CANADIAN AND U.S. COOPERATION FOR THE DEVELOPMENT OF STANDARDS AND SPECIFICATIONS FOR EMERGING MAPPING TECHNOLOGIES

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ABSTRACT

The mapping community is witnessing significant advances in available sensors, such as medium format digital cameras (MFDC) and Light Detection and Ranging (LiDAR) systems. In this regard, the Digital Photogrammetry Research Group (DPRG) of the Department of Geomatics Engineering at the University of Calgary has been actively involved in the development of standards and specifications for regulating the use of these sensors in mapping activities. More specifically, the DPRG has been working on developing new techniques for the calibration and stability analysis of medium format digital cameras. This research is essential since these sensors have not been developed with mapping applications in mind. Therefore, prior to their use in Geomatics activies, new standards should be developed to ensure the quality of the developed products. In another front, the persistent improvement in direct geo-referencing technology has led to an expansion in the use of LiDAR systems for the acquisition of dense and accurate surface information. However, the processing of the raw LiDAR data (e.g., ranges, mirror angles, and navigation data) remains a non-transparent process that is proprietary to the manufacturers of LiDAR systems. Therefore, the DPRG has been focusing on the development of quality control procedures to quantify the accuracy of LiDAR output in the absence of initial system measurements. This paper presents a summary of the research conducted by the DPRG together with the British Columbia Base Mapping and Geomatic Services (BMGS) and the United States Geological Survey (USGS) for the development of quality assurance and quality control procedures for emerging mapping technologies. The outcome of this research will allow for the possiblity of introducing North American Standards and Specifications to regulate the use of MFDC and LiDAR systems in the mapping industry.

INTRODUCTION

Significant advances in mapping technologies have led to the recent expansion in mapping applications, in addition to an increase in the variety of users. With the emergence of new developments in mapping technologies, including MFDC and LiDAR systems, some challenges have also become apparent. Some of these challenges are in the areas of quality assurance and quality control of the mapping products. Quality assurance involves management activities performed before data collection to ensure that the end product is of the quality required by the user, while quality control involves routines and consistent checks that are done to ensure data integrity, correctness and completeness. One of the key activities in quality assurance is the calibration procedure. Before the advent of digital cameras, analog cameras alone were used for mapping purposes. Since analog cameras all have similar system designs, the same basic procedure and facilities could be used to calibrate metric mapping cameras used in photogrammetric projects. The calibration process for these cameras was performed by a regulating body (such as

Natural Resources Canada (NRCan) or the USGS), through which trained professionals ensured that high quality calibration was upheld. There is, however, a wide variety of digital camera designs, including small/large format, to single/multi-head, and frame/line cameras. It has therefore become more practical for camera manufacturers and/or users to perform their own calibration when dealing with digital cameras. In essence, the burden of the camera calibration has been shifted into the hands of the airborne data providers. There has come an obvious need for the development of standards and procedures for simple and effective digital camera calibration. The USGS and the BMGS have been working with the DPRG at the University of Calgary to develop standards and procedures for digital camera calibration and stability assessment that can be adopted by the mapping industry, in order to regulate and ensure consistent quality assurance when using MFDC for mapping purposes. In addition to conducting a high quality camera calibration, other quality assurance factors for MFDC involve the appropriate selection of the percentage of image overlap and sidelap, the number and distribution of ground control points, and the georeferencing method used. For further information regarding the selection of these factors that affect MFDC quality assurance, interested readers can refer to Habib et al. (2007c).

In addition to performing high quality camera calibration, the data provider and/or user must also ensure that the camera selected for their project is structurally stable, in that the product quality of the system does not deteriorate over time. The accuracy of the derived positional information depends on the quality of the internal camera characteristics, specifically, the Interior Orientation Parameters (IOP) of the utilized camera(s). If a camera is stable, the object space derived by the set of IOP at one epoch should be equivalent to that derived by the set of IOP from a second epoch. If this can be proven for a particular camera, that camera can then be considered stable, and thus acceptable for use in mapping applications. Through practical experience with analog mapping cameras, these cameras have been proven to possess a strong structural relationship between the elements of the lens system and the focal plane, and thus possess stable internal camera characteristics. However, there has not yet been a comprehensive study done to investigate the stability of the internal characteristics of digital cameras, specifically MFDC, for photogrammetric applications. This void in the literature can be attributed to the absence of standards for the quantitative analysis of camera stability. This paper will address this issue, and some preliminary standards for stability will be outlined.

A pre-requisite for quality assurance is transparency, in that all data collected by the system, as well as any editing performed on the raw data, must be accessible and visible to the end user. This, however, is not the case when using a LiDAR system. LiDAR is seen as a black box, in which the raw data (such as mirror rotation angles, bore-sighting parameters, ranges, navigation data, etc.) is not visible to the end user. Instead, usually only the XYZ coordinates and intensity values of each footprint are delivered to the customer. There are several reasons for this, whether it be that some companies decide to withhold proprietary information or simply the fact that LiDAR raw data is currently so immense that no average user would desire such information. Regardless of the reason, the fact that LiDAR is currently a “black box” system makes LiDAR quality assurance a challenge. According to several mapping companies, the system calibration performed by the manufacturer must sometimes be repeated, when biases are found to be present in the output data. Other quality assurance activities that can be performed when using LiDAR systems for data collection include selecting an appropriate length for the GPS baseline, a suitable time for the mapping mission according to GPS satellite availability and distribution, and appropriate overlap percentages between strips.

In addition to the new challenges in performing quality assurance, the quality control of these new technologies has also created some new issues that must be addressed. Although photogrammetric data affords several means of performing quality control by assessing the results from a photogrammetric triangulation (variance component, variance-covariance matrix of the derived object coordinates, check point analysis, etc.), the LiDAR system poses more issues that must be addressed. Unlike photogrammetric techniques, footprints derived from a LiDAR system are not based on redundant measurements, which are manipulated in an adjustment procedure. Consequently, we do not have the associated measures to use to evaluate the quality of LiDAR data. Although some methods of LiDAR quality control do exist, the majority only assess the vertical accuracy, which is insufficient since it is the horizontal accuracy that is most affected when using a LiDAR-derived point cloud. This paper introduces a procedure that could be adopted by the mapping community in order to sufficiently evaluate the quality of LiDAR data.

In response to the above issues that have arisen due to advances in mapping technologies, this paper will address these concerns in the following order. Section 2 will outline the requirements for a successful MFDC calibration procedure and stability analysis. Section 3 will summarize some standards and specifications for calibration and stability analysis, as compiled through joint efforts with the USGS and BMGS. In Section 4, LiDAR calibration is explained and a new method of LiDAR quality control is outlined in detail. Section 5 of this paper displays some results for the implemented quality control method, and Section 6 makes some conclusions and future recommendations.

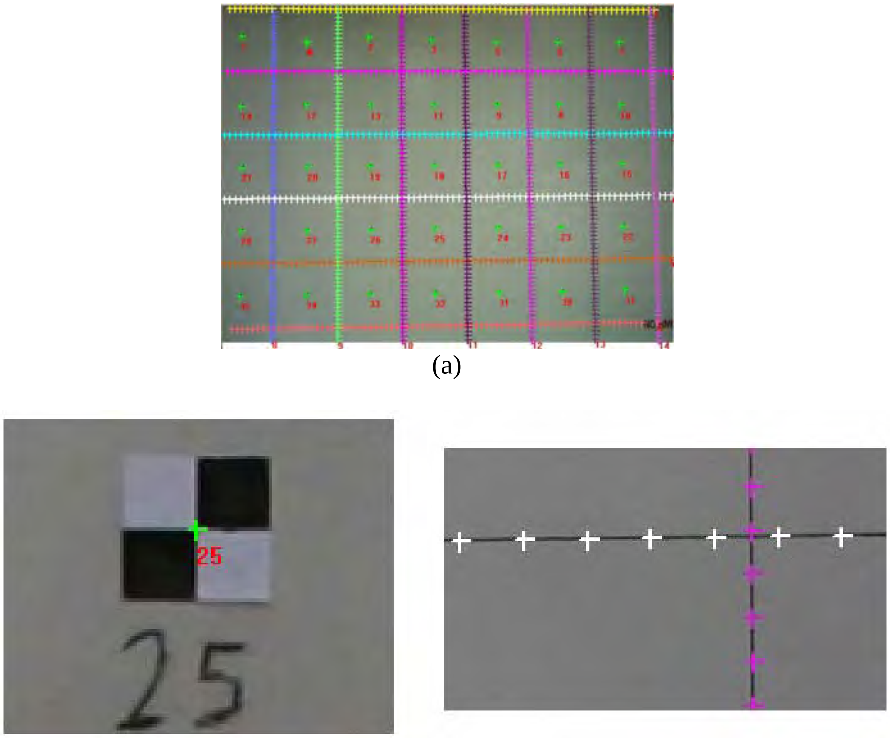
CAMERA CALIBRATION AND STABILITY ANALYSIS

Camera calibration and stability analysis are crucial activities that are involved in the quality assurance procedures when using MFDC for mapping projects. The following subsections outline the importance of these activities and give suggested approaches that can be carried out by the user of these systems.

MFDC Calibration

Deriving accurate 3D measurements from imagery is contingent on precise knowledge of the internal camera characteristics. These characteristics, which are usually known as the interior orientation parameters (IOP), are derived through the process of camera calibration, in which the coordinates of the principal point, camera constant and distortion parameters are determined. The calibration process is well defined for traditional analog cameras, but the case of digital cameras is much more complex. Due to the various designs of digital cameras, it has become more practical for the calibration procedure to be conducted by the camera manufacturers and/or users. As such, the burden of the camera calibration has been shifted into the hands of the airborne data providers. There has thus come an obvious need for the development of standards and procedures for simple and effective digital camera calibration.

Control information is required such that the IOP may be estimated through a bundle adjustment procedure. This control information is often in the form of specially marked ground targets, whose positions have been precisely determined through surveying techniques. Establishing and maintaining this form of test field can be quite costly, which might limit the potential users of these cameras. The need for more low cost and efficient calibration techniques was addressed by Habib and Morgan (2003), in which the use of linear features in camera calibration was proposed as a promising alternative. Their approach incorporated the knowledge that in the absence of distortion, object space lines are imaged as straight lines in the image space. Since then, other studies have been done by the Digital Photogrammetry Research Group (DPRG) at the University of Calgary, in collaboration with the British Columbia Base Mapping and Geomatic Services (BMGS) and the United States Geological Survey (USGS), to confirm that the use and inclusion of line features in calibration can yield comparable results to those obtained using traditional point features. Figure 1a shows the suggested calibration test field, and Figures 1b and 1c show examples of point and line targets.



(a)

(b)

(c)

Figure 1. a) Suggested calibration test field with automatically extracted point and linear features, b) Point feature, and c) Line features.

To simplify the often lengthy procedure of manual image coordinate measurement, an automated procedure is introduced for the extraction of point targets and line features. The steps involved in the procedure are described in detail in Habib et al. (2006b) and are briefly outlined in the following strategy:

Acquired colour imagery is reduced to intensity images, and these intensity images are then binarized. A template of the target is constructed, and the defined template is used to compute a correlation image to indicate the most probable locations of the targets on the binary image. The correlation image maps the correlation values (0 to ±1) to gray values (0 to 255). Peaks in the correlation image are automatically identified and are interpreted to be at the locations of signalized targets (Figure 1b).

The extraction of linear features, on the other hand, proceeds according to the following strategy:

Acquired imagery is resampled to reduce its size, and then an edge detection operator is applied. Straight lines are identified using the Hough transform (Hough, 1962), and the line end points are extracted. These endpoints are then used to define a search space for the intermediate points along the lines (Figure 1c).

In camera calibration, the purpose is to determine the internal characteristics of the involved camera, which consist of the coordinates of the principal point, the principal distance, and the image coordinate corrections that compensate for various deviations from the collinearity model (e.g., the lens distortion). In order to include straight lines in the bundle adjustment procedure, two main issues must be addressed. The first is to determine the most convenient model for representing straight lines in the object and image space, and the second is to determine how the perspective relationship between corresponding image and object space lines is to be established. In Habib et al. (2007c*)*, two points were used to represent the object space straight line. These end points are measured in one or two images in which the line appears, and the relationship between the image points and the corresponding object space points is modeled by the collinearity equations. In addition to the use of the line endpoints, intermediate points are measured along the image lines, enabling continuous modeling of distortion along the linear feature. The incorporation of the intermediate points into the adjustment procedure is done via a mathematical constraint (Habib et al., 2006b). It should be noted, however, that in order to determine the principal distance and the perspective center coordinates of the utilized camera, distances between some point targets must be measured and used as additional constraints in the bundle adjustment procedure.

Stability Analysis

It is well known that professional analog cameras, which have been designed specifically for photogrammetric purposes, possess strong structural relationships between the focal plane and the elements of the lens system. Medium format digital cameras, however, are not manufactured specifically for the purpose of photogrammetric reconstruction, and thus have not been built to be as stable as traditional mapping cameras. Their stability therefore requires thorough analysis. If a camera is stable, then the derived IOP should not vary over time. In the work done by Habib et al. (2006a), three different approaches to assessing camera stability are outlined; in this paper, two sets of IOP of the same camera that have been derived from different calibration sessions are compared, and their equivalence assessed. The similarity between the two bundles is then determined by computing the Root Mean Square Error (RMSE) of the offsets between conjugate light rays from the two bundles, along the image plane. If the RMSE is within the range defined by the expected standard deviation of the image coordinate measurements, then the camera is considered stable. In their research, different constraints were imposed on the position and orientation of reconstructed bundles of light, depending on the georeferencing technique being used. The hypothesis is that the object spaces that are reconstructed by two sets of IOP will be equivalent if the two sets of IOP are similar. For detailed descriptions of these methods, see Habib et al. (2006a). Figure 2 shows the concept behind stability analysis, in which we derive a quantitative measure to describe the degree of similarity between the two bundles derived from two IOP sets.

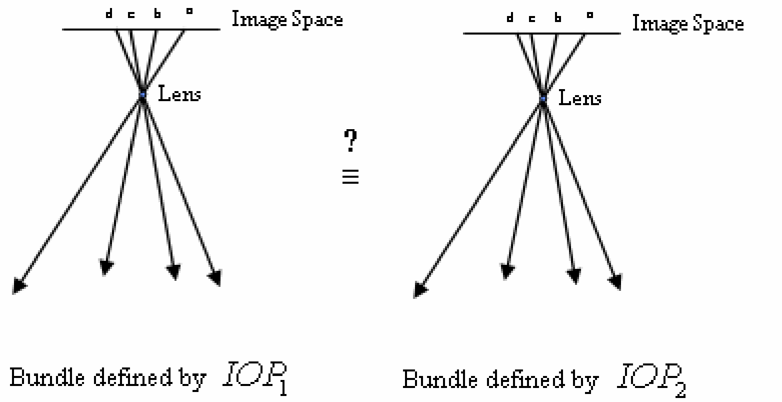


Figure 2. Concept behind stability analysis.

STANDARDS AND SPECIFICATIONS

In Section 2.1 of the paper, the need for clear and concise standards for camera calibration was explained. That is, due to the variety in the types of digital imaging systems available, it is no longer feasible to have permanent calibration facilities run by a regulating body to perform calibration. The calibration process is now in the hands of the data providers, and thus the need for the development of standards and procedures for simple and effective digital camera calibration has emerged. In Section 2.2, it was acknowledged that digital imaging systems have not been created for the purpose of photogrammetric mapping, and therefore, that their stability over time must also be investigated. These have been the observations of many governing bodies and map providers, and therefore, several efforts have begun to address this situation.

BMGS Work on Standards and Specifications

The British Columbia Base Mapping and Geomatic Services established a Community of Practice involving experts from academia, mapping, photo interpretation, aerial triangulation, and digital image capture and system design. Their purpose was to develop a set of specifications and procedures that would realize the objective of obtaining calibration information and specifying camera use in a cost-effective manner, while ensuring that continuing innovation in the field would be encouraged (BMGS, 2006). The developed methodologies will be utilized to as a framework for establishing standards and specifications for regulating the utilization of MFDC in mapping activities. These standards can be adopted by provincial and federal mapping agencies.

The DPRG group at the University of Calgary, in collaboration with the BMGS, conducted a thorough investigation into the digital camera calibration process, in which an indoor test site in BC was utilized as the test field. Through this collaboration, a three-tier system was established to categorize the various accuracy requirements, acknowledging that imagery will not be used for one sole application. The three broad categories in which these applications can be placed are the following:

- Tier I: Category for very precise, high end mapping purposes. This would include large scale mapping in urban areas or engineering applications. Cameras used for this purpose require calibration.
- Tier II: Category for mapping purposes in the area of resource applications (TRIM, inventory, and the like). Cameras used for this purpose require calibration.
- Tier III: Imagery in this category would not be used for mapping or inventory. It is suitable for observation or reconnaissance but not for measurement. Cameras used for these purposes do not require calibration.

Camera Calibration. Through this joint research effort, some standards and specifications for acceptable accuracies when performing camera calibration were compiled and are as follows:

1. Variance component of unit weight:

- Tier I: < 1 Pixel
- Tier II: < 1.5 Pixels
- Tier III: < N/A

2. No correlations should exist among the estimated parameters

3. Standard deviations of the estimated IOP parameters (xp, yp, c):

- Tier I: < 1 Pixel

- Tier II: < 1.5 Pixels
- Tier III: < N/A

In the document produced by the DPRG and BMGS, entitled *Small & Medium Format Digital Camera Specifications*, precise details are given in terms of the relationships of the GSD, the flying height, and the camera specifications to the above categories.

MFDC Stability Analysis. The estimated IOP from temporal calibration sessions must undergo stability analysis to evaluate the degree of similarity between reconstructed bundles. When the stability analysis is performed according to Section 2, the $RMSE_{offset}$ value is computed to express the degree of similarity between the bundles from two sets of IOP. The cameras must meet the following specifications to be deemed stable.

- Tier I: $RMSE_{offset} < 1$ Pixel
- Tier II: $RMSE_{offset} < 1.5$ Pixels
- Tier III: $RMSE_{offset}$ N/A

USGS Work on Standards and Specifications

The USGS, under the direction of the ASPRS Camera Calibration Panel, developed processes and guidelines that will ensure that high-quality digital aerial imagery can be procured and produced. A four-part process (USGS Quality Assurance Plan for Digital Imagery Data) has been developed and reviewed in consultation with major U.S. federal agencies, industry, and academia. To address the needs of the federal consumers of digital aerial imagery and to support the development of the plan, the USGS established the Inter-Agency Digital Image Working Group (IADIWG) to help address issues that arise when contracting for digital imagery. The IADIWG consists of fourteen U.S. government agencies and represents the largest purchasers of data in the nation. By focusing on the processes involved in procuring and generating digital aerial data, the plan seeks to ensure quality at each major step and to place the responsibility for maintaining quality with those most directly able to affect it. The USGS and its partner agencies hope to encourage the use of digital aerial imaging systems to meet the needs of providers and consumers of aerial data.

The Quality Plan outlines four distinct elements in two domains, as follows. 1) Data Procurement: The first element is the definition of contract requirements and data specifications to include quality measures, and the second element is the definition of a quality assurance process and the quality control criteria to ensure that the deliverables meet the terms of the contract. 2) Data Production: Here the first element is the evaluation of a camera manufacturer's processes and the camera system from both a hardware and a software perspective, to ensure that the system can perform the necessary primary data acquisition as required. This leads to manufacturer certification. The second element is the evaluation of the data providers using these camera to ensure that the systems have been integrated into production environments properly, to ensure that proper processes to produce consistent quality data have been established, and to evaluate whether required data products can be produced (The USGS Plan for Quality Assurance of Digital Aerial Imagery).

This plan has been used mainly for large format digital mapping systems and will be adapted over time to support MFDC systems. However, the USGS has been using laboratory and *in situ* system/product characterization of MDFC systems over defined test ranges to geometrically calibrate them and to evaluate their accuracy and calibration stability. USGS has been working with the DPRG software and continues to test the accuracy and stability of these systems. There is also a strong need for additional work related to spatial and radiometric accuracy and consistency of digital mapping sensors. The need to better understand and provide characterization methodologies to assess the digital sensor's ability to discriminate image content across spectral bands, spatially, and radiometrically, is very important and will be more so in the future. The USGS is working to establish test methods for assessment in these areas and will be looking for research partners in this endeavor.

The USGS is working with the DPRG and the BMGS to ensure common practices for digital aerial mapping systems, and is interested in working internationally to standardize processes and guidelines, and to share ideas and knowledge related to digital sensors. The advantage of having similar manufacturer certification processes and other quality processes is huge for the manufacturers and data providers, as well as the consumers. An international effort similar to the IADIWG could be beneficial to all digital image users worldwide, by helping to standardize digital imagery quality processes and efforts, and by aiding the work toward meeting future needs and developing processes in this rapidly changing environment.

So far, we addressed the need for standards and specifications for MFDC, and will now expand this focus to include LiDAR systems. Both MFDC and LiDAR systems have had recent advances in technology, as well as increased use in mapping applications, and therefore both require thorough investigation and analysis.

LiDAR DATA QUALITY CONTROL

The ever improving capabilities of the direct geo-referencing technology is having a positive impact on the widespread adoption of LiDAR systems for the acquisition of dense and accurate surface models over extended areas. Unlike photogrammetric techniques, derived footprints from a LiDAR system are not based on redundant measurements, which are manipulated in an adjustment procedure. The accuracy of derived LiDAR footprints depends on the quality of the bore-sighting parameters among the system components: namely, the laser, GNSS, and INS units. Current methodologies for estimating the bore-sighting parameters of a LiDAR system are based on complicated and empirical calibration procedures. Quality control, on the other hand, can be performed by the user, and this paper outlines one of the proposed QC methods. The main premise of the proposed method is that overlapping LiDAR strips will represent the same surface if, and only if, there are no biases in the derived surfaces. Therefore, we will use the quality of coincidence of conjugate surface elements in overlapping strips as the basis for deriving the quality control measures.

LIDAR System Calibration

Although the individual measurement capabilities of the LiDAR system components (GNSS, INS and laser scanner system) are quite precise, serious errors can occur from the inaccurate combination of theses components. For this reason, bore-sighting parameters should be well defined. The calibration of a LiDAR system is a complex task, and there is often a need for re-calibration when biases are detected in the output data. Raw measurements, however, are often not provided. As such, a LiDAR system is usually viewed as a black box that does not allow the user to perform calibration of the system. Another challenge in LiDAR system calibration, is the control information to be used for calibration.

For a system calibration, control information is essential. Traditionally, distinct control points have been used for the calibration of photogrammetric systems. One of the key characteristics of LiDAR data is the irregularity of the derived point cloud. While LiDAR data provides very accurate three-dimensional positional information, its visual information is not sufficient to extract distinct points. For example, it is nearly impossible to identify the laser footprint in the corresponding images (Ghanma, 2006). For this reason, using control planar patches is easier and more effective for LiDAR system calibration. The control patches can be obtained through ground surveys, or through the integration of photogrammetric and LiDAR data. The target function of the system calibration using the control patches, is to minimize the normal distance between the LiDAR footprints and the patches (Figure 3). The DPRG is currently working on a flexible LiDAR calibration procedure.

The following section will address LiDAR quality control (QC). There are two type of quality control, namely internal quality control and external quality control. Internal QC involves comparing features in overlapping strips, while External QC involves comparing features extracted from LiDAR strips with ground control points or features. The methods addressed in this work focus on internal quality control (IQC), but the method could also be applied for external quality control (EQC) if desired.

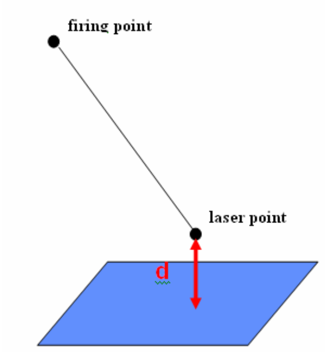


Figure 3. Concept behind LiDAR Calibration using Control Planar Patches.

Quality Control Through Automated Matching of LiDAR Footprints in Overlapping Strips

Many of the current approaches to LiDAR quality control require post-processing of the raw LiDAR data (for example, interpolation to yield range and intensity images and segmentation). Therefore, the validity of the derived measures depends on the amount of error introduced in the processing steps. To mitigate this dependency, an alternative quality control approach can be based on surface matching and registration of the original LiDAR data in overlapping strips to identify biases in the data acquisition system without the need for interpolation or segmentation. One way of doing this is to perform automated registration of two overlapping LiDAR strips while checking for consistent deviations between them; these deviations are the IQC measure. The registration is undertaken via a surface matching procedure in which one surface is represented by points and the other surface is represented by triangular patches, as shown in Figure 4. The matching criterion is that the points of the first surface must be coplanar with the corresponding patches of the second surface, and the point lies inside the triangular patch. The proposed procedure is based on evaluating the similarity transformation parameters, which are needed for the co-alignment of conjugate surface elements in overlapping LiDAR strips. In the ideal case (i.e., in the absence of biases) the estimated 3D similarity parameters should be zeros for the estimated translations and rotations, and the scale factor should be 1.

This QC method has been named the Iterative Closest Patch (ICPatch), and it does not assume a point to point correspondence, only a point to patch relationship. Consider two LiDAR strips, where the first strip is provided in the form of a Triangulated Irregular Network (TIN), and the second strip is represented as a cloud of points. For a given area, consider that the two datasets represent the same physical surface, but with different point distribution. Figure 4 shows the point to patch correspondence. Starting from initial approximations of the transformation parameters, the points in the second strip are matched with the closest triangular patch in the TIN. The matching is based on the constraints that the point is located within the boundaries of the triangle and the normal distance between a conjugate point-patch pair is minimized (Equations 1). Minimization of the volume of the triangle formed by the point and the TIN patch, for each point-patch pair, is then used to estimate new transformation parameters. This procedure is repeated until the parameters no longer change between successive iterations.

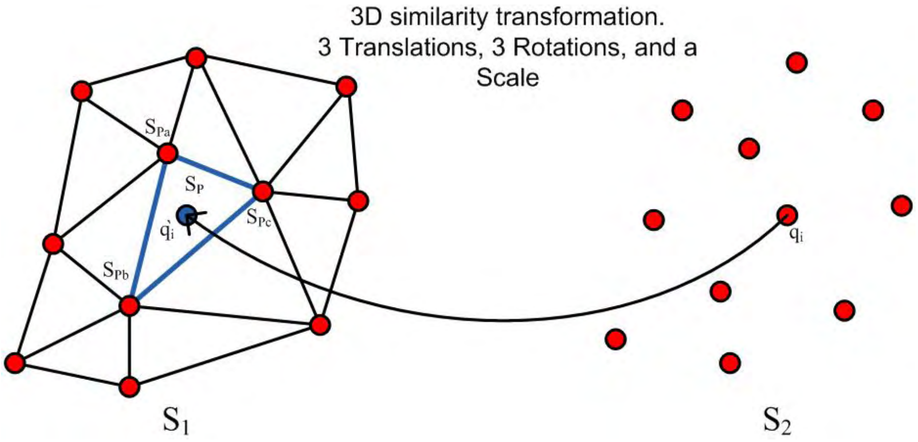


Figure 4. Point to patch correspondence using the ICPatch method.

$$\begin{vmatrix} X_{\grave{q}_i} & Y_{\grave{q}_i} & Z_{\grave{q}_i} & 1 \\ X_{Pa} & Y_{Pa} & Z_{Pa} & 1 \\ X_{Pb} & Y_{Pb} & Z_{Pb} & 1 \\ X_{Pc} & Y_{Pb} & Z_{Pc} & 1 \end{vmatrix} = 0$$

(Equation 1)

Where:

$$\begin{bmatrix} X_{\grave{q}_i} \\ Y_{\grave{q}_i} \\ Z_{\grave{q}_i} \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + S \times R_{\Omega.\Phi.K} \times \begin{bmatrix} X_{q_i} \\ Y_{q_i} \\ Z_{q_i} \end{bmatrix}$$

(Equation 2)

The computed transformation parameters serve as the measure of quality control, based on how close they are to the ideal values (zero rotations, zero translations, and unity scale). This method for QC can be used for IQC, but can also be extended to EQC by use of ground surveyed control patches.

EXPERIMENTAL RESULTS

This section provides experimental results to illustrate the feasibility and the pperformance of the proposed procedures. For detailed discussions of the experimenatl results realted to the QA/QC of MFDCs, intersted readers can refer to Habib et al. (2007b). The main focus of this section is the performance analysis of the proposed procedure for the QC of LiDAR data.

LiDAR Quality Control

To test the quality control approach outlined in Section 4.1, we extracted several areas in overlapping LiDAR strips, where the strips were flown in opposite directions (NE→SW, and SW→NE). The proposed procedure, which is based on estimating the similarity transformation parameters needed for the co-alignment of conjugate surface elements in overlapping LiDAR strips, was evaluated using the system and data specifications outlined in Table 1. In the ideal case, that is, in the absence of biases, the estimated 3D similarity parameters should be zeros for the estimated translations and rotations, and the scale factor should be 1. The estimated parameters together with the average normal distance between conjugate surface elements are as shown in Table 2. The performance of this approach was tested under various scenarios. One of the chosen test areas was a patch located over a building. A second test was performed using three patches over three different buildings, and a final test was done using seven patches over seven different buildings. The numbers in the header line of Table 2 indicate the number of buildings that were used for the various tests (refer to Figure 5). Table 2 also shows the average normal distance between conjugate surface elements after the application of the estimated similarity transformation parameters. In addition, the results from this quality control procedure indicate that there is a bias acting mainly in the x-direction, which can be seen in the X_T row in Table 2. It was found that all tests (1,3, and 7 buildings) yielded similar results; however, the 7 building results are the most trusted, as they offer a better representation of the strip area.

Table 1: System and Data Specifications

	Dataset 1
Data Provider	LACTEC
Survey Location	Brazil
Sensor Model	ALTM 2050
Scanner Type	Linear
Flying Height (m)	~1000
Pulse Rate (kHz)	50
Ground Point Spacing (m)	~0.70
Reported Vertical RMS (cm)	15
Overlap Percentage (%)	~75
Number of Strips	3
Number of Pairs	3

Table 2: Estimated transformation parameters using automated matching of conjugate surface elements in overlapping strips.

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

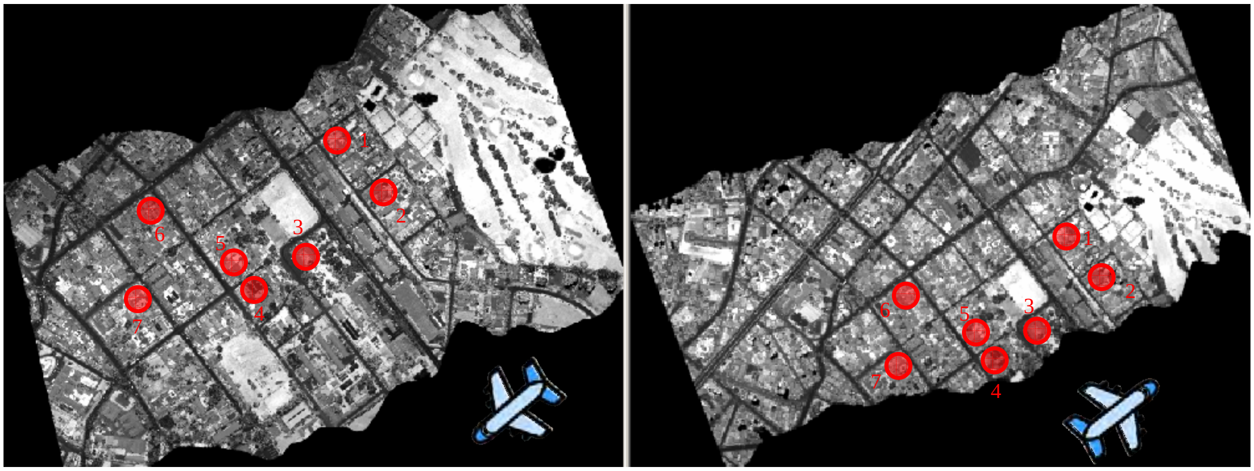
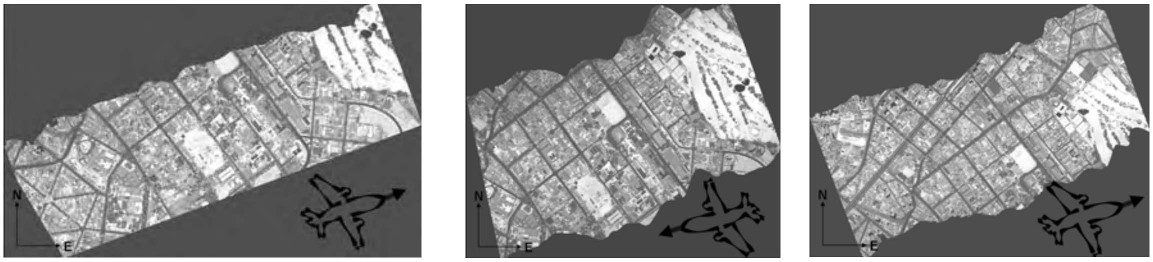


Figure 5. Locations of selected areas for the registration and automated matching of conjugate surface elements in two overlapping LiDAR strips.

In other tests, we collected different areas in the three overlapping strips to run the ICPatch procedure (Figure 6). Table 3 summarizes the similarity transformation parameters that have been estimated together with the average normal distance between conjugate surface elements after applying the transformation parameters. It is quite evident that the degree of coincidence among conjugate features is within the expected noise level as reported by the system manufacturer (refer to the last two rows in Table 3). A closer look at the reported numbers in the table below indicates that the estimated discrepancies between the strips, which are mainly in the planimetric coordinates, depend on the flying direction. Such a dependency excludes range biases from being the source of this discrepancy.



Strip 2 Strip 3 Strip 4

Figure 6. Overlapping strips in which conjugate surface elements were identified.

Table 3: Estimated transformation parameters using conjugate planar patches in overlapping strips

Transformation parameter	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
Κ (°)	-0.0009	-0.0003	0.0012
Average Normal Dist., m	0.09	0.09	0.10

CONCLUSIONS

With new technologies being employed in mapping applications, quality assurance and quality control of all sensors must be performed consistently by all service providers. This paper addressed medium format digital cameras and LiDAR systems, in particular. Camera calibration is an important quality assurance procedure, and new users of any camera system should become aware of its importance and procedure. Calibration performed using linear features allows all users the ability to setup a simple calibration test field without incurring large expenses, as well as reducing the required number of point features for in-situ or indoor calibration. The calibration process can be long and tiresome when performed manually. The procedures referred to for the automated extraction of image points and line features will greatly aid in the efficiency and ease of the overall calibration process, and thus encourage companies and manufacturers to perform reliable camera calibrations. Camera stability analysis must also be conducted on new or refurbished digital cameras, to ensure that the IOP of the selected camera(s) are stable over time. In addition to the procedures mentioned for camera calibration and validation, the initiatives undertaken by the British Columbia Base Mapping and Geomatic Services, in collaboration with the Digital Photogrammetry Research Group at the University of Calgary, and the U.S. Geological Survey, were briefly outlined. The standards and specifications being compiled through this joint effort can serve as a reference for the mapping industry, for the purpose of regulating the product quality attained through the use of digital cameras in airborne mapping, and to serve as a guide for newcomers to the industry. These efforts do not focus exclusively on quality assurance but also address the regulation of quality control.

Quality control is an essential procedure to ensure that the derived data from a given system meets the user's requirements. For MFDC, the quality can be assessed by the variance component, the variance-covariance matrix of the derived object coordinates, and check point analysis etc. For LiDAR, quality control is critical since the users' role in the quality assurance process is very limited due to the non-transparent nature of current LiDAR systems. The proposed procedure is based on evaluating the similarity transformation parameters, which are needed for the co-alignment of conjugate surface elements in overlapping LiDAR strips. Deviations in the estimated transformation parameters from the theoretical ones (zero rotations and translations and unit scale factor) are used as quality control measures to detect the presence of biases in the data acquisition system. When dealing with overlapping LiDAR strips, the deviations are considered as measures of internal quality control. The automated approach that was introduced is based on identifying conjugate surface elements while estimating the transformation parameters. Experimental results with real data have shown the feasibility of the proposed algorithms in detecting biases in the horizontal directions between two overlapping LiDAR strips.

In addtion, the LiDAR QC approach has the ability to be applied for any coverage area with no requirement for LiDAR targets or structures with linear features (e.g., urban areas). The proposed QC methods have the possibility of being applied in external quality control by comparing LIDAR and ground truth data. It should be noted that in current specifications, only the vertical accuracy is carefully verified by the data provider with precisely surveyed check surfaces. On the other hand, horizontal accuracies are more difficult to verify due to the lack of distinct topographic features for testing. In addition, no specific regulations and verification requirements are defined by the photogrammetric and mapping societies for reporting horizontal accuracies of LiDAR data (ASPRS, 2004). However, both horizontal and vertical accuracies should be assessed for quality control since errors in both directions can greatly affect the accuracy of mapping products generated from LiDAR (e.g., digital elevation models). This is especially important for applications such as marine navigation and floodplain management where highly accurate mapping products are needed. The presented methodology constitutes an effective and economic tool for checking the quality of derived LiDAR surfaces in the planimetric and vertical directions.

The USGS and BMGS are continuing to test digital imaging systems as well as LiDAR systems, and are working with the DPRG to produce quality assurance and quality control guidelines and standards. Once clearly defined standards are accepted, the accuracy of the final product will be definite, thus ensuring high quality work and customer satisfaction, and offering well-founded encouragement for the use of digital imaging systems and LiDAR systems in current and emerging markets.

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