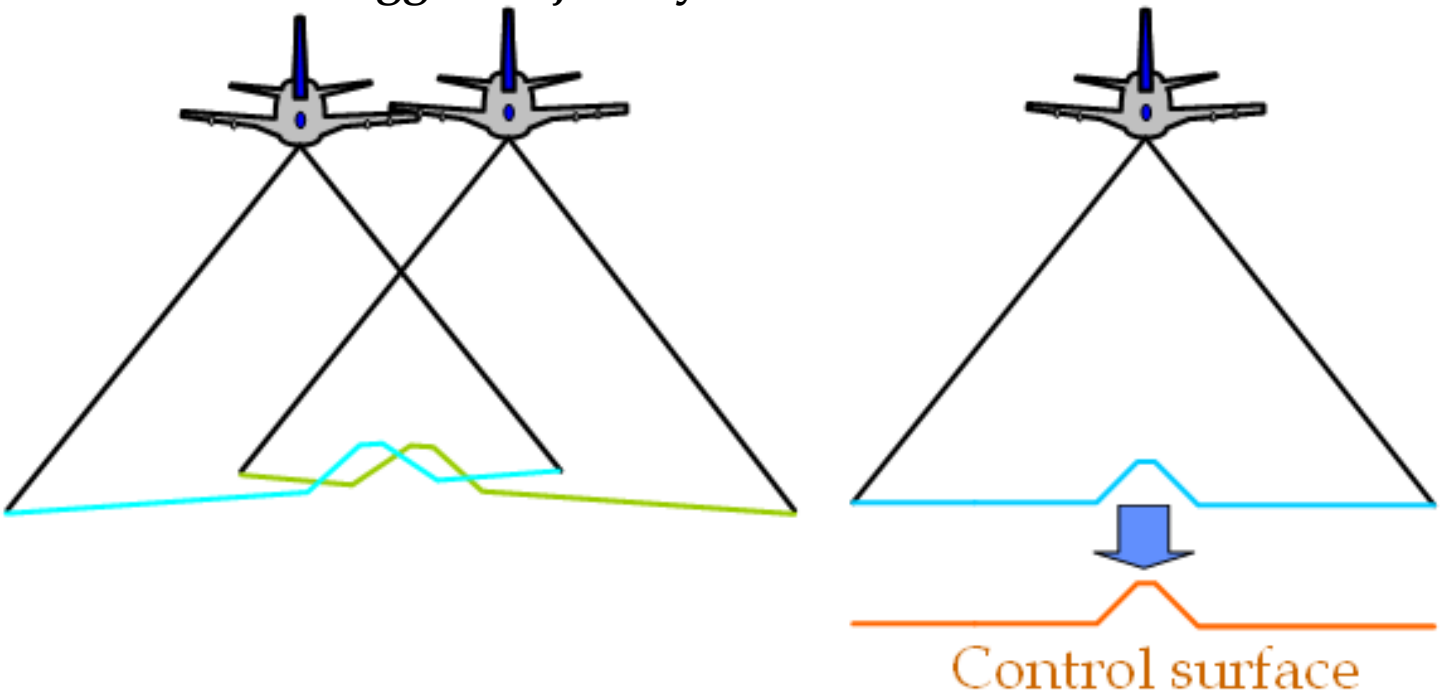




LiDAR System Calibration

Quasi-Rigorous Calibration

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

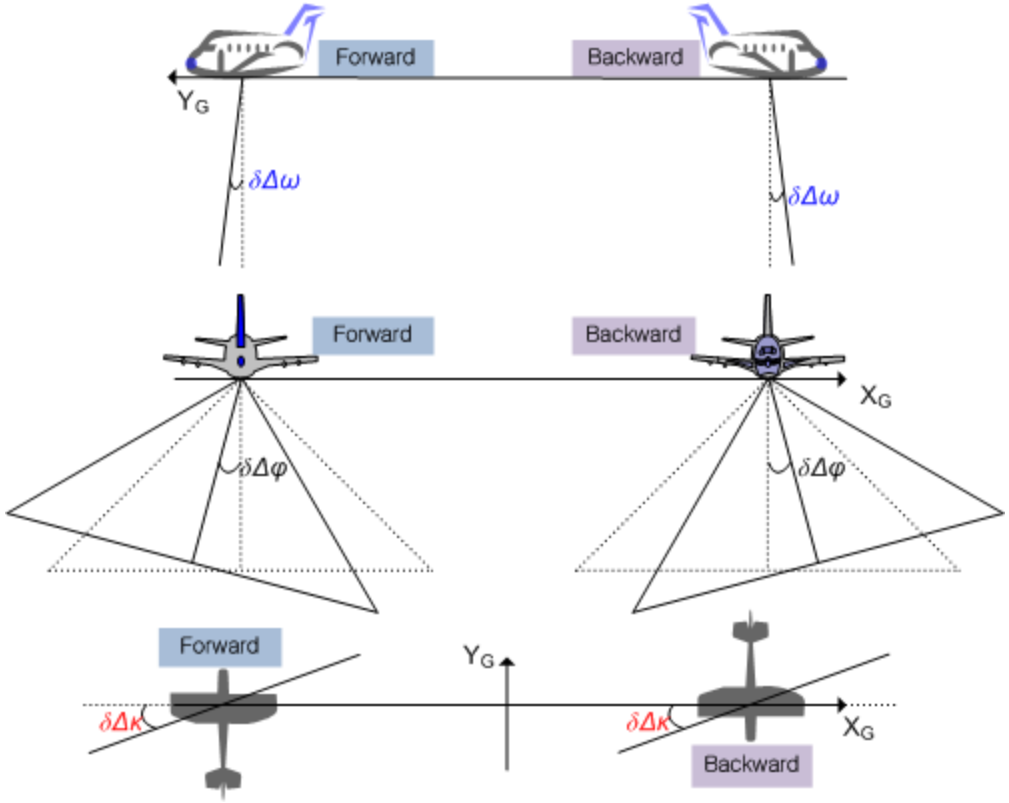


LiDAR System Calibration

Boresighting Pitch Bias (δΔω)

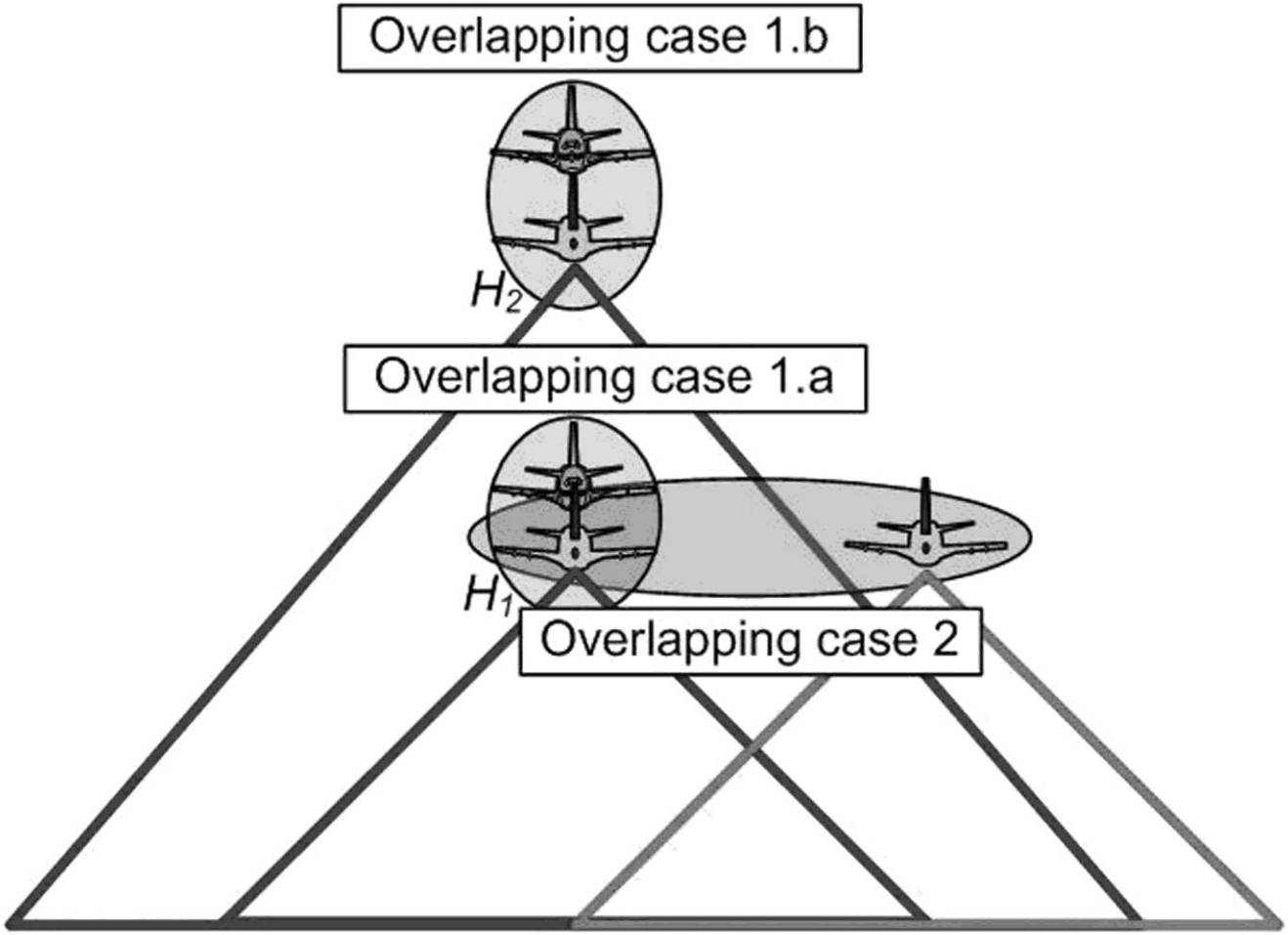
Boresighting Roll Bias (δΔϕ)

Boresighting Heading Bias (δΔκ)



LiDAR System Calibration

Optimum Flight Configuration

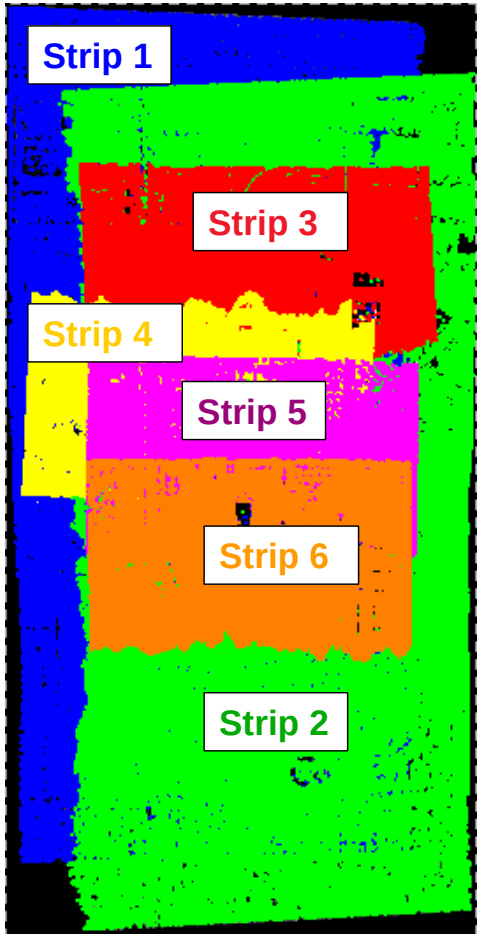


Vertical control points would be helpful.

Evaluation Criteria

- Relative Accuracy
  - Qualitative Evaluation:
    - Intensity images before and after the point cloud adjustment
    - Profiles before and after the point cloud adjustment
  - Quantitative Evaluation:
    - Discrepancies between overlapping strips before and after the point cloud adjustment
- Absolute Accuracy
  - LiDAR features, derived from the original and adjusted point cloud, are used for photogrammetric geo-referencing
  - Check point analysis

LiDAR System Calibration: Results



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

Data Captured by ALS50

LiDAR System Calibration: Results

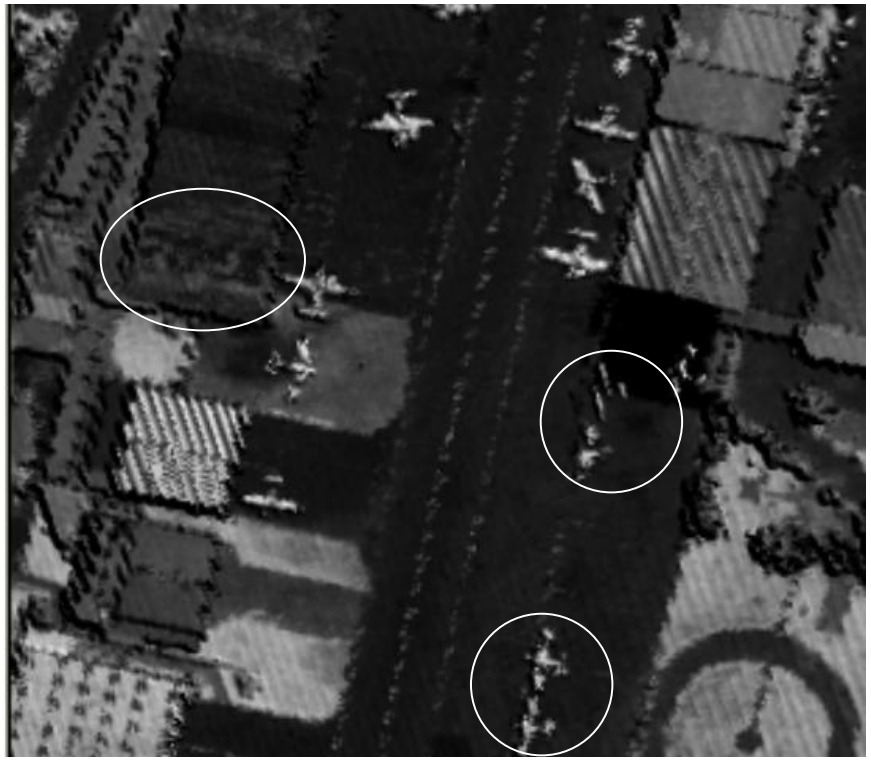
Overlapping Strip Pairs	Overlap %	Direction
Strips 1&2	80%	Opposite directions
Strips 3&4	25%	Opposite directions
Strips 4&5	75%	Opposite directions
Strips 5&6	50%	Same direction

LiDAR System Calibration: Results

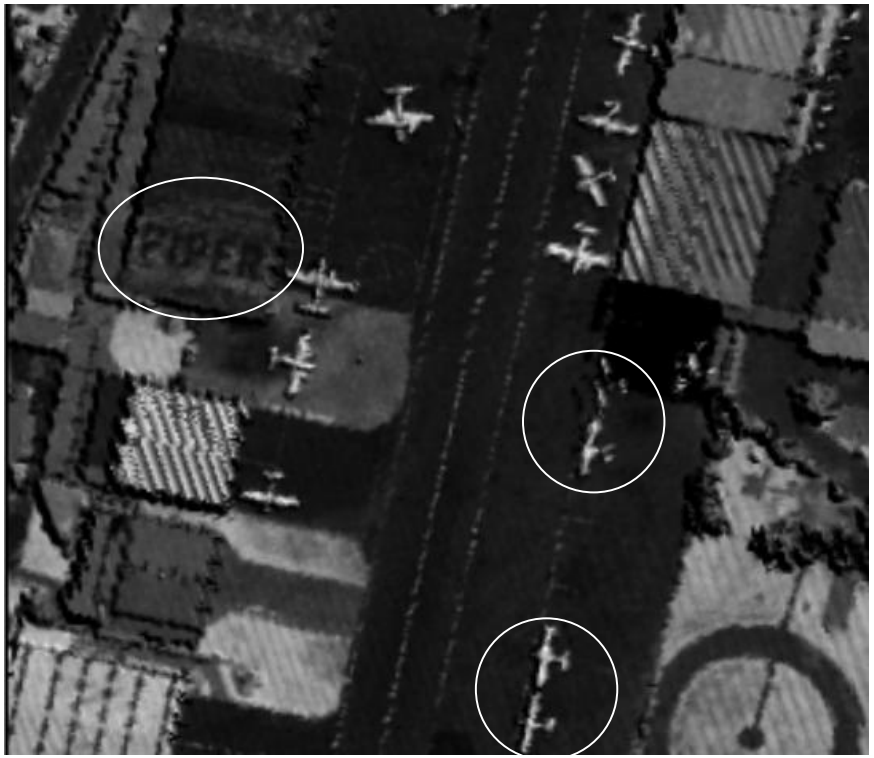
Estimated Mounting Parameters

$\delta\Delta X$ (m)	$\delta\Delta Y$ (m)	$\delta\Delta\omega$ (")	$\delta\Delta\phi$ (")	$\delta\Delta\kappa$ (")
-0.01	**0.02**	**-40.2**	**-90.9**	**-4.58**

LiDAR System Calibration: Results

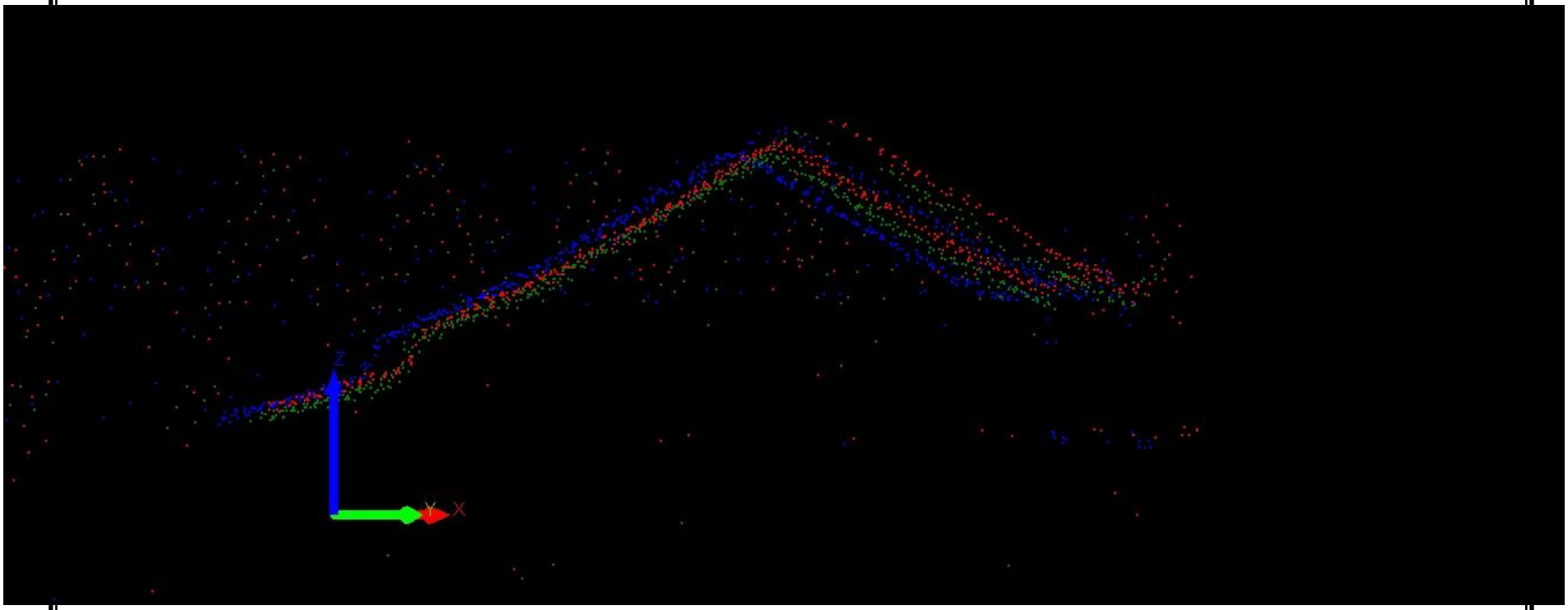


Intensity Image (Before)



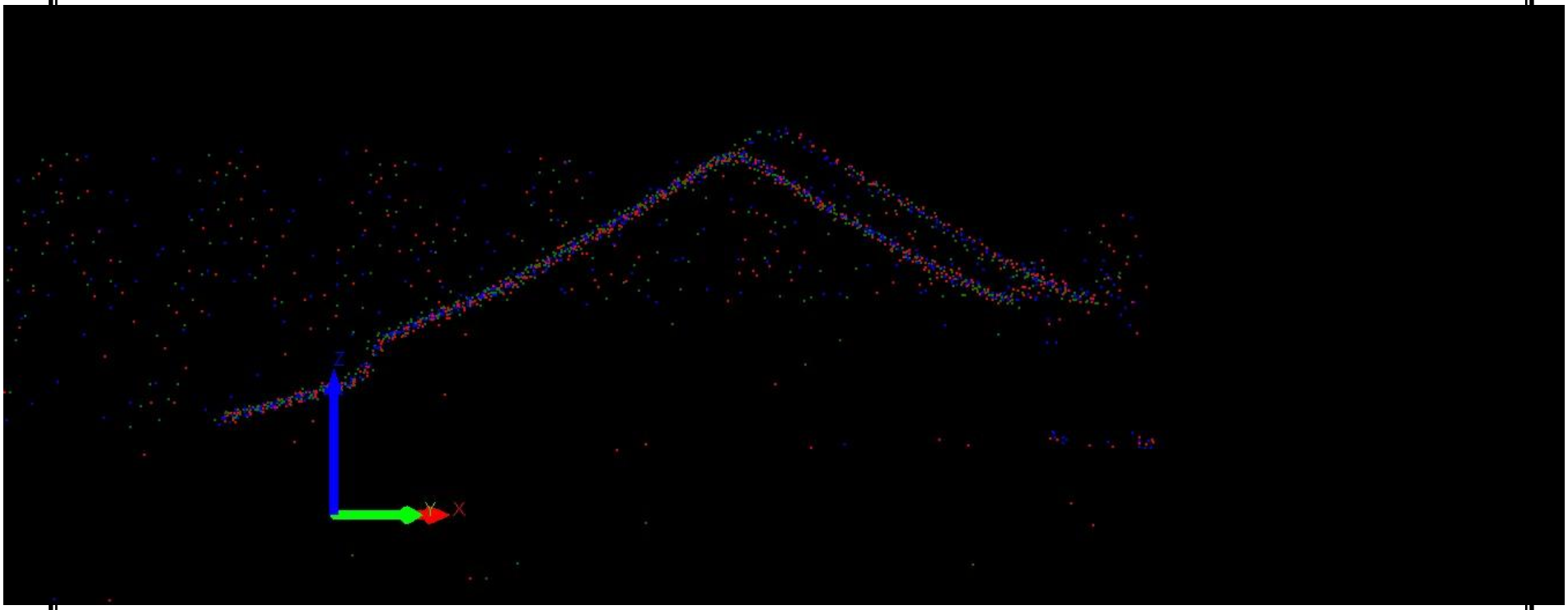
Intensity Image (After)

LiDAR System Calibration: Results



Before Calibration

LiDAR System Calibration: Results



After Calibration

LiDAR System Calibration: Results

Before Calibration			After Calibration		
Strips 1&2			Strips 1&2		
X_T (m)	Y_T (m)	Z_T (m)	X_T (m)	Y_T (m)	Z_T (m)
1.10	-0.32	-0.01	0.11	0.07	-0.05
ω (deg)	φ (deg)	κ (deg)	ω (deg)	φ (deg)	κ (deg)
0.0001	-0.052	-0.002	0.0012	-0.0016	-0.0051
Strips 3&4			Strips 3&4		
X_T (m)	Y_T (m)	Z_T (m)	X_T (m)	Y_T (m)	Z_T (m)
0.18	0.41	-0.01	-0.01	-0.01	0.01
ω (deg)	φ (deg)	κ (deg)	ω (deg)	φ (deg)	κ (deg)
0.0484	-0.0005	-0.0011	0.0052	0.0008	-0.0045

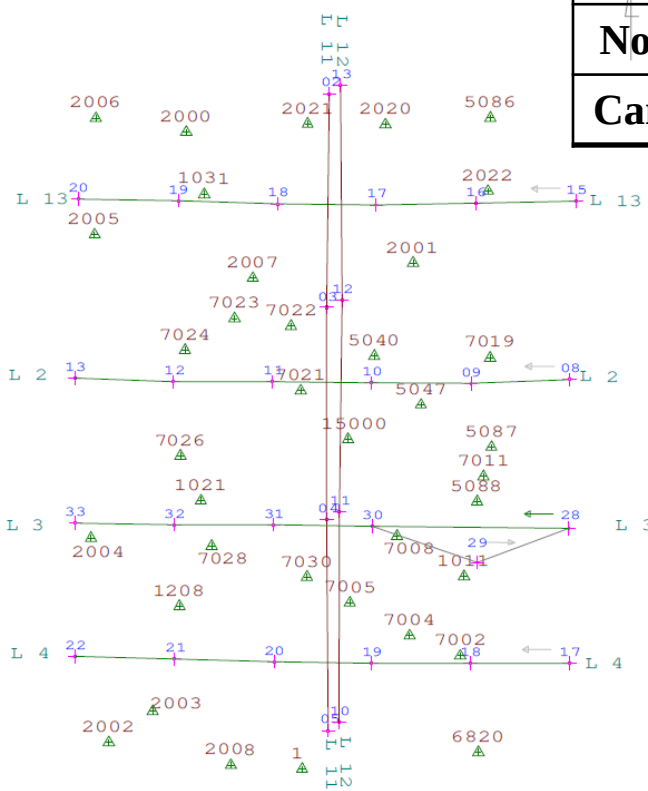
Compatibility between overlapping strips before and after the calibration procedure

LiDAR System Calibration: Results

Photogrammetric Data

Camera Specifications

Camera model	**Rollei P-65**
Array dimension	**8984x6732 pixels**
Pixel size	**6µm**
Nominal focal length	**60mm**
Camera classification	**Normal Angle Camera (AFOV = 58.6°)**



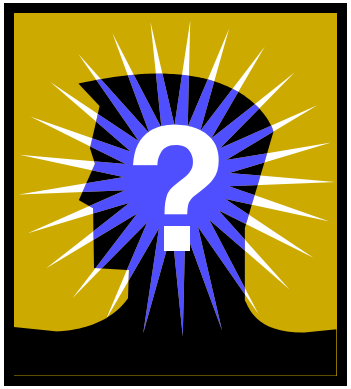
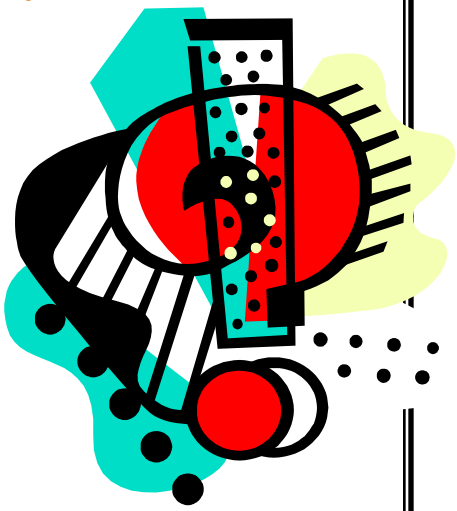
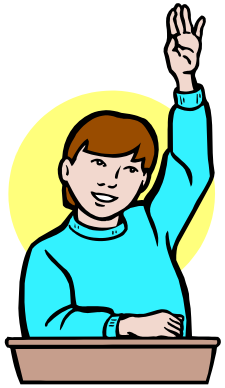
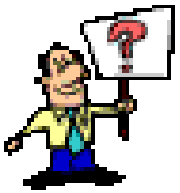
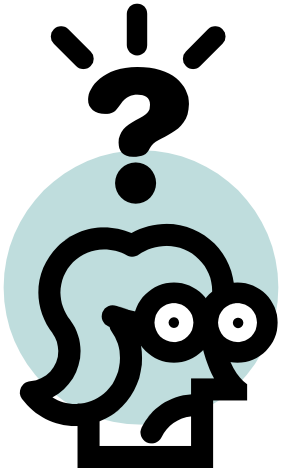
- **Six flight lines:**
  - **Four parallel flight lines @ 500m (60% side lap)**
  - **Two opposite flight lines @ 1000m (100% side lap)**

LiDAR System Calibration: Results

	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

Concluding Remarks

- Modern mapping systems (e.g., directly geo-referenced cameras and laser scanners) provide 3D data that meets the needs of several users.
- The quality of the delivered data depends on the accuracy of the system calibration procedure.
- This research developed a procedure for system calibration:
  - Minimizes discrepancies among derived surfaces from overlapping flight lines
  - Minimizes ground control requirements
  - Establishes the optimum flight configuration
- Conducted experiments verified the feasibility of the proposed calibration procedure.

Comments and Questions?