

STANDARDS AND SPECIFICATIONS FOR THE CALIBRATION AND STABILITY OF AMATEUR DIGITAL CAMERAS FOR CLOSE-RANGE MAPPING APPLICATIONS

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ABSTRACT:

Photogrammetry is concerned with the accurate derivation of spatial and descriptive information from imagery that can be used in several applications such as mapping, DEM generation, orthophoto production, construction planning, environmental monitoring, structural analysis, 3D visualization, and change detection. The type of cameras traditionally used for high accuracy projects were large format analogue cameras. In recent years, however, the use of digital cameras for photogrammetric purposes has become more prevalent. The switch by some users from analogue to digital cameras has been fuelled by the ease of use, decreasing cost, and increasing resolution of digital cameras. Digital photogrammetric cameras can be classified into several categories: line cameras (e.g., ADS40 from Leica Geosystems), large format frame cameras (e.g., DMCTM from Zeiss/Intergraph), and medium to small-format digital cameras. More recently, amateur medium-format digital cameras (MFDC) and small-format digital cameras (SFDC) are being used in photogrammetric activities (e.g., in conjunction with LiDAR systems, smaller flight blocks, and for close-range photogrammetric applications). The continuing development in the capabilities of digital photogrammetry coupled with users' needs has spawned new markets in photogrammetric mapping with amateur digital cameras. With the wide spectrum of designs for amateur digital cameras, several issues have surfaced, including the method and quality of camera calibration, as well as long-term stability. This paper addresses these concerns and outlines possible solutions. First, we will start by introducing an automated methodology for an in-door camera calibration. The main objective of such a procedure is to provide mapping companies using these cameras with a simple calibration procedure that requires an easy-to-establish test field. The paper will then discuss the concept of how to evaluate camera stability, which will be followed by the introduction of a set of tools for its evaluation. Following the discussion on calibration and stability analysis, the paper will deal with several related questions: How to develop meaningful standards for evaluating the outcome from the calibration procedure; How to develop meaningful standards for evaluating the stability of the involved camera; Is there a flexibility in choosing the stability analysis tool based on the geo-referencing procedure; Can the stability analysis be used for evaluating the equivalency of different distortion models. Finally, experimental results are then provided for two small format digital cameras.

1. INTRODUCTION

The recent growth in the field of photogrammetry, which has been driven by the increase in available types of digital cameras, has numerous advantages. In particular, new areas of applications are coming into existence, and new users are entering the market. The growth in the variety of products is beneficial both to product manufacturers and users. The use of small format digital cameras in particular offers an attractive alternative for convenient and inexpensive close-range applications, such as deformation monitoring of building structures. The benefits of using digital cameras for this type of application are that costly equipment such as strain gauges and accelerometers are not required, information can be gathered in a non-contact approach, and existing photogrammetric methods can be used to process imagery of structures acquired at different times to determine the structure deformation. With these new applications emerging, however, come new areas of concern, such as camera calibration, stability analysis, and standards to regulate the use of amateur small and medium format digital cameras in photogrammetric activities.

The calibration of large format analogue and digital photogrammetric cameras is traditionally performed by dedicated organizations (such as the USGS, NRCAN), where trained professionals ensure that high calibration quality is upheld. With the wide spectrum of designs for amateur SFDC and MFDC, however, it has become more practical for the data providers to perform their own calibrations and analysis of the utilized cameras. As such, the burden of camera calibration has been shifted into the hands of the data providers. Such a shift has led to a need for the development of procedures and standards for simple and effective calibration. In addition to camera calibration, stability analysis of amateur digital cameras should also be addressed. It is well known that analogue and digital cameras, which have been specifically designed for photogrammetric purposes, possess strong structural relationships between the focal plane and the elements of the lens system. Amateur digital cameras, however, are not manufactured for photogrammetric reconstruction, and thus have not been built to be as stable as mapping cameras. Their stability therefore requires thorough analysis. In other words,

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one needs to check whether the estimated internal characteristics of these cameras from a calibration session remain stable over time. The question that arises from such a need is what are the tools and standards that can be used to evaluate the stability of a given camera?

This paper will thus focus on these issues in relation to amateur digital cameras. First, an automated method for an indoor camera calibration procedure is introduced. The main objective of such a procedure is to provide mapping companies using these cameras with a simple calibration procedure that requires an easy-to-establish test field. More specifically, a test field that is comprised from a set of linear features and few point targets will be used to carry out the camera calibration procedure. The determination of the interior orientation parameters will be based on the observed deviations from straightness in the image space linear features as well as the measured distances between the point targets. In addition to having a simplified calibration test field, we will outline an automated procedure for the extraction of the linear features and point targets from the captured imagery. The simplified test field and the automated extraction of the linear features and point targets are the key factors for enabling the data providers to effectively carry out the calibration procedure, which is general enough to handle any amateur digital camera. The paper will then discuss the concept of how to evaluate camera stability, which will be followed by the introduction of a set of tools for its evaluation. The stability analysis tools will be based on quantitative evaluation of the degree of similarity between the reconstructed bundles from temporal calibration sessions. The bundle similarity is used since the camera calibration procedure aims at generating a bundle that is as similar as possible to the incident bundle onto the camera at the moment of exposure.

Following the calibration and stability analysis discussions, the paper will deal with several related questions as follows: 1) How to develop meaningful standards for evaluating the outcome from the calibration procedure, 2) How to develop meaningful standards for evaluating the stability of the involved camera, 3) Is there a flexibility in choosing the stability analysis tool, which is commensurate with the geo-referencing procedure to be implemented for this camera, and 4) Can the stability analysis be used for evaluating the equivalency of different distortion models. These questions will be discussed in turn, and some experiment results from datasets captured by two amateur small format digital cameras are presented.

2. CAMERA 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 analogue cameras, but the case of digital cameras is much more complex due to the wide spectrum of designs for digital cameras. It has thus become more practical for camera manufacturers and/or users to perform their own calibrations when dealing with digital cameras. In essence, the burden of the camera calibration has been shifted into the hands of the data providers. There has thus become 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 specifically 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), where 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), to confirm that the use and inclusion of line features in calibration can yield comparable results to the traditional point features. 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 secondly, to determine how the perspective relationship between corresponding image and object space lines is to be established. In this research, 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 these points and the corresponding object space points is modelled by the collinearity equations. In addition to the use of the line endpoints, intermediate points are measured along the image lines, which enable continuous modelling of distortion along the linear feature. The incorporation of the intermediate points into the adjustment procedure is done via a mathematical constraint (Habib, 2006a). It should be noted, however, that in order to determine the principal distance and the perspective centre coordinates of the utilized camera, distances between some point targets must be measured and used as additional constraints in the bundle adjustment procedure.

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 (2006a) and are briefly outlined in the following sub-section.

2.1 Automated Extraction of Point and Line Features

The 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. 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 the locations of signalized targets. Once the automated extraction of point features is completed, the focus is shifted to the extraction of linear features. The 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. Once the point and linear features have been extracted through this automated procedure, they are incorporated into the bundle adjustment, according to the method outlined in Section 2, to determine the camera IOP.

A test field suitable for such procedures is seen in Figure 1. A closer look at the extracted point and line features is given in Figures 2a and 2b, respectively. In Figure 2b it is clearly seen that the line features are composed of individual points.

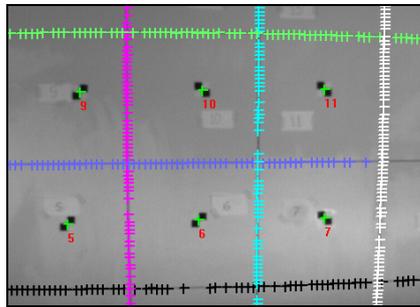


Figure 1: Suggested calibration test field with automatically extracted point and linear features

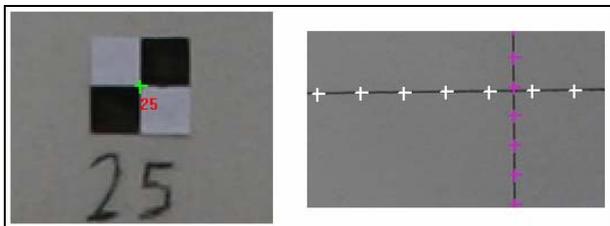


Figure 2a: Point feature

Figure 2b: Line feature

3. CAMERA STABILITY

It is well known that professional analogue cameras, which have been designed specifically for photogrammetric purposes, possess strong structural relationships between the focal plane and the elements of the lens system. Amateur digital cameras, however, are not manufactured specifically for the purpose of photogrammetric mapping, and thus have not been built to be as stable as traditional mapping cameras. Their stability thus requires thorough analysis. If a camera is stable, then the derived IOP should not vary over time. In the work done by Habib and Pullivelli (2006b), three different approaches to assessing camera stability are outlined, where two sets of IOP of the same camera that have been derived from different calibration sessions are compared, and their equivalence assessed. In their research, different constraints were imposed on the position and orientation of reconstructed bundles of light rays, depending on the georeferencing technique being used. The hypothesis is that the object space that is reconstructed by two sets of IOP is equivalent if the two sets of IOP are similar. The three different approaches to stability analysis are briefly outlined in the following sections. In these methods, two sets of IOP are used to construct two bundles of light rays. A synthetic regular grid is then defined in the image plane. The distortions are then removed at the defined grid vertices, using the two sets of IOP in order to create distortion-free grid points. The distortion-free grid points of each IOP are then compared to assess their similarity.

3.1 Zero Rotation Method (ZROT)

In the ZROT method, a constraint is applied on the bundles such that they must share the same perspective centre and have parallel image coordinate systems. If the two IOP sets are

equivalent, then the coordinates of the distortion-free vertices in the two synthetic grids should be the same. Therefore, the differences in the x and y coordinates between the two distortion-free grids are used to estimate the offset between the two sets of IOP. When the principal distances of the two sets of IOP are different, the distortion-free grid points from one IOP are projected onto the image plane of the other, before the x and y coordinate offsets are measured (Figure 3). The similarity between the two bundles is then determined by computing the Root Mean Square Error (RMSE) of the offsets. If the RMSE is within the range defined by the expected standard deviation of the image coordinate measurements, then the camera is considered stable. This similarity imposes restrictions on the bundle position and orientation in space, and thus has similar constraints to those imposed by direct georeferencing with GPS/INS. Therefore, if the IOP sets are similar according to the ZROT method, the relative quality of the object space that is reconstructed based on the direct georeferencing technique using either IOP set will also be similar.

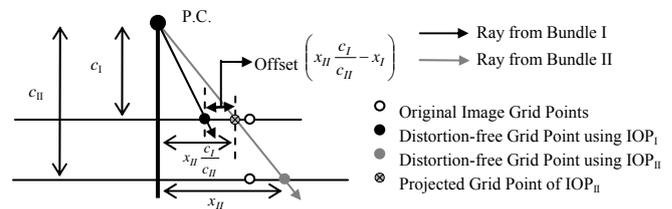


Figure 3: The offset between distortion-free coordinates of conjugate points in the ZROT method

3.2 Rotation Method (ROT)

In comparison with the ZROT method, which restricted the bundles orientation, this method allows the comparison of bundles that share the same perspective centre but which have different orientation in space (Figure 4). The purpose of the stability analysis is to determine if conjugate light rays coincide with each other, and this should be independent of the bundle orientation. This method checks if there is a set of rotation angles (ω, ϕ, κ) that can be applied to one bundle to produce the other. A least-squares adjustment is performed to determine the rotation angles, and the variance component of the adjustment, which represents the spatial offset between the rotated bundles in the image plane, is used to determine the similarity of the two bundles. The bundles are deemed similar if the variance component from the least squares adjustment is in the range of the variance of the image coordinate measurements. This similarity imposes restrictions on the bundle positions in space, and thus has similar constraints to those imposed by GPS controlled photogrammetric georeferencing. Therefore, if the IOP sets are similar according to the ROT method, the relative quality of the object space that is reconstructed based on the GPS controlled georeferencing technique, using either IOP set, will also be similar.

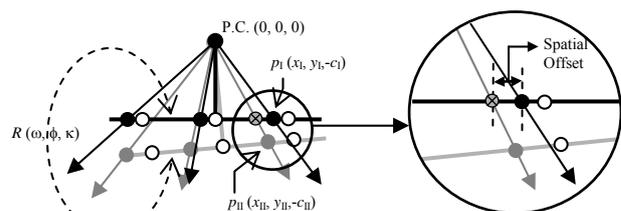


Figure 4: The two bundles in the ROT method are rotated to reduce the angular offset between conjugate light rays

3.3 Single Photo Resection (SPR)

The SPR method has fewer constraints on the bundles than the previous two methods. In this stability analysis procedure, the two bundles are allowed to have spatial and rotational offsets between their image coordinate systems. This approach, like the previous two methods, defines one grid in the image plane. The various distortions are removed from the grid vertices, and a bundle of light rays is defined for one set of IOP and grid vertices. This bundle of light rays is then intersected with an arbitrary object space to produce object space points. A single photo resection is then performed using the object space points in order to estimate the exterior orientation parameters of the second bundle. The variance component produced through this method represents the spatial offset between the distortion-free grid vertices as defined by the second IOP and the image coordinates computed through the back-projecting of the object space points onto the image plane (Figure 5). The IOP are deemed stable if the variance component is within the range of the variance of the image coordinate measurements. This similarity imposes no restrictions on the bundle position and rotation in space, and thus has similar constraints to those imposed by indirect georeferencing. Therefore, if the IOP sets are judged to be similar according to the SPR method, the relative quality of the object space that is reconstructed based on the indirect georeferencing technique using either IOP set, will also be similar.

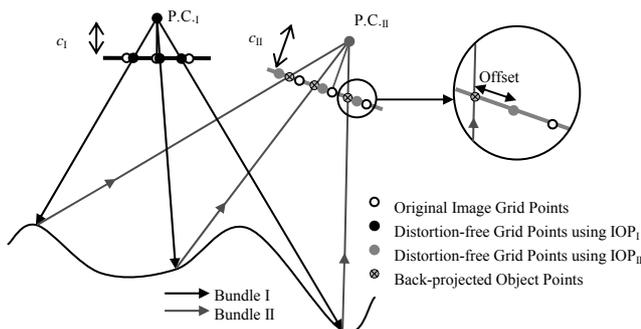


Figure 5: SPR method allows for spatial and rotational offsets between the two bundles to achieve the best fit at a given object space

3.4 Comparing Equivalence of Different Distortion Models

There exist several variations of distortion models that can be used to model lens distortion. The stability analysis tool can be used to evaluate the equivalence of different distortion models. This can be accomplished by calibrating the same dataset using different distortion models, and then comparing the output IOP. If the IOP produced using different distortion models are deemed to be similar, then the respective distortion models can be considered to be equivalent. Three different models were tested, and the results from these tests using real data are provided in the Experimental Results section of this paper.

4. DEVELOPING MEANINGFUL STANDARDS

Due to the various types of digital imaging systems, it is no longer feasible to have permanent calibration facilities run by a regulating body to perform the calibrations. 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. Some digital imaging systems have not been created for the purpose of photogrammetric mapping, and thus their stability over time must also be investigated. These have been the observations of many governing bodies and map providers, and thus several efforts have begun to address this situation. 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 to develop a set of specifications and procedures that would realize the objective of obtaining this calibration information and specify camera use in a cost effective manner while ensuring the continuing innovation in the field would be encouraged (BMGS, 2006). The developed methodologies will be utilized to constitute 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, where an in-door 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: This imagery 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.

Similar initiative between the United States Geological Survey (USGS), BMGS, and the Digital Photogrammetry Research Group is underway where the issues of camera calibration, stability analysis, and achievable accuracy are being investigated for the purpose of generating a North-American guideline for regulating the use of medium format digital cameras in mapping applications.

4.1 Standards and Specifications for Digital Camera Calibration

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

1. Variance component of unit weight:
 - Tier I < 1 Pixel
 - Tier II < 1.5 Pixels
 - Tier III < N/A Pixels
2. No correlation should exist among the estimated parameters
3. Standard deviations of the estimated IOP parameters (x_p , y_p , 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 relationship of the ground sampling distance (GSD), flying height, camera specifications, and the above categories.

4.2 Standards and Specifications for Digital Camera Stability

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 3, the $RMSE_{offset}$ value is computed to express the degree of similarity between the bundles from two sets of IOPs. 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 $RMSE_{offset} : N/A$

5. EXPERIMENTAL RESULTS

The cameras tested in this research were two Prosilica GC1020 CCD cameras with Gigabit Ethernet interface (Figure 6). These sensitive cameras can collect 33 frames per second, are based on the Sony ICX204AL CCD sensor, have a resolution of 1024x768, and a pixel size of 4.65µm (Prosilica Inc., 2007). The camera lenses used were two 6mm Pentax TV lenses. The camera and lens specifications are summarized in Table 1. The camera calibration test field used to perform all calibrations of the Prosilica cameras is roughly 5x5 m² and contains both line features and signalized targets.

Sensor Type	Sony ICX204AL CCD
Image Resolution	1024 x 768 pixels
Pixel Size	4.65µm x 4.65µm
Size	33mm (height) x 46mm (width) x 59mm (length)
Lens	6mm Pentax TV Lens

Table 1: Camera and lens specifications



Figure 6: Prosilica GC1020 cameras

5.1 Calibration Results

The Prosilica cameras were calibrated by the DPRG at the University of Calgary in March and April of 2008. Each camera

was calibrated three times over the course of a month. Between each calibration session, the lenses were removed and re-attached. The calibration results for the first camera (herein referred to as camera 1) are shown in Tables 2, 3, and 4. The IOP shown in the tables, however, cannot be compared directly in order to determine stability due to correlation among parameters. The camera stability analysis, which will determine if these cameras have remained stable over time, will be performed in Section 5.2.

x_p (mm)	0.1774	σx_p (mm)	0.0017
y_p (mm)	-0.0977	σy_p (mm)	0.0018
c (mm)	6.1377	σc (mm)	0.0027
k_1 (mm ⁻¹)	-5.1259e-03	σk_1 (mm ⁻¹)	2.0281e-05

Table 2: IOP from the Camera 1, calibration #1

x_p (mm)	0.1793	σx_p (mm)	0.0019
y_p (mm)	-0.0862	σy_p (mm)	0.0018
c (mm)	6.1400	σc (mm)	0.0026
k_1 (mm ⁻¹)	-5.0751e-03	σk_1 (mm ⁻¹)	2.1265e-05

Table 3: IOP from Camera 1, calibration #2

x_p (mm)	0.1646	σx_p (mm)	0.0020
y_p (mm)	-0.0837	σy_p (mm)	0.0020
c (mm)	6.1390	σc (mm)	0.0027
k_1 (mm ⁻¹)	-5.1111e-03	σk_1 (mm ⁻¹)	2.1276e-05

Table 4: IOP from Camera 1, calibration #3

5.2 Stability Results

Stability analysis was performed on the two Prosilica cameras, according to the ROT method outlined in Section 3.2. This method was chosen because under the terrestrial applications being considered in this work, the only constraints likely to be imposed on the cameras are that the camera positions may be restricted. In some cases there may be no restrictions imposed on the cameras in terms of position and orientation, and in such cases the SPR method could be employed. However, since the ROT method gives more conservative results than the SPR method, this stability analysis method was chosen for use in this research. To demonstrate the stability of the utilized cameras, we evaluated the degree of similarity between the reconstructed bundles from the various calibrations, and the $RMSE_{offset}$ values for the two cameras are shown in Table 5. It is evident that these $RMSE_{offset}$ values are no greater than one pixel size (0.00465mm), which indicates excellent stability of the tested cameras.

Data sets:	RMSE For Camera 1 (mm)	RMSE For Camera 2 (mm)
Set 1 vs. Set 2	0.0006	0.0039
Set 1 vs. Set 3	0.0004	0.0015
Set 2 vs. Set 3	0.0005	0.0025

Table 5: Camera stability results

5.3 Analysis of Distortion Model Equivalence

The stability analysis tool was also used for the comparison of IOP derived using different distortion models. In this research, the equivalence between three distortion models was investigated. These models include: Krauss (Equation 1), SMAC (Equation 2), and PCI (Equation 3) distortion models. In

order to assess equivalence, the same dataset from the same camera was calibrated three times, each time using a different distortion model. If the distortion models are equivalent, the resulting IOP should be equivalent. In order to compare the three sets of IOP, the stability analysis software was used to assess the IOP similarity.

$$\begin{aligned} \Delta x &= K_1(r^2 - R_0^2)\bar{x} + K_2(r^4 - R_0^4)\bar{x} + P_1(r^2 + 2\bar{x}^2) + 2P_2\bar{x}\bar{y} - A_1\bar{x} + A_2\bar{y} \\ \Delta y &= K_1(r^2 - R_0^2)\bar{y} + K_2(r^4 - R_0^4)\bar{y} + P_2(r^2 + 2\bar{y}^2) + 2P_1\bar{x}\bar{y} + A_1\bar{y} \end{aligned} \quad (1)$$

$$\begin{aligned} \Delta x &= \bar{x}(K_0 + K_1r^2 + K_2r^4 + K_3r^6) + (1 + P_3r^2)(P_1(r^2 + 2\bar{x}^2) + 2P_2\bar{x}\bar{y}) \\ \Delta y &= \bar{y}(K_0 + K_1r^2 + K_2r^4 + K_3r^6) + (1 + P_3r^2)(2P_1\bar{x}\bar{y} + P_2(r^2 + 2\bar{y}^2)) \end{aligned} \quad (2)$$

$$\begin{aligned} \Delta x &= \frac{(R_0 + R_1r + R_2r^2 + R_3r^3 + R_4r^4 + R_5r^5 + R_6r^6 + R_7r^7)}{r} \bar{x} \\ &\quad + (1 + P_3r^2 + P_4r^4)(P_1(r^2 + 2\bar{x}^2) + 2P_2\bar{x}\bar{y}) \\ \Delta y &= \frac{(R_0 + R_1r + R_2r^2 + R_3r^3 + R_4r^4 + R_5r^5 + R_6r^6 + R_7r^7)}{r} \bar{y} \\ &\quad + (1 + P_3r^2 + P_4r^4)(2P_1\bar{x}\bar{y} + P_2(r^2 + 2\bar{y}^2)) \end{aligned} \quad (3)$$

The results from this equivalence analysis are presented in Table 6. The RMSE values are all well under the size of a pixel. From these experiments, we can thus conclude that the tested distortion models are equivalent.

Distortion models:	Camera 1 RMSE (mm)	Camera 2 RMSE (mm)
Krauss vs. SMAC	0.0012	0.0009
Krauss vs. PCI	0.0010	0.0011
SMAC vs. PCI	0.0017	0.0004

Table 6: Equivalence analysis

5.4 Photogrammetric Reconstruction

Sections 5.1 and 5.2 have dealt with the calibration and stability of the investigated cameras. In this section, the achievable accuracy that can be obtained using the investigated terrestrial cameras is analyzed. To assess the accuracy, the point targets on the calibration test field were surveyed to millimetre accuracy, using a Total Station. Photogrammetric reconstruction was then performed, using the IOP from calibration session 1 for Camera 1, and the imagery data collected from session 3. The point targets were extracted automatically from the imagery, using the procedure outlined in Section 2.1. An RMSE analysis was performed between the surveyed and reconstructed points. The mean, standard deviation, and RMSE results are tabulated in Table 7. From these results, it can be concluded that the achievable accuracy of these cameras has been determined to be within one millimetre of the results obtained using a Total Station. In addition, considering the average object space pixel size is 2.3 mm, the RMSE from the reconstructed object space compared to the Total Station survey results are less than half a pixel size in the object space.

Mean _{AX} ± σ _X (mm)	-0.38 ± 0.87
Mean _{AY} ± σ _Y (mm)	-0.38 ± 1.04
Mean _{AZ} ± σ _Z (mm)	-0.38 ± 0.77
RMSE _X (mm)	0.92
RMSE _Y (mm)	1.07
RMSE _Z (mm)	0.83
RMSE _{Total} (mm)	1.64

Table 7: Mean, standard deviation, and RMSE for the comparison between the reconstructed and surveyed coordinates

6. CONCLUSION

This paper has addressed several issues that are coming to surface with the increase in adoption of amateur digital cameras for photogrammetric mapping applications. In particular, the method and quality of camera calibration, as well as long-term stability has been investigated. First a low cost and efficient calibration technique was outlined, in which a test field composed of linear and point features was utilized. An automated method for the extraction of the point and line features was then summarized, after which several stability analysis methods were presented. The stability analysis was then used to evaluate the equivalency of different distortion models. Finally, the achievable accuracy of the tested terrestrial cameras was investigated. These procedures were performed on two Prosilica GC1020 CCD cameras, and the experimental results were presented in Section 5. Based on these results, it was determined that the tested amateur digital cameras remained stable over time, and provided an accuracy of one millimetre. These results can be used to promote the use of small format digital cameras as an attractive alternative for convenient and inexpensive close-range applications, such as deformation monitoring of building structures. Furthermore, although the tests conducted in this work were performed on small format digital cameras for close-range photogrammetric applications, the outlined calibration and stability procedures and tools are valid for use in analysis for aerial applications.

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