Quality Assurance and Quality Control of LiDAR Systems and Derived Data

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Introduction

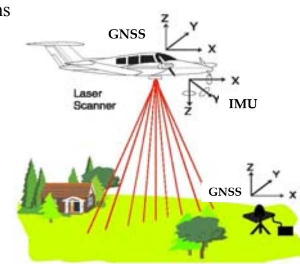
Overview

- General background: LiDAR principles
- Error budget for LiDAR
- LiDAR quality assurance
- LiDAR quality control
  - Internal/relative quality control (IQC)
  - External/absolute quality control (EQC)
- Experimental results
- Final remarks

LiDAR Principles

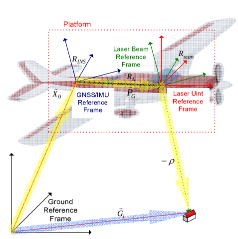
Three Measurement Systems

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



LiDAR Equation

$$\vec{G}_i = \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \vec{X}_0 + R_{INS}\vec{P}_G + R_{INS} R_\Delta R_{scan} \begin{bmatrix} 0 \\ 0 \\ -\rho \end{bmatrix}$$



LiDAR Output

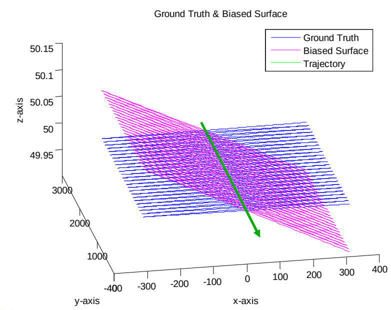
Range Data (Shaded Relief)

Intensity Data

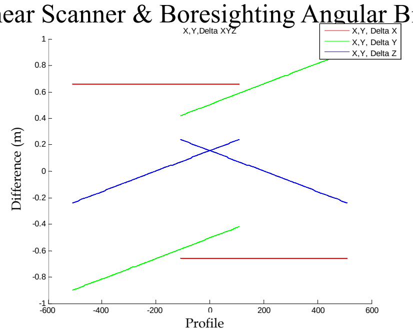
Error Sources: Systematic Biases

- We would like to show the effect of biases in the LiDAR measurements on the reconstructed object space.
- The effects will be derived through a simulation process:
  - Simulated surface & Trajectory → LiDAR measurements → Add biases → Reconstructed surface.
- The effects will be shown through the difference between the reconstructed footprints and the simulated surface (i.e., ground truth).
- These effects will be shown for linear LiDAR systems.

Linear Scanner & Boresighting Angular Bias



Linear Scanner & Boresighting Angular Bias



- Opposite Flight Directions & 30% Overlap
- Overlap area can be used to check the presence of biases

Error Sources: Systematic Biases

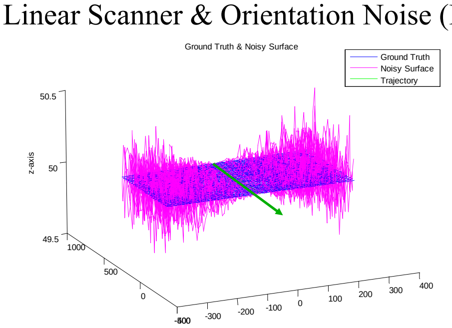
	Flying Height	Flying Direction	Look Angle
Boresighting Offset Bias	Effect is independent of the Flying Height	Effect is dependent on the Flying Direction (Except ΔZ)	Effect is independent of the Look Angle
Boresighting Angular Bias	Effect Increases with the Flying Height	Effect Changes with the Flying Direction	Effect Changes with the Look Angle (Except ΔX)
Laser Beam Range Bias	Effect is independent of the Flying Height	Effect is independent of the Flying Direction	Effect Depends on the Look Angle (Except ΔY)
Laser Beam Angular Bias	Effect Increases with the Flying Height	Effect Changes with the Flying Direction (Except ΔY)	Effect Changes with the Look Angle (Except ΔX)

- Assumption:
  - Linear Scanner
  - Constant Attitude & Straight Line Trajectory
  - Flying Direction Parallel to the Y axis
  - Flat horizontal terrain

Error Sources: Random Errors

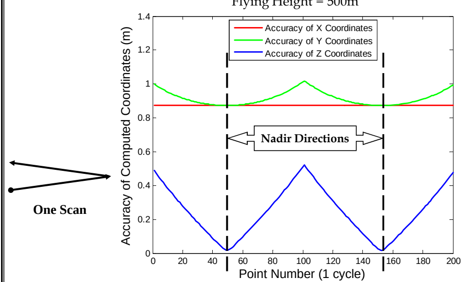
- The effect of random errors can be analyzed in one of two different ways:
  - Approach # I:
    - Simulated surface & Trajectory → LiDAR measurements → Add noise → Reconstructed surface.
    - Evaluate the difference between the reconstructed footprints and the simulated surface (i.e., ground truth).
  - Approach # II:
    - Use the law of error propagation to evaluate the accuracy (noise level) of the derived point cloud as it is determined by the accuracy (noise level) in the LiDAR measurements.

Linear Scanner & Orientation Noise (I)



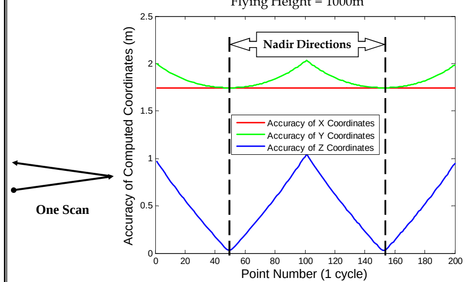
- Propagates with the flying height
- Dependent on the look angle

Linear Scanner & Orientation Noise (II)



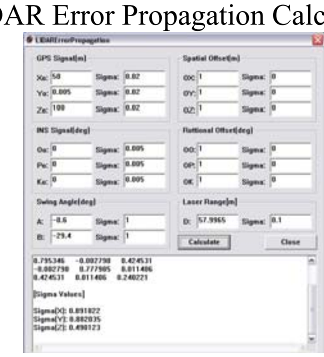
- Propagates with the flying height
- Dependent on the look angle

Linear Scanner & Orientation Noise (II)



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

LiDAR Error Propagation Calculator



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

Quality Assurance & 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.

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.
  - In-situ calibration.
- Total system calibration.
  - Spatial and rotational offsets between various system components (e.g., camera, GPS, and IMU).
- Other QA measures include:
  - Number & configuration of GCP, side lap percentage, distance to GPS base station.

Photogrammetric Quality Assurance

Laboratory Calibration: Multi-Collimators

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.
  - Variance component (overall measure of the quality of fit between the observed quantities and 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., GPS survey) → RMSE analysis.

Photogrammetric Quality Control

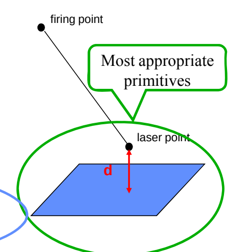
Check Point Analysis

LiDAR QA: System Calibration

- Possible systematic errors:
  - Spatial and rotational offsets between the various system components.
  - Range bias.
  - Angular mirror bias.
- Calibration requires some control information.
  - What are the most appropriate primitives?
- The appropriate configuration of the control information and the flight mission.

LiDAR QA: System Calibration

- **Target Function:** 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 parameters (LAS ?)

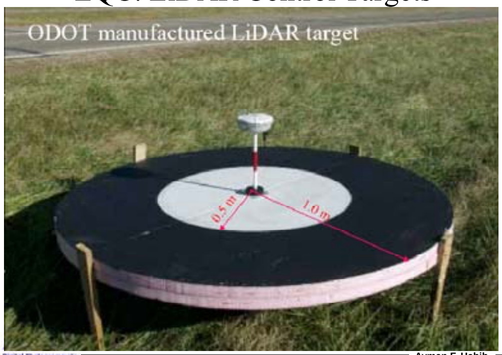
LiDAR Quality Control

- 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 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.

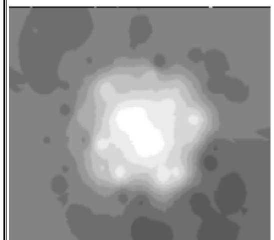
EQC: LiDAR Control Targets

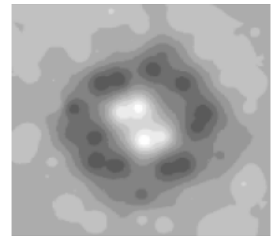
- External/absolute quality control measures (EQC):
  - Similar to photogrammetric quality control, the derived LiDAR coordinates can be compared with independently surveyed targets.
    - Check point analysis.
  - Problem: How to correlate the non-selective LiDAR footprints to the utilized check points.
  - Solution: Use specially designed targets.
    - The target design depends on the involved LiDAR system.

EQC: LiDAR Control Targets



EQC: LiDAR Control Targets


Range Data


Intensity Data

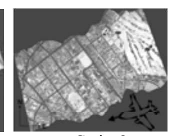
- We have to implement a segmentation procedure to derive the LiDAR coordinates of the target.

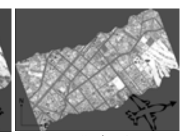
IQC: LiDAR Quality Control

- 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 adopt 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.

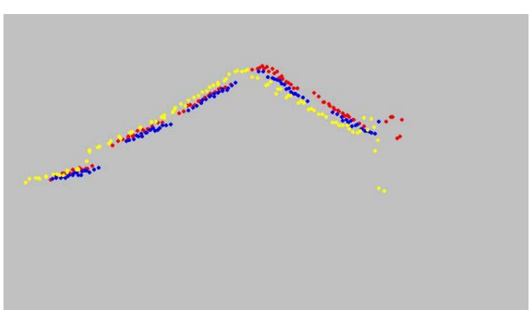
IQC: LiDAR Quality Control


Strip 2


Strip 3


Strip 4

IQC: LiDAR Quality Control



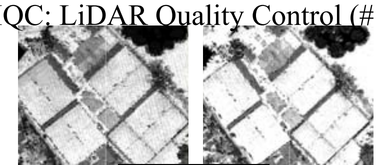
IQC: LiDAR Quality Control (#1)

- Using interpolated intensity and range images:
  - Interpolate the intensity and range data into a grid → Intensity and range 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.
- Caution: **Interpolation would lead to artifacts** in the interpolated images (especially at the vicinity of discontinuities in the intensity and range data).

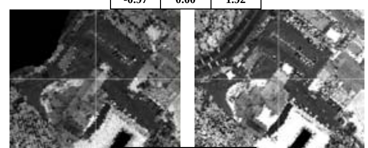
IQC: LiDAR Quality Control (#1)

Intensity Images

IQC: LiDAR Quality Control (#1)



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 (#1)

- The average and standard deviation of the estimated discrepancies between 100 points in two overlapping strips

	Average (m)	Standard deviation (m)
X	0.45	±0.36
Y	0.50	±0.37
Z	0.22	±0.28

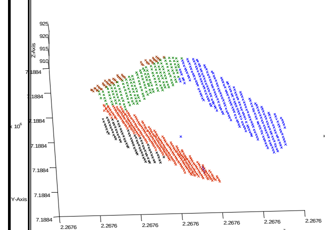
IQC: LiDAR Quality Control (#1)

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

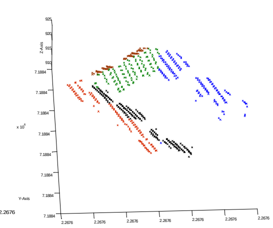
IQC: LiDAR Quality Control (#2)

- Check the quality of coincidence of conjugate planar patches.

IQC: LiDAR Quality Control (#2)



Strip # 3



Strip # 4

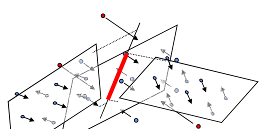
IQC: LiDAR Quality Control (#2)

	Strips 2 & 3	Strip 3&4	Strips 2 & 4
Transformation parameter / # of Patches	21	22	22
Scale Factor	1.0000	0.9996	0.9995
X_T (m)	-0.52	0.72	0.08
Y_T (m)	-0.13	-0.17	-0.21
Z_T (m)	0.05	0.09	0.14
Ω (°)	0.0289	-0.0561	-0.0802
Φ (°)	0.0111	-0.0139	-0.0342
Κ (°)	0.0364	0.0288	0.0784
Normal Distance, m (After)	0.04	0.03	0.04

Estimated transformation parameters using conjugate planar patches in overlapping strips.

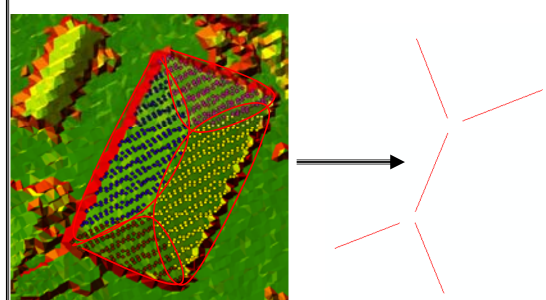
IQC: LiDAR Quality Control (#3)

manual identification of LiDAR patches with the aid of imagery

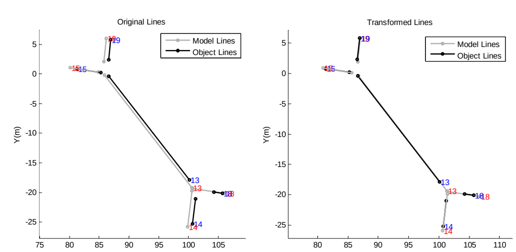


Linear Feature Extraction

IQC: LiDAR Quality Control (#3)



IQC: LiDAR Quality Control (#3)



IQC: LiDAR Quality Control (#3)

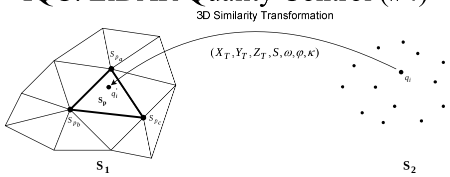
	Strips 2 & 3	Strips 3 & 4	Strips 2 & 4
Transformation parameter / # of Lines	24	36	24
Scale Factor	1.0002	1.0006	1.0013
X_T (m)	-0.56	0.75	0.10
Y_T (m)	0.04	-0.17	-0.16
Z_T (m)	0.03	0.05	0.13
Ω (°)	0.0205	-0.0386	-0.0147
Φ (°)	0.0062	-0.0125	-0.0073
K (°)	0.0261	-0.0145	-0.0113
Normal Distance, m (Before)	0.38 ± 0.22	0.49 ± 0.24	0.26 ± 0.14
Normal Distance, m (After)	0.18 ± 0.19	0.18 ± 0.18	0.16 ± 0.11

Estimated transformation parameters using conjugate linear features in overlapping strips

IQC: LiDAR Quality Control (# 1 – 3)

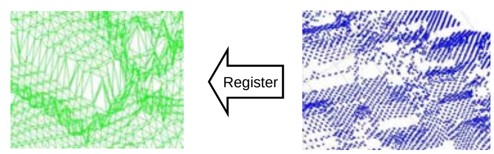
- The previous IQC measures requires preprocessing of the raw LiDAR data:
  - Interpolation, planar patch segmentation, plane fitting, and/or intersection.
- Another approach can be devised while using the original point cloud.
  - One strip is represented by a set of irregularly distributed points (LiDAR point cloud).
  - Second strip is represented by a TIN generated from the LiDAR point cloud.
  - Iterative Closest Patch (ICPatch).

IQC: LiDAR Quality Control (#4)

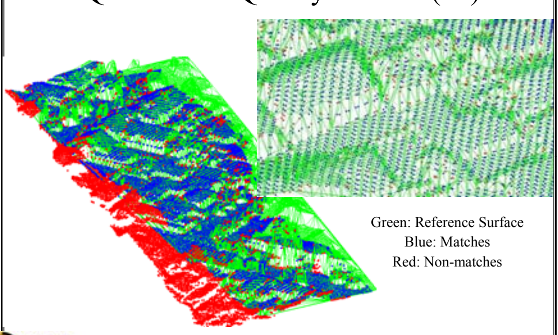


- Starting from a given set of approximate parameters, we determine conjugate point-patch pairs in overlapping strips.
- Conjugate primitives are used to estimate an updated set of parameters, which are then used to determine new correspondences.
- The approach is repeated until convergence.

IQC: LiDAR Quality Control (#4)



IQC: LiDAR Quality Control (#4)

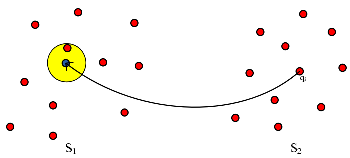


Green: Reference Surface
Blue: Matches
Red: Non-matches

IQC: LiDAR Quality Control (#4)

	Strips 2& 3	Strips 3& 4	Strips 2& 4
Scale Factor	0.9996	0.9998	0.9993
X_T (m)	-0.55	0.75	0.19
Y_T (m)	-0.06	-0.13	-0.18
Z_T (m)	0.03	0.12	0.16
Ω (°)	0.0080	-0.0267	-0.0213
Φ (°)	0.0059	-0.0088	-0.0053
K (°)	-0.0009	-0.0003	0.0012
Average Normal Dist., m	0.09	0.09	0.10

IQC: LiDAR Quality Control (#5)



- Iterative Closest Point (ICP):
  - Do we have conjugate points?
  - Is the performance impacted by the average point density?

IQC: LiDAR Quality Control (#5)

- This approach is similar to the ICPatch procedure. However, instead of using a TIN to represent the second strip, we use the original LiDAR point cloud.
- Iterative Closest Point (ICPoint) is used to determine the correspondence between conjugate points in overlapping strips (starting from an approximate set of transformation parameters).
  - Is there conjugate points?
- Conjugate points are used to estimate an updated set of parameters, which are then used to determine new correspondences.
- The approach is repeated until convergence.

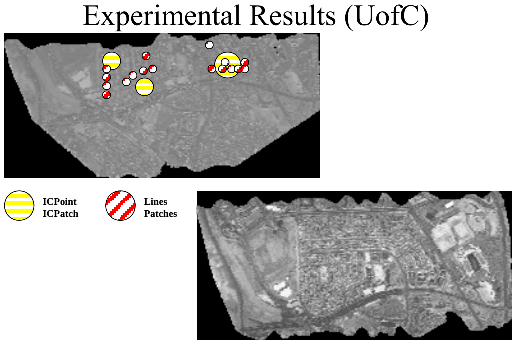
IQC: LiDAR Quality Control (#5)

	Strips 2& 3	Strips 3& 4	Strips 2& 4
Scale Factor	0.9997	1.0002	0.9994
X_T (m)	-0.47	0.70	0.26
Y_T (m)	-0.27	-0.32	-0.41
Z_T (m)	0.00	0.04	0.15
Ω (°)	0.0132	-0.0394	-0.0302
Φ (°)	0.0082	-0.0141	-0.0059
K (°)	0.0039	-0.0007	-0.0100
Average Distance, m	0.51	0.51	0.60

Experimental Results

- Previous results were derived from three strips captured in Brazil:
  - Triple overlap, ~ 1000 m flying height, 50 KHZ pulse rate, ~ 0.70 m point spacing, 15 cm $RMSE_Z$ & 50 cm $RMSE_{XY}$ (manufacturer specification).
- The following results are derived from eleven strips captured over the University of Calgary (UofC) Campus.
  - 50% overlap, ~ 1200 m flying height, 50 KHZ pulse rate, ~ 0.75 m point spacing, 9 cm $RMSE_Z$ (reported by the data provider).

Experimental Results (UofC)



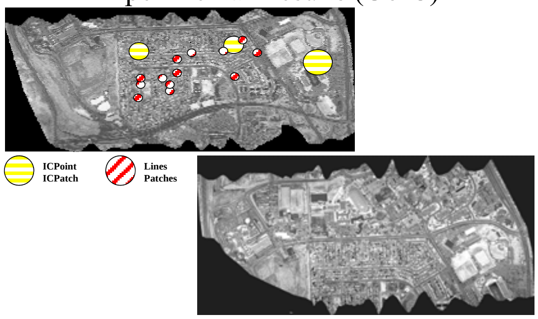
Strips 3 & 4

Experimental Results (UofC)

	Method \ Parameters		SF	XT (m)	YT (m)	ZT (m)	Omega (deg)	Phi (deg)	Kappa (deg)	Av_Dist Ndist(m)
			Estimated Transformation parameters							
08803 & 08804	Patches method		1.00019	-0.02	-0.02	0.02	-0.0151	0.0023	0.0052	0.03
	Lines	Collinearity	1.00009	0.04	-0.08	0.02	-0.0132	0.0020	0.0039	0.10
		endpoint	0.99995	0.02	-0.02	0.01	-0.0084	-0.0003	0.0068	0.08
	ICPatch		0.99990	-0.01	-0.12	0.01	-0.0023	-0.0009	0.0029	0.04
	ICPoint		0.99980	-0.08	-0.27	0.00	-0.0036	-0.0011	0.0022	0.51

Consistency in the results coming from various methods

Experimental Results (UofC)



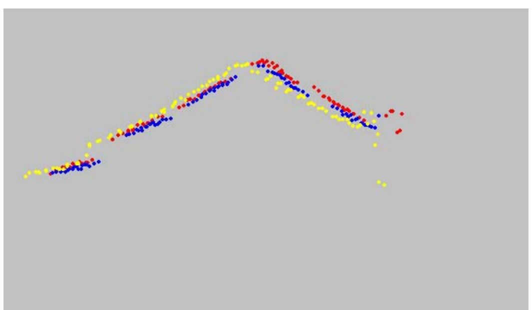
Strips 4 & 5

Experimental Results (UofC)

	Parameters / Method		SF	XT (m)	YT (m)	ZT (m)	Omega (deg)	Phi (deg)	Kappa (deg)	Av_Dist Ndist(m)
			Estimated Transformation parameters							
08804 & 08805	Patches method		1.00003	0.76	0.14	-0.01	0.0185	0.0060	0.0175	0.03
	Lines	Collinearity	1.00037	0.80	0.10	-0.03	0.0156	0.0022	-0.0011	0.16
		End point	0.99987	0.80	0.25	-0.02	0.0164	0.0054	0.0270	0.13
	ICPatch		1.00010	0.86	0.10	-0.02	0.0039	0.0006	0.0073	0.04
	ICPoint		1.00000	0.80	-0.08	-0.04	0.0089	0.0004	0.0080	0.57

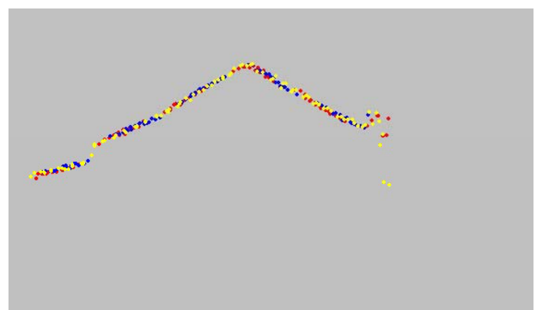
Consistency in the results coming from various methods

IQC: LiDAR Quality Control



Before Adjustment

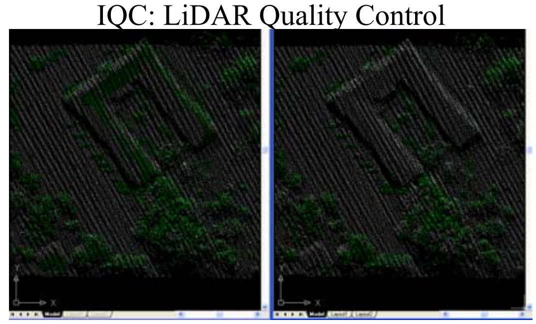
IQC: LiDAR Quality Control



After Adjustment

IQC: LiDAR Quality Control

IQC: LiDAR Quality Control

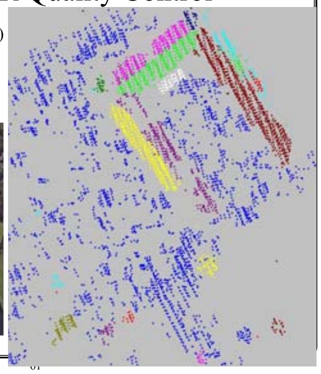


Before After

Points that belong to non-planar patches

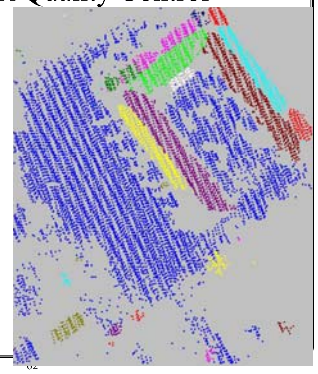
IQC: LiDAR Quality Control

Segmentation Results (Biased Data)



IQC: LiDAR Quality Control

Segmentation Results (Adj. Data)



IQC: LiDAR Quality Control

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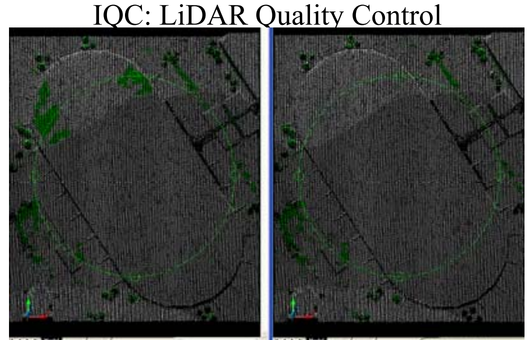
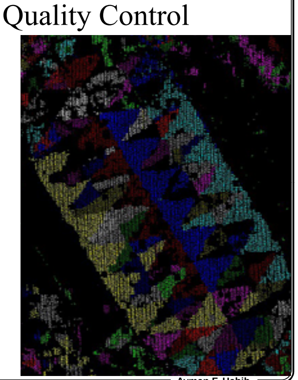


Before After

Points that belong to non-planar patches

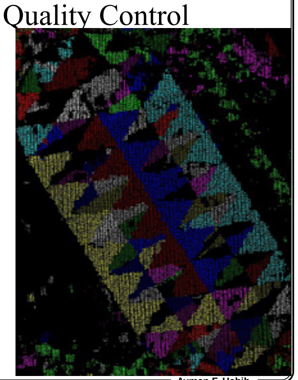
IQC: LiDAR Quality Control

Segmentation Results (Biased Data)



IQC: LiDAR Quality Control

Segmentation Results (Adj. Data)



IQC: LiDAR Quality Control

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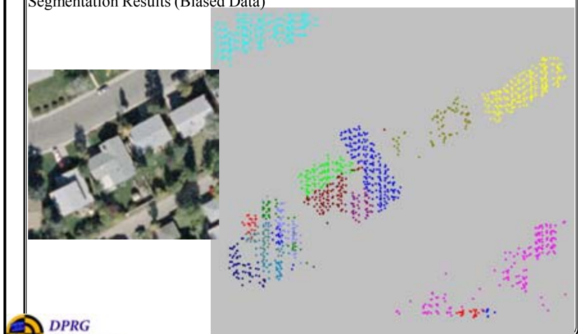
IQC: LiDAR Quality Control

Segmentation Results (Biased Data)



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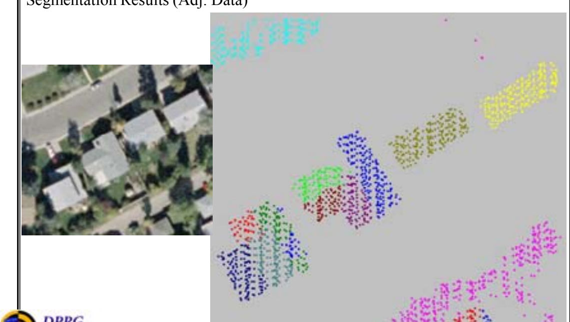
IQC: LiDAR Quality Control

Segmentation Results (Adj. Data)



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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 (ground truth).
- Approaches 2-4 will lead to more reliable estimation of the internal and external quality of the LiDAR data.
- The ICPatch approach is preferred since it is based on the original/raw LiDAR point cloud without the need for any preprocessing.

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

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Concluding Remarks

- QA and QC procedures are essential for any spatial data acquisition system.
- QA of LiDAR data 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.

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Concluding Remarks

- The derived quality control procedures takes into account the irregular and random nature of the LiDAR point cloud.
  - Different measures with varying degrees of reliability and complexity.
- Current work is focusing on:
  - Relating the derived discrepancies to systematic biases in the LiDAR system components.
  - Deriving methodologies for LiDAR calibration using control planar patches.
    - The control patches can be derived from photogrammetric data.

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