

Quality Assurance and Quality Control of LiDAR Systems and Derived Data

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Abstract

LiDAR systems have been widely adopted for the acquisition of dense and accurate topographic data over extended areas. Although the utilization of this technology has increased in different applications, the development of standard methodologies for the quality assurance of LiDAR systems and quality control of the derived data has not followed the same trend. In other words, a lack in reliable, practical, cost-effective, and commonly-acceptable methods for ensuring and evaluating the quality of the LiDAR data is evident. For example, LiDAR calibration is usually conducted through proprietary procedures, which depend on the system manufacturer as well as the expertise of the personnel in charge of the calibration procedure. On the other hand, a frequently adopted procedure for quality evaluation is the comparison of LiDAR data and ground control points. Besides being expensive, this approach is not accurate enough for the verification of the horizontal accuracy, unless specifically-designed targets are utilized. This document is dedicated to providing a discussion of existing techniques for ensuring and evaluating the quality of LiDAR data together with a future outlook. It should be noted that the emphasis of this document is quality assurance and quality control procedures, which would affect the positional accuracy of the point cloud coordinates. In other words, quality control of the LiDAR data processing (e.g., DTM generation and LiDAR data classification/segmentation techniques) is beyond the scope of this document.

1. Introduction

The direct acquisition of a high density and accurate 3D point cloud has made LiDAR systems the preferred technology for the collection of topographic data to satisfy the needs of several applications such environmental monitoring, contour mapping, transportation planning, emergency management, military simulation, ortho-rectification, oil and gas exploration, mining, hydrology, shoreline management, 3D city modeling, and forest mapping. A LiDAR system consists of a laser ranging and scanning unit together with a Position and Orientation System (POS), which encompasses an integrated Global Navigation Satellite System (GNSS) and an Inertial Navigation System (INS). The laser ranging unit measures the distances from the sensor to the mapped surface while the onboard GNSS/INS component provides the position and orientation of the platform. The laser scanner measurements, the position and orientation information, and the mounting parameters (i.e., the parameters describing the spatial and rotational offsets between the system

components) are integrated in the LiDAR equation to provide the ground coordinates of the point cloud. The mounting parameters are determined through a calibration procedure.

As for any spatial data acquisition, activities aiming at ensuring and evaluating the quality of the derived data are essential for LiDAR systems. In this document, the term “Quality Assurance – QA” is used to denote pre-mission activities focusing on ensuring that a process will provide the quality needed by the user. On the other hand, the term “Quality Control – QC” is used to denote post-mission procedures for evaluating the quality of the final product. QA mainly deals with creating management controls including the calibration, planning, implementation, and review of data collection activities. An example of a LiDAR QA activity is gaining prior knowledge of the area to be surveyed in terms of its extent and terrain coverage (e.g., vegetation and buildings) in order to set up the appropriate flight specifications. In forested areas, a slower speed, smaller scan angle, higher overlap percentage, and/or lower flying height might be necessary to increase the point density and to have more pulses penetrating to the ground. Also, the selection of the appropriate mission time according to the GNSS satellite constellation distribution is another important QA item. For example, a typical requirement is to have at least 4 well-distributed satellites with elevation angles above 15° throughout the survey. Moreover, it is recommended that the aircraft should stay within a given distance from the GNSS base station. As for the LiDAR system calibration, one should have access to the original observations (GNSS, IMU, and the laser measurements) or at least the trajectory and time-tagged point cloud (Burman, 2000; Filin, 2001; Morin, 2002; Toth, 2002; Friess, 2006; Skaloud and Lichti, 2006). Such quantities might not be always available to the end user. Therefore, as far as the user is concerned, the acquisition system is a black-box. Such a nature is leaving the users with quality control procedures as the only means for assessing the LiDAR system performance. Consequently, the LiDAR community is in great need for practical and effective tools to evaluate the quality of the delivered point cloud.

To illustrate what is meant by QC activities, one can refer to the well-established photogrammetric procedures for the evaluation of the internal/relative and the external/absolute accuracy of the final product. For the evaluation of the internal/relative quality (IQC) of the outcome from a photogrammetric reconstruction exercise, we typically use the a-posteriori variance factor and the variance-covariance matrix resulting from the bundle adjustment procedure. As for the external/absolute quality (EQC) evaluation, checkpoint analysis using independently measured targets is usually performed. Since the computation of the LiDAR point cloud is not based on redundant measurements, which are manipulated in an adjustment procedure, standard photogrammetric IQC measures are not possible. Moreover, the irregular and sparse nature of the LiDAR point cloud makes the EQC process more challenging. A commonly used EQC procedure compares the LiDAR surface with independently collected control points (Hodgson and Bresnahan, 2004; Wotruba et al., 2005). Besides being expensive, this procedure does not provide accurate

verification of the horizontal quality of the LiDAR points, unless specifically designed targets are utilized (Csanyi and Toth, 2007). Such inability is a major drawback since the horizontal accuracy of the LiDAR points is known to be inferior to the accuracy of these points in the vertical direction.

“Strip Adjustment – SA” is another quality control activity for detecting and mitigating the impact of systematic discrepancies among overlapping LiDAR strips. Therefore, the strip adjustment goes beyond the quality control in the sense that it is designed to not only detect but also reduce or eliminate the effect of biases in the system parameters and/or measurements on the point cloud by improving the compatibility among overlapping LiDAR strips. In the past few years, several strip adjustment methods have been developed (Kilian et al., 1996; Crombaghs et al., 2000; Maas, 2002; Bretar et al., 2004; Vosselman, 2004; Filin and Vosselman, 2004; Kager, 2004; Pfeifer et al., 2005). In Crombaghs et al. (2000), a method for reducing vertical discrepancies between overlapping strips is proposed. This approach does not deal with planimetric discrepancies, which might have larger magnitude when compared with vertical discrepancies. In Kilian et al. (1996), an adjustment procedure similar to the photogrammetric strip adjustment was introduced for detecting discrepancies and improving the compatibility between overlapping strips. The drawback of this approach is relying on distinct points to relate overlapping LiDAR strips and control surfaces. Due to the irregular nature of the LiDAR points, the identification of distinct points (e.g., building corners) is quite difficult and not reliable. More suitable primitives have been suggested by Kager (2004), where planar features are used in the strip adjustment procedure. Maas (2002) proposed a least-squares matching procedure to derive the correspondence between discrete points in one LiDAR strip and TIN patches in the other one. This work focused on detecting the discrepancies between conjugate surface elements rather than improving the compatibility between neighboring strips. Pfeifer et al. (2005) utilized segmented planar patches while Vosselman (2004) used linear features to improve the compatibility between overlapping LiDAR strips. Bretar et al., (2004) proposed an alternative methodology for improving the quality of LiDAR data using derived surfaces from photogrammetric procedures. The main disadvantage, which limits the practicality of this methodology, is relying on having aerial imagery over the same area. Filin and Vosselman (2004) proposed a strip adjustment procedure where natural surfaces, which are locally approximated by planes, are used to estimate the 3D offsets between LiDAR strips. Generally speaking, the main limitation of strip adjustment procedures is that the utilized transformation functions to improve the compatibility of overlapping strips are mostly empirical. Moreover, the strip adjustment process does not take advantage of the estimated transformation parameters to infer what went wrong in the data acquisition system (i.e., what caused the identified discrepancies?).

The development of effective QA/QC procedures for LiDAR systems and derived data should be based on a clear understanding of the sensor model. More specifically, the user community should have a good handle of

how the system measurements and parameters are integrated to derive the ground coordinates of the point cloud. In addition, we need to recognize the impact of systematic and random errors in the system parameters and measurements on the point cloud coordinates. Having developed a clear understanding of these issues, one can decide on:

1. Which parameters should be considered in the calibration process? Such parameters should be based on the systematic errors that could be present in a LiDAR system as well as the possibility of estimating these parameters in the calibration procedure (i.e., whether these parameters are correlated or not). Highly correlated parameters can be combined in a single parameter.
2. What are the possible scenarios for system calibration? For example, models utilizing the system raw measurements, time-tagged point cloud coordinates and the system trajectory, or just the point cloud coordinates for the system calibration should be investigated and/or developed.
3. What is the appropriate flight configuration for an accurate system calibration? Based on the analysis of the calibration parameters, we need to establish the appropriate flight configuration (e.g., flight pattern, flight height, overlap percentage, scan angle, etc.). The flight configuration should ensure the decoupling of the calibration parameters.
4. What is the appropriate control for the system calibration process? Traditionally, control points are being used for the calibration of mapping systems (e.g., photogrammetric systems). For LiDAR systems, this control is not appropriate. Therefore, other control information such as specifically-designed LiDAR control targets, control planar patches, and or control surfaces should be investigated.
5. What are the appropriate quality control procedures? Effective, practical, and economical quality control procedures should be developed to evaluate and quantify systematic discrepancies and noise level in the acquired data. These techniques should be simple such that they can be carried out by the end user for any LiDAR mission.

To shed some light on these issues, the rest of this document will deal with the LiDAR mathematical model, possible systematic and random errors and their impact on the point cloud, and some discussion of existing calibration and quality control procedures as well as a future outlook.

2. LiDAR Mathematical Model

The coordinates of the LiDAR points are the result of combining the derived measurements from each of its system components, as well as the mounting parameters relating such components. The relationship between the system measurements and parameters is embodied in the LiDAR equation (Vaughn et al., 1996; Schenk, 2001; El-Sheimy et al., 2005), Equation 1. As it can be seen in Figure 1, the position of the LiDAR point,

\vec{X}_G , can be derived through the summation of three vectors (\vec{X}_o , \vec{P}_G , and $\vec{\rho}$) after applying the appropriate rotations: $R_{yaw, pitch, roll}$, $R_{\Delta\omega, \Delta\phi, \Delta\kappa}$, and $R_{\alpha, \beta}$. In this equation, \vec{X}_o is the vector between the origins of the ground and the Inertial Measurement Unit (IMU) coordinate systems, \vec{P}_G is the offset between the laser unit and IMU coordinate systems (lever-arm offset), and $\vec{\rho}$ is the laser range vector whose magnitude is equivalent to the distance from the laser firing point to its footprint. The term $R_{yaw, pitch, roll}$ stands for the rotation matrix relating the ground and IMU coordinate systems, $R_{\Delta\omega, \Delta\phi, \Delta\kappa}$ represents the rotation matrix relating the IMU and laser unit coordinate systems (which is defined by the bore-sighting angles), and $R_{\alpha, \beta}$ refers to the rotation matrix relating the laser unit and laser beam coordinate systems with α and β being the mirror scan angles. For a linear scanner, the mirror is rotated in one direction only (i.e., α is equal to zero). The involved quantities in the LiDAR equation are all measured during the acquisition process except for the lever-arm components and bore-sighting angles (collectively known as the mounting parameters), which are usually determined through a calibration procedure.

$$\vec{X}_G = \vec{X}_o + R_{yaw, pitch, roll} \vec{P}_G + R_{yaw, pitch, roll} R_{\Delta\omega, \Delta\phi, \Delta\kappa} R_{\alpha, \beta} \begin{bmatrix} 0 \\ 0 \\ -\rho \end{bmatrix} \quad (1)$$

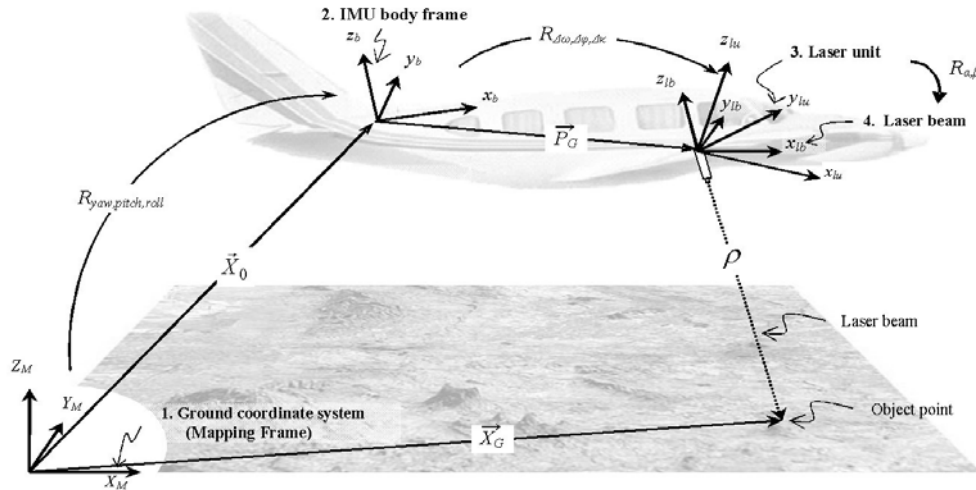


Figure 1. Coordinate systems and involved quantities in the LiDAR equation

3. LiDAR Error Budget

The quality of the derived point cloud from a LiDAR system depends on the random and systematic errors in the system measurements and parameters. A detailed description of LiDAR random and systematic errors can be found in Huising and Pereira (1998), Baltsavias (1999), Schenk (2001), Latypov (2002), and Glennie (2007). The magnitude of the random errors depends on the precision of the system's measurements, which include position and orientation measurements from the GNSS/IMU, mirror angles, and ranges. Systematic errors, on the other hand, are mainly caused by biases in the mounting parameters relating the system components as well as biases in the system measurements (e.g., ranges, mirror angles, and drifts in the position and orientation information). In the following sub-sections, the impact of random and systematic errors in the system measurements and parameters on the reconstructed object space will be analyzed.

Random Errors

The purpose of studying the impact of random errors is to provide sufficient understanding of the nature of the noise in the derived point cloud as well as the achievable precision from a given flight and system configuration. In this document, the effect of random errors in the system measurements is analyzed through a simulation process starting from a given surface and trajectory, which are then used to derive the system measurements (i.e., ranges, mirror angles, position and orientation information for each pulse). Then, noise is added to the system measurements, which are later used to reconstruct the surface through the LiDAR equation. The differences between the noise-contaminated and the true coordinates of the LiDAR points are used to represent the impact of the introduced. The following list summarizes the impact of noise in the system measurements assuming a LiDAR system with moderate flight dynamics.

- Position noise will lead to similar noise in the derived point cloud. The resulting noise in the point cloud coordinates is independent of the flying height and scan angle.
- For reasonable values of the scan angle β (e.g., within the range $\pm 25^\circ$), orientation noise (attitude or mirror angles) will affect the horizontal coordinates more than the vertical coordinates. In addition, the effect is dependent on the flying height and scan angle.
- For reasonable values of the scan angle β (e.g., within the range $\pm 25^\circ$), range noise mainly affects the vertical component of the derived coordinates. The effect is independent of the flying height. The impact, however, is dependent on the scan angle.

As it can be seen in the previous list, noise in some of the system measurements affects the relative precision of the derived point cloud. For instance, noise in the GNSS/INS derived orientation affects the nadir region

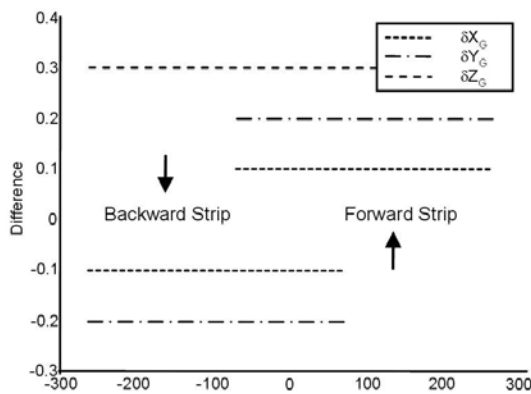
of the flight trajectory less significantly than off nadir regions. Such a phenomenon is contrary to derived surfaces from photogrammetric mapping where the measurements noise does not affect the relative precision of the final product.

Systematic Errors

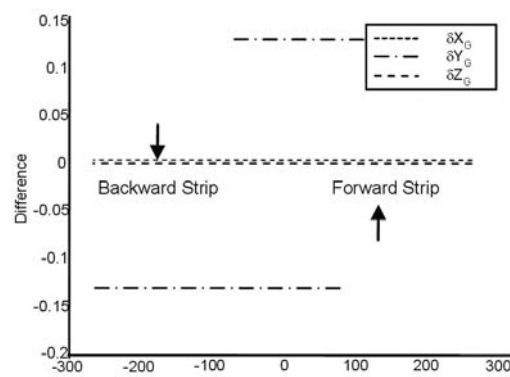
Systematic errors might be caused by biases in the mounting parameters relating the system components as well as biases in the system measurements. Biases in the system measurements include systematic errors in the laser scanner (e.g., biases in the range and mirror angle measurements) and systematic errors in the derived GNSS/INS position and orientation (e.g., differential troposphere and ionosphere, multi-path, INS initialization and misalignment errors, and gyro drifts). In this document, biases in the mounting parameters as well as biases in the range and mirror angle measurements are singled out due to the fact that their impact does not come with prior warning signs regarding the potential of having discrepancies among overlapping strips. Although position and orientation drifts might have a more significant impact, these errors and their impact do not come as a surprise if the quality of the GNSS/INS integration process is carefully examined (e.g., through the forward and backward processing of the individual flight lines). Moreover, the position and orientation drifts cannot be considered in the calibration process since their magnitude and impact change from one mission to another. Therefore, in this document we will focus on the analysis of the impact of biases in the system mounting parameters as well as biases in the range and mirror-angle measurements on the derived point cloud. In order to study the impact of such biases, a simulation process is performed. The process starts with a given simulated surface and trajectory, which are then used to derive the system measurements (i.e., ranges, mirror angles, position and orientation information for each pulse). Then, biases are added to the system parameters and measurements, which are used to reconstruct the surface through the LiDAR equation. The differences between the bias-contaminated and true coordinates of the LiDAR points are used to represent the impact of the bias in question. The differences along a profile across the flight direction for two parallel strips, which are flown in opposite directions, after the introduction of biases in the lever-arm offset components, bore-sighting pitch, bore-sighting roll, bore-sighting yaw, range measurements, and mirror-angle scale are shown in Figures 2a, 2b, 2c, 2d, 2e and 2f, respectively. A summary of the impact of the investigated biases for a LiDAR system with moderate flight dynamics as they relate to the flying direction, flying height, and scan angle is given below:

- Lever-arm offset bias: biases in the lever-arm offsets will lead to constant shifts in the derived point cloud. The planimetric shifts are dependent on the flying direction. The shift in the Z-direction, on the other hand, is independent of the flying direction. The planimetric and vertical shifts are independent of the flying height and scan angle.

- Bore-sighting pitch bias: bore-sighting pitch bias will cause a constant shift along the flight direction, which is dependent on the flying direction and flying height and independent of the scan angle.
- Bore-sighting roll bias: bore-sighting roll bias will cause a constant shift across the flight direction and a shift in the Z direction with its magnitude varying linearly across the flying direction. Both effects are dependent on the flying direction. The planimetric effect across the flight is dependent on the flying height and independent of the scan angle. The vertical effect, on the other hand, is dependent on the scan angle and independent of the flying height.
- Bore-sighting yaw bias: this bias will only cause a shift along the flying direction with its magnitude varying linearly across the flight direction. This effect is independent of the flying height and direction while being dependent on the scan angle.
- Range bias: For reasonable values of the scan angle β (e.g., within the range $\pm 25^\circ$), the ranging bias will cause a planimetric shift across the flying direction, whose magnitude varies almost linearly. At the same time, the range bias will cause an almost constant vertical shift. Both effects are independent of the flying height and direction.
- Mirror angle scale bias: For reasonable values of the scan angles β (e.g., within the range $\pm 25^\circ$), the mirror angle scale bias will cause a planimetric shift across the flying direction, whose magnitude varies linearly. At the same time, it causes a vertical shift, whose magnitude varies non-linearly across the flying direction. Both effects are dependent on the flying height and independent of the flying direction.



(a)



(b)

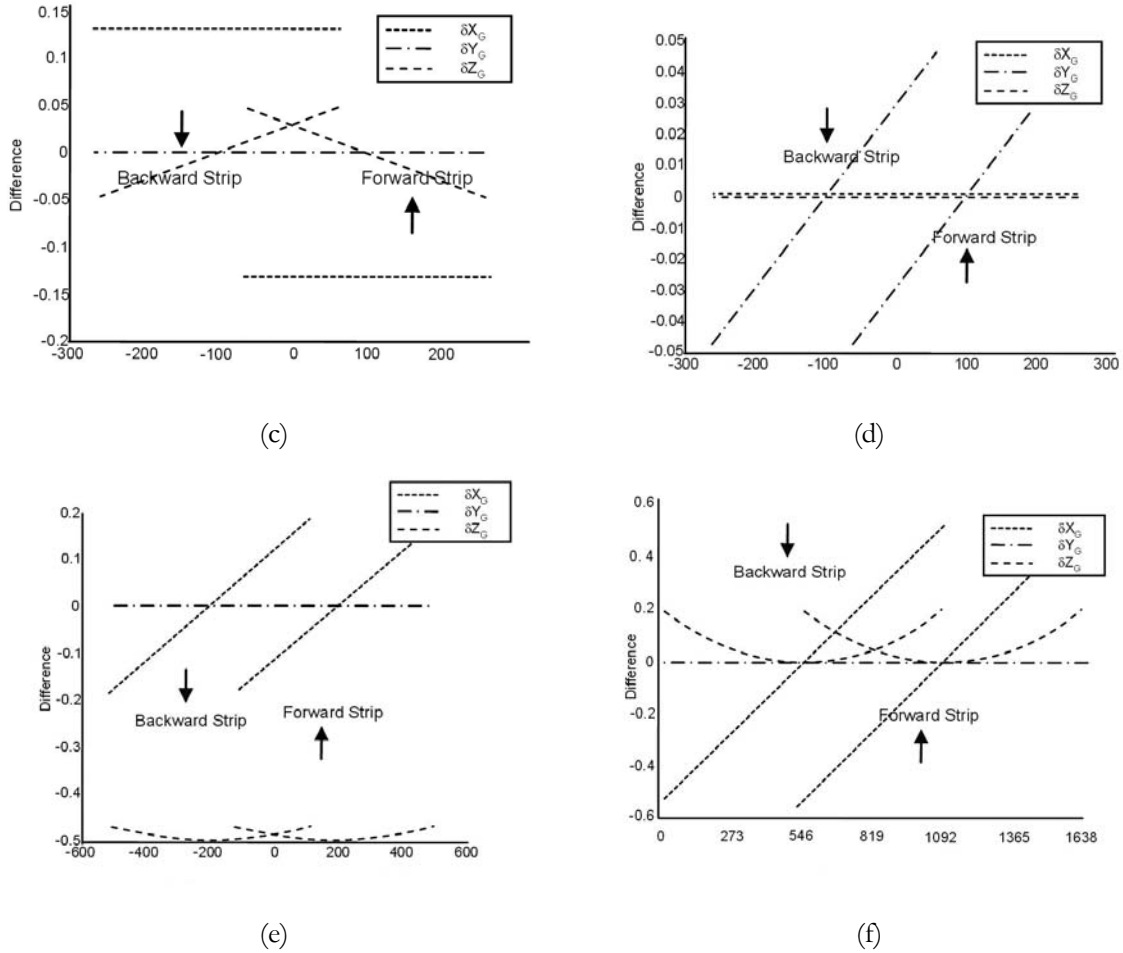


Figure 2. Differences between the bias-contaminated and true locations of the LiDAR point for two overlapping parallel strips, which are flown in opposite directions, after the introduction of lever-arm offset biases (a), bore-sighting pitch bias (b), bore-sighting roll bias (c), bore-sighting yaw bias (d), range bias (e), and mirror angle scale bias (f) [δX_G , δY_G , and δZ_G represent the differences in the across-flight, along-flight, and vertical directions, respectively]

4. LiDAR Calibration: Existing Procedures and Future Outlook

LiDAR data collection is usually carried out in a strip-wise fashion where the ground coordinates of the laser points are derived using the measured ranges and mirror angles together with the direct geo-referencing information furnished by the onboard GNSS/IMU. The bore-sighting angles and lever-arm offsets, which are known as the mounting parameters, between the system's components are also needed for the computation of the ground coordinates of the laser points. The mounting parameters together with other system parameters are derived through a calibration process, which is usually accomplished in several steps: (i) Laboratory calibration, (ii) Platform calibration, and (iii) In-flight calibration. In the laboratory calibration,

which is conducted by the system manufacturer, the individual system components are calibrated. In addition, the eccentricity and misalignment between the laser mirror and the IMU as well as the eccentricity between the IMU and the sensor reference point are determined. In the platform calibration, the eccentricity between the sensor reference point and the GNSS antenna is determined. The in-flight calibration utilizes a calibration test field composed of control surfaces for the estimation of the LiDAR system parameters. The observed discrepancies between the LiDAR-derived and control surfaces are used to refine the mounting parameters and systematic errors in the system measurements (mirror angles and ranges). Current in-flight calibration methods have the following drawbacks: (i) They are time consuming and expensive; (ii) They are generally based on complicated and sequential calibration procedures; (iii) They require some effort for surveying the control surfaces; (iv) Some of the calibration methods involve manual and empirical procedures; (v) Some of the calibration methods require the availability of the LiDAR raw measurements such as ranges, mirror angles, as well as position and orientation information for each pulse (Filin, 2001; and Skaloud and Lichti, 2006); and (vi) There is no commonly accepted methodology since the calibration techniques are usually based on a manufacturer-provided software package and the expertise of the LiDAR data provider.

Schenk (2001) introduced the sources of systematic errors that might be present in a LiDAR system. A calibration procedure was then proposed using such an analysis. This work comprehensively explained possible errors in LiDAR systems, but it seems to be too complex for a practical calibration procedure. Furthermore, the introduced calibration parameters were not simultaneously solved for due to their correlations (e.g., biases in the scanner mirror angles and bore-sighting parameters). The method introduced by Morin (2002) solves for the bore-sighting angles and the scanner torsion. These parameters are either estimated using ground control points or by manually observing discrepancies between tie points in overlapping strips. The drawback of this approach is that the identification of distinct control and tie points in LiDAR data is a difficult task due to the irregular nature of the collected point cloud. Skaloud and Lichti (2006) presented a calibration technique using tie planar patches in overlapping strips. The underlying assumption of this procedure is that systematic errors in the LiDAR system will lead to non-coplanarity of conjugate planar patches as well as bending effects in these patches. The calibration method uses the LiDAR equation to simultaneously solve for the plane parameters as well as the bore-sighting angles and the bias in the laser ranges. However, this approach requires relatively large planar patches, which might not always be available. Habib et al. (2007a, 2007b) used planar patches derived from photogrammetric data for the LiDAR system calibration, where the photogrammetric bundle adjustment was augmented by adding the LiDAR equation. In this research, the LiDAR mounting parameters are determined by minimizing the normal distances between the LiDAR points and the photogrammetric areal patches. In addition to the estimation of the bore-sighting parameters, the proposed methodology also ensures the co-registration between the photogrammetric and LiDAR data to a common reference frame, which has a positive impact on later

products such as ortho-photos and photo-realistic 3D models. The drawbacks of this approach are the need for imagery captured over the same area as the LiDAR data. LiDAR data providers use control sites composed of well-known features such as building edges and flat surfaces in run-ways for the calibration process. Discrepancies between the LiDAR points and the control features are observed and used to determine the calibration parameters such as the bore-sighting roll and pitch angles together with a bias and scale factor in the laser ranges (Jung and Lee, 2006). The drawbacks of this calibration method are the need for control features and the reliance on manual and empirical procedures. Furthermore, the bore-sighting heading angle is not considered in this calibration procedure.

In spite of the prior literature dealing with LiDAR system calibration, there is still no standard and commonly-accepted calibration procedure. For example, the calibration parameters under consideration are not consistent throughout prior literature, Table 1. The parameters in this table represent the considered parameters in the error model and this does not necessarily mean that they can be accurately estimated in the calibration process. The lever-arm components are sometimes ignored, while the bore-sighting angles are considered by most authors. In addition, the bias and scale factor in the ranges and mirror angles are rarely considered.

Table 1. LiDAR systematic errors considered in the previous research

Proposed by	Considered systematic errors									
	$\triangle\omega$	$\triangle\varphi$	$\triangle\phi$	$\triangle X$	$\triangle Y$	$\triangle Z$	$\triangle\rho$	S_ρ	$\triangle\theta$	S_θ
Baltavista, 1999	•	•	•	•	•	•	•		•	
Morin, 2000	•	•	•							•
Shenk, 2001	•	•	•	•	•	•	•	•	•	•
Skaloud/Lichti, 2006	•	•	•				•			
Jung/Lee, 2006	•	•				•		•		
Filin, 2006	•	•	•				•			
Habib et al., 2007a/b	•	•	•	•	•	•				

$\triangle\omega$, $\triangle\varphi$, and $\triangle\phi$ are bore-sighting angular offsets,

$\triangle X$, $\triangle Y$, and $\triangle Z$ are lever-arm components,

$\triangle\rho$ and S_ρ are bias and scale factors of laser ranges, and

$\triangle\theta$ and S_θ are bias and scale factors of mirror angles of a laser scanner.

The LiDAR community should still continue with more research to develop commonly-accepted calibration procedures, while considering the following:

1. The research should define the necessary parameters (i.e., error sources) that should be included in a calibration procedure. The possibility of estimating these parameters without correlation problems should be also investigated.
2. The calibration procedures should be capable of dealing with LiDAR data in the absence of the raw measurements and/or control information.
3. The research should establish the appropriate features that need to be identified in overlapping trips and/or control surfaces. Practical considerations should be investigated when establishing such features (e.g., the possibility of identifying these features in any type of terrain coverage).
4. The appropriate mathematical constraints that can incorporate the system parameters and the established features in the calibration process.
5. Standard procedures and/or measures should be developed to evaluate the quality of the estimated system parameters.

5. Proposed Strategy for Quality Control of LiDAR Data

The user community is in great need for standard measures to evaluate the quality of the positional accuracy of the LiDAR points. These measures should be capable of evaluating the relative and absolute quality of the points (i.e., IQC and EQC). A potential IQC procedure can be based on evaluating the degree of consistency among the LiDAR points in overlapping strips, Figure 3. The conceptual basis of such a procedure is that conjugate surface elements in overlapping strips should perfectly match in the absence of random and systematic errors. If consistent discrepancies are detected, then one can infer the presence of biases in the system parameters and/or measurements, Figure 4a. Moreover, one can evaluate the noise level in the data by quantifying the goodness of fit between conjugate surface elements after removing systematic discrepancies, Figure 4b. To reliably evaluate the consistency between overlapping strips, one must address the following questions:

- What is the appropriate transformation function relating conjugate features in overlapping strips in the presence of systematic errors in the data acquisition system?
- What are the appropriate primitives, which can be used to identify conjugate surface elements in overlapping strips comprised of irregular sets of non-conjugate points in any type of terrain coverage?
- What is the procedure for automated/semi-automated derivation of the involved features/primitives?
- What is the procedure for automated identification of conjugate primitives in overlapping strips?
- What is the appropriate similarity measure, which utilizes the involved primitives and the defined transformation function to describe the correspondence of conjugate primitives in overlapping strips?

The same IQC measures can be extended to evaluate the EQC of the LiDAR points. Instead of comparing conjugate surface elements in overlapping strips, one can utilize these measures to compare the LiDAR data to control surfaces.

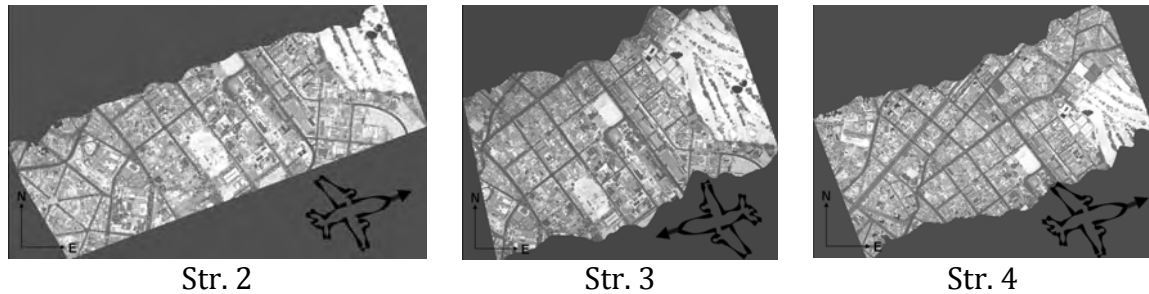


Figure 3: Three overlapping strips, which can be used evaluate the internal quality of LiDAR data

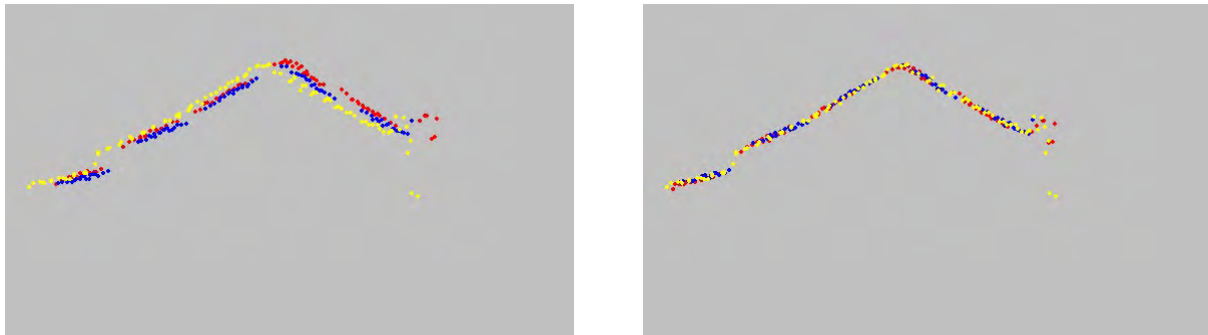


Figure 4: Roof profile in three overlapping strips indicates the presence of systematic biases in the data acquisition system (a) while the quality of fit between conjugate surface elements after bias removal to quantify the noise level in the point cloud (b)

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