

MEDIUM-FORMAT DIGITAL CAMERAS: A STUDY INTO THE CALIBRATION, STABILITY ANALYSIS, AND ACHIEVABLE ACCURACY

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ABSTRACT

In recent years, the use of medium format digital cameras (MFDC) for mapping purposes has become more prevalent, where MFDC is used to refer to digital cameras with CCD or CMOS array size of up to 40MP. This trend has been fueled by the decreasing cost and increasing resolution capabilities of these cameras. These advances have given smaller companies the capability to enter the market and generate high-quality photogrammetric products, which otherwise would not have been possible. The quality of the used camera in photogrammetry, however, greatly affects the resulting product accuracy. There is currently no universal outline of standards and specifications being used throughout the industry, nationally or internationally, and thus different map providers follow different accuracy criteria. This can result in maps of different accuracy being produced, and can greatly complicate the integration of maps from different sources. Map production through photogrammetric reconstruction requires the interior and exterior orientation parameters of the imaging system. The exterior orientation parameters can be derived by indirect georeferencing, direct georeferencing when GPS/INS data is available, or through GPS-aided aerial triangulation when GPS is available onboard the imaging platform. In this research, a calibration test range is used to test the validity of including line features in camera calibration, in addition to and in comparison with point features. Following the calibration, a stability analysis procedure will be introduced while considering the different geo-referencing alternatives. Standards and specifications for calibration and stability analysis will be outlined, and finally, the research will investigate the performance of medium format digital cameras for various applications using different georeferencing techniques, and suggests guidelines that can be adopted by the mapping industry.

INTRODUCTION

The study of photogrammetry involves the determination of three-dimensional positional information from two-dimensional imagery. This information is used for countless applications, including ortho-image production, map creation, construction planning, military reconnaissance, etc. The type of camera predominantly employed for these various applications 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 fueled by the decreasing cost and increasing resolution capabilities of digital cameras. There are several other benefits that come from their use, some of which include: ease of use; availability; and rapid development. The use of MFDC in photogrammetry will not completely replace analogue ones, however, since it cannot entirely compete with the ground coverage and resolution capabilities of film cameras. However, for close-range applications, or smaller flight blocks, digital cameras have become more practical and cost efficient. In addition to replacing analogue cameras in certain applications, digital photogrammetry has also spawned new markets in photogrammetry and mapping to emerge.

It was in the early 2000s when large and medium format digital cameras began their introduction into the commercial mapping market. In today's market, some of the current large format digital cameras (LFDC) include the DMCTM from Intergraph/ZI-Imaging and the UltracamD from the Microsoft Corporation, while the providers of medium format digital cameras (MFDC) are predominantly Applanix Corporation (DSS322 and DSS301), Rollei (AIC), and IGI (DigiCAM). To

date, roughly 120 large format digital imaging systems have been sold, while the sales of the medium format digital imaging systems amounts to around 150, as reported by Petrie (Petrie, 2006). Although large format digital cameras most closely resemble the traditional analogue mapping cameras, there is a definite and growing interest in medium format digital cameras. The market for their use in various new and emerging applications will likely cause the MFDC sales to continue to increase. Some of their current applications include aerial surveys of hurricane ravaged regions (NOAA, 2005), modeling of 3D scenes, computer vision (Klette, 2005), and rapid mapping as performed by the Canadian Department of National Defense in such places as Haiti and Afghanistan (Applanix, 2006).

The affordable price and ease of use of these digital imaging systems has given rise to new users entering the field of airborne mapping. Although the growth of the field as well as the increase in the diversity of applications has numerous advantages, it has been noted (Petrie, 2006) that some users who possess little photogrammetric background have obtained these new imaging systems, and are unfamiliar with the importance of accurate camera calibration. These same users may also be unaware or unable to determine their product accuracy. Therefore, one focus of this paper will be to outline standards and procedures for the camera calibration of medium format digital cameras, in addition to their expected performance under various configurations.

In previous research, it has been acknowledged that the advantage of large format imaging based on high-end digital sensors is well known, yet for smaller area projects or due to cost limitations, there is a definite and growing market for medium and small format cameras, to be used in more flexible and cost effective ways, when the required geometric accuracy is not as stringent (Cramer, 2005). In this same research, however, it was recognized that long-term experiences based on the use of digital cameras is of yet to be available. Before digital imaging systems can be fully accepted as a viable option for airborne mapping by all industry and research organizations, it must be shown that the product quality of these systems 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 analogue mapping cameras, they 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 to investigate the stability of the internal characteristics of digital cameras, specifically MFDC, for photogrammetric applications. This void in literature can be attributed to the absence of standards for quantitative analysis of camera stability. Therefore, in addition to outlining camera calibration techniques and performance analysis of MFDCs, this paper will present a methodology for comparing two sets of IOP of the same camera that have been derived from two different calibration sessions, to evaluate the stability of medium format digital cameras.

Section 2 of this paper deals with the topic of camera calibration. The importance and purpose of calibration is introduced, and the process is briefly outlined. Section 3 addresses camera stability analysis, where three different methods are outlined and compared. Section 4 outlines standards that can be used to qualify the various degrees of accuracy attained using digital imaging systems, and gives specific guidelines that can be followed to ensure the desired product quality is achieved. Section 5 outlines the expected performance of digital imaging systems under various conditions, and displays experimental results to support the drawn conclusions.

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 lens distortion is composed of radial, de-centering and affine distortions, of which, for the case of medium format digital cameras, the radial lens distortion (RLD) is the most significant.

The calibration process is well defined for traditional analogue cameras, but the case of digital cameras is much more complex. Since analogue cameras have similar system designs, the same basic procedure and facility can be used to calibrate analogue cameras. The calibration procedure for high accuracy analogue mapping cameras is traditionally performed by a regulating body (such as NRCAN and the USGS), where trained professionals ensure that high calibration quality is upheld. There is, however, a wide spectrum of designs for digital cameras, where some of these designs include large format, medium format, small format, multi-head, line camera, frame camera, etc. 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 airborne data providers. There has thus become an obvious need for the development of standards and procedures for simple and effective digital camera calibration.

In order to perform 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. This research is outlined in the following paragraphs.

During camera calibration, we are interested in determining the internal characteristics of the involved camera, which comprise the coordinates of the principal point, the principal distance, and 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 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 modeled by the collinearity equations. In addition to the use of the line endpoints, intermediate points are measured along the image lines, which enable 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, 2006a). 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. 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 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. 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, which can proceed 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.

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.

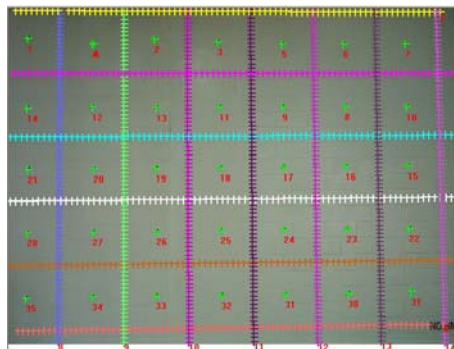


Figure 1. Suggested calibration test field with automatically extracted point and linear features.

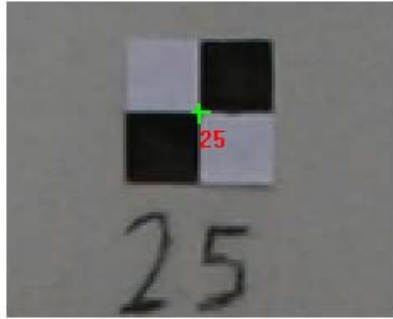


Figure 2a. Point feature.

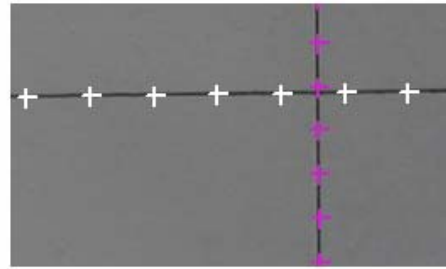


Figure 2b. Line feature.

Through the research conducted by the Digital Photogrammetry Research Group at the University of Calgary, in collaboration with the BMGS, numerous tests have been performed on seven different medium format digital cameras (50mm TERRA 2815 13MP camera, 80mm WBM 32MP camera, 35mm QC 16MP camera, 60mm DAC101 22MP camera, 60mm DAC102 22MP camera, and two 35mm Canon 8MP camera). One of the conclusions is visible in Table1 and Table2, where the same calibration procedure was performed for a dataset, in which a calibration conducted using point features was shown to be compatible to a second calibration performed using point and line features.

Table1. The IOP from the Canon camera #1, from a calibration using both line and point features

x_p (mm)	0.0411	σx_p (mm)	0.0028
y_p (mm)	0.0427	σy_p (mm)	0.0028
c (mm)	36.594	σc (mm)	0.0037
k_1 (mm ⁻¹)	-6.3775737939e-005	σk_1 (mm ⁻¹)	2.8292409874e-007

Table2. The IOP from the Canon camera#1, from the calibration using point features only

x_p (mm)	0.0471	σx_p (mm)	0.0054
y_p (mm)	0.0373	σy_p (mm)	0.0055
c (mm)	36.587	σc (mm)	0.0064
k_1 (mm ⁻¹)	-6.3470941975e-005	σk_1 (mm ⁻¹)	1.0982101649e-006

STABILITY ANALYSIS

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. Medium format digital cameras, however, are not manufactured specifically for the purpose of photogrammetry, 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, 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.

Zero Rotation Method (ZROT)

In this method, two sets of IOP are used to construct two bundles of light rays. A synthetic regular grid is 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. In the ZROT method, a constraint is applied on the bundles such that they must share the same perspective center 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.

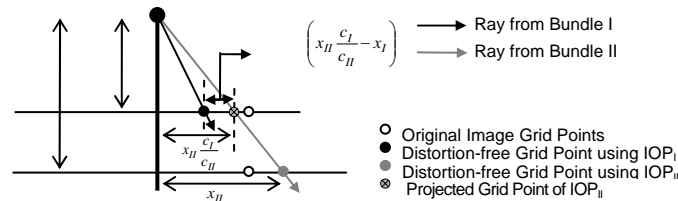


Figure 3. The offset between distortion-free coordinates in the ZROT method.

Rotation Method (ROT)

The ROT method is similar to the ZROT method, in that a synthetic regular grid is defined in the image plane, and the various distortions are removed from the defined grid vertices using the two sets of IOP. Two bundles of light rays are defined using the IOP and the distortion-free grid points. In comparison with the ZROT method, which restricted the bundles orientation, this method allows the comparison of bundles that share the same perspective center but which have different orientation in space (Figure 4). The purpose of 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 direct georeferencing with GPS. 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 direct georeferencing technique with GPS, using either IOP set, will also be similar.

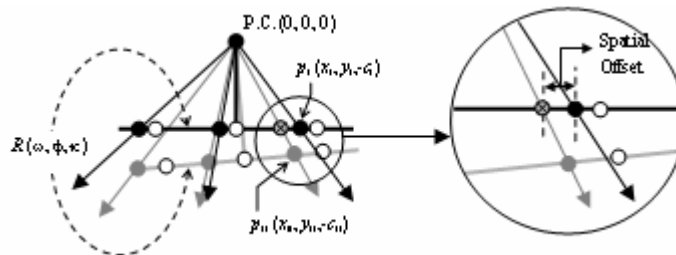


Figure 4. The two bundles in the ROT method are rotated to reduce the angular offset between conjugate light rays.

Single Photo Resection method (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.

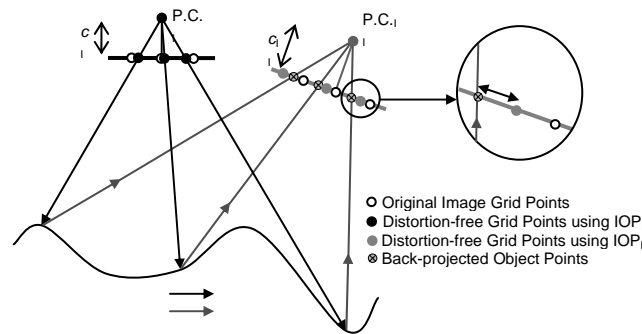


Figure 5. SPR method allows for spatial and rotational offsets between the two bundles to achieve the best fit. at a given object space.

PERFORMANCE AND STANDARDS

In section 2 of the paper, the need for clear and concise standards for camera calibration was explained. That is, 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. In section 3, it was acknowledged that digital imaging systems have not been created for the purpose of photogrammetry, 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.

It should be noted that a 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.

Standards and Specifications for MFDC 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 GSD, flying height, camera specifications, and the above categories.

Standards and Specifications for MFDC 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 $RMSE_{offset} : N/A$

Performance Assessment of MFDC

The expected accuracy of the derived positional information in photogrammetric applications is of utmost importance. Whether the end product requires a high degree of accuracy or not, it is nonetheless essential to be aware of the quality of the final product. With the increasing use of digital imaging systems for mapping purposes, several national and international organizations, including the USGS, BMGS, and EuroSDR, have begun addressing the issues of calibration and validation for these cameras. There is currently no defined outline or standards for mapping accuracies, which leads to different companies and individuals performing their own, independent analyses. Numerous tests have been already undertaken for Large Format Digital Cameras, such as the Vexcel UltraCamD (tested in Finland, U.K., and Australia), while a few investigations have also been done in terms of MFDC analysis (Mostafa 2003, Toth 1998), where the accuracy of derived object space points was investigated for the case of direct georeferencing. The next section of the paper will outline some standards and guidelines for positional accuracy that can be achieved using MFDC under various georeferencing methods and ground control/tie point configurations. Outlining clear standards and performance criteria will not only simplify and standardize accuracy analysis, but will also encourage the use of digital imaging systems.

Expected Performance

Although the use of onboard GPS/INS is becoming a trend in airborne mapping, in some cases INS or both GPS/INS are not available. Different companies have different resources and/or preferences – some prefer to use direct georeferencing with GPS/INS, some use direct georeferencing with GPS alone, while others prefer indirect georeferencing through the use of GCPs. These three scenarios thus deserve equal discussion and analysis, and will be the topics of discussion and comparison within this section.

A simulation program, developed by the Digital Photogrammetry Research Group at the University of Calgary, was used to simulate flight data for a 4x8 block of images (4 strips, with 8 images per strip). Direct and Indirect Georeferencing was performed for each test that was conducted, in order to compare and contrast the performance of MFDC and large format analogue cameras (LFAC). The performance of these tests is evaluated through check point analysis. Some variables were changed from one test to another, for the purpose of investigating the effect of the number and distribution of GCP (see Figure 6), the number of tie points per image, and the percentage of side lap between block strips. An additional analysis was done to investigate the effect on the derived object space accuracy due to biases in the IOP and the attitude parameters ω , ϕ , κ , under direct georeferencing. In order to make a direct comparison between these two formats, the simulations conducted in this section were performed for both MFDC and LFAC while maintaining the same GSD for both systems.

MFDC simulation specifications

- The camera of choice is a 60mm 22MP medium format digital camera, with a defined pixel size of 0.009mm.
- The GCP accuracy was set to 0.04m
- Image point measurement accuracy was set to 0.0045mm (1/2 pixel)
- GPS accuracy was set to 10cm for Direct Georeferencing
- INS accuracy was set to 18 second, 18 seconds and 29 seconds for ω , ϕ , κ , respectively
- IOP bias of 0.05mm and ω , ϕ , κ bias of 180 seconds (0.05°)
- The flying height was chosen as 1000m
- The base distance is 320m, and the GSD is 0.15m.

LFAC simulation specifications

- The camera of choice is 150mm, 9"x 9" image format, with a defined pixel size of 0.015mm
- All accuracies (GCP, GPS, INS and bias) were taken as the same as those listed in the MFDC specifications
- The image point measurement accuracy is set to 0.0075mm (1/2 pixel)
- The flying height is 1500m, the base distance is 920m, and the GSD is 0.15m.

Test 1

- The overlap was defined as: 60% overlap, 20% sidelap
- The tie point distribution: a 5x5 grid, for each image in the block

The Root Mean Squared Errors (RMSE) from the check point analysis were computed between the estimated and actual ground point coordinates for 5 scenarios, and the results are summarized in Table 3 and Table 4.

Table 3. RMSE of derived ground coordinates, for MFDC

	Direct with GPS only		Direct with GPS/INS			Indirect (4GCP)		Indirect (5GCP)		Indirect (10GCP)		Expected accuracy
	No bias	IOP bias	No bias	IOP bias	Bias in ω, ϕ, κ	No bias	IOP bias	No bias	IOP bias	No bias	IOP bias	
X(m)	0.1701	0.9092	0.0765	0.8535	0.9214	0.0997	0.1147	0.0994	0.1034	0.0778	0.0887	0.075
Y(m)	0.3737	1.1853	0.1644	0.9783	1.0959	0.1329	0.1368	0.1081	0.1031	0.0839	0.1177	0.075
Z (m)	0.3133	0.9552	0.2796	0.7954	0.3979	0.7651	0.8181	0.7471	0.7349	0.3596	0.3782	0.331

Table 4. RMSE of derived ground coordinates, for LFAC

	Direct with GPS only		Direct with GPS/INS			Indirect (4GCP)		Indirect (5GCP)		Indirect (10GCP)		Expected accuracy
	No bias	IOP bias	No bias	IOP bias	Bias in ω, ϕ, κ	No bias	IOP bias	No bias	IOP bias	No bias	IOP bias	
X(m)	0.0939	0.5208	0.0825	0.5185	0.5302	0.0991	0.1647	0.1256	0.1260	0.0918	0.0728	0.075
Y(m)	0.1172	0.4895	0.1015	0.4846	0.7684	0.1302	0.1359	0.1691	0.1252	0.9925	0.0956	0.075
Z (m)	0.1904	0.5742	0.1804	0.5757	0.5763	5.3629	4.1391	2.2952	1.7809	0.2106	0.1854	0.173

The expected accuracies were computed using the image scale, height-base ratio and the image coordinate measurement accuracy (1/2 pixel). The results from the simulations performed in Test 1 can be summarized as follows:

- From the RMSE results for MFDC (Table 3), when performing direct georeferencing under the conditions of Test 1, the inclusion of INS has a significant impact on the derived object space point accuracy. This is clearly seen by comparing the RMSE values in columns 1 and 3 in Table 3.
- In terms of indirect georeferencing, the number and distribution of GCP also has a significant impact on ground point accuracy, in particular in terms of the z-direction. For the case of 10GCP, the accuracy is comparable to that achieved from Direct with GPS/INS. The RMSE for indirect with 4GCP and 5GCP are similar to one another, yet are significantly less accurate in comparison with the 10GCP scenario.
- The bias in the IOP has a significant effect for both cases of direct georeferencing, yet is not significant at all in the results from indirect georeferencing, as the EOP compensate for the IOP biases. This observation applies to both the MFDC and LFAC results (Table 3 and Table 4), although the effect is more prevalent for the case of MFDC (1m vs. 0.5m)

- The bias in the attitude parameters, seen in the fifth columns of Tables 3 and 4, has a similar effect on the accuracy as the IOP bias.
- From Table 4, the results for the same test performed on a LFAC, it is seen that in contrast to MFDC, The GPS/INS georeferencing technique is only slightly more accurate than the other methods (by around 1-2cm).
- The three methods (Direct with INS/GPS, Direct with GPS only, and Indirect Georeferencing with 10 GCPs) yield similar accuracies, which meet the expected accuracies within 2-4cm. It can be concluded that for Direct Georeferencing with LFAC, the inclusion of INS does not have a significant impact on the determination of the attitude parameters.
- It can also be concluded, by inspecting the above RMSE value in Table 4, that the vertical accuracy from Indirect Georeferencing is strongly affected by the number and distribution of available GCPs. For the case of 5 GCPs, the vertical accuracy is in the range of 2m, while for the case of 4 GCPs the vertical accuracy decreases to around 5m.
- In comparison with the MFDC results in Table 3, it is observed that the number and distribution of GCPs more strongly affects the accuracy for LFAC than for MFDC, although both require a sufficient amount when the tie point distribution is limited to 5x5 within each image.
- For LFAC, the effect of the bias in the IOP and ω , ϕ , κ amounts to an average decrease in accuracy by around 0.4m for both Direct Georeferencing with GPS/INS and Direct with GPS alone.

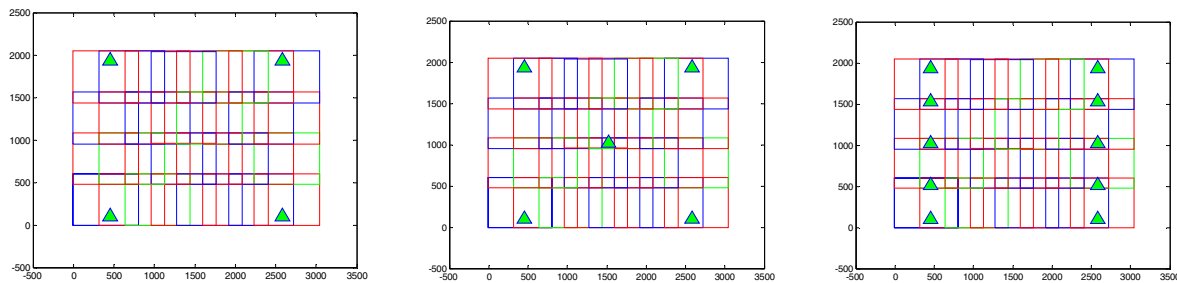


Figure 6. Distribution for the 4GCP, 5GCP and 10 GCP configurations.

Test 2

- The overlap was defined as: 60% overlap, 20% sidelap
- The tie point distribution: increased to a 7x7 grid, for each image in the block

The Root Mean Squared Errors (RMSE) were computed between the estimated and actual ground point coordinates for 5 scenarios, and the results are summarized in Table 5 and Table 6.

Table 5. RMSE of derived ground coordinates, for MFDC

	Direct with GPS only		Direct with GPS/INS			Indirect (4GCP)		Indirect (5GCP)		Indirect (10GCP)		Expected accuracy
	No bias	IOP bias	No bias	IOP bias	Bias in ω, ϕ, κ	No bias	IOP bias	No bias	IOP bias	No bias	IOP bias	
X(m)	0.1078	0.8213	0.0874	0.8539	0.8186	0.1166	0.1160	0.1012	0.1015	0.1135	0.1122	0.075
Y(m)	0.0977	0.8627	0.0830	0.8087	0.9200	0.1416	0.1404	0.0883	0.0890	0.1052	0.1037	0.075
Z (m)	0.3024	0.9263	0.2713	0.9131	0.4879	0.4162	0.4192	0.4149	0.4109	0.3110	0.3126	0.331

Table 6. RMSE of derived ground coordinates, for LFAC

	Direct with GPS only		Direct with GPS/INS			Indirect (4GCP)		Indirect (5GCP)		Indirect (10GCP)		Expected accuracy
	No bias	IOP bias	No bias	IOP bias	Bias in ω, ϕ, κ	No bias	IOP bias	No bias	IOP bias	No bias	IOP bias	
X(m)	0.1038	0.5609	0.0953	0.5465	0.7250	0.1102	0.1261	0.1174	0.0982	0.0790	0.0787	0.075
Y(m)	0.0955	0.4816	0.0969	0.4761	0.5910	0.1312	0.1374	0.1107	0.1150	0.0867	0.0875	0.075
Z (m)	0.1633	0.5363	0.1634	0.5495	0.7576	0.2843	0.2269	0.2293	0.1868	0.1593	0.1596	0.173

The results from the simulations performed in Test 2, where the tie point distribution was increased, can be summarized as follows.

- The RMSE results in Table 5 show that for the case of a 7x7 tie point distribution, Direct Georeferencing with GPS/INS yields slightly better accuracy (2-14cm), and most closely fit the expected accuracies, although the results from Direct with GPS only and Indirect with 10 GCP are also sufficiently accurate.
- Similar to the results in Test 1, the inclusion of 10 GCPs as opposed to 4 or 5 GCPs does not make a significant difference in terms of horizontal accuracy, but does affect the vertical accuracy by close to 10cm, for MFDC.
- Although the vertical accuracy of the Indirect Georeferencing with 4GCP and 5GCP is still around 10cm worse in comparison with the other methods, the extension of the point density in the image space has improved their accuracy from their previous 30cm difference as seen in Test1.
- A conclusion for the use of INS in the georeferencing, with Medium Format Digital Cameras with a tie point distribution of 7x7, is that from the increase in tie points, the INS data improves the accuracy by only a few cm.
- The bias effect as can be seen in Test 2 is similar to those in Test 1. For both the MFDC and LFAC, the bias in the IOP and the bias in the attitude parameters degrade the reconstructed object space coordinates when using direct georeferencing, but for indirect georeferencing the bias (in the IOP) does not have an effect on the derived ground coordinates. In addition, the bias in the IOP affects is more significant for the case of MFDC.
- Looking at the results from the simulation using a LFAC (Table 6), the results for Direct Georeferencing with GPS/INS, direct with GPS only, and Indirect georeferencing with 10GCPs all yield similar accuracies.
- The results from the Indirect Georeferencing with 4 GCPs and 5 GCPs may be slightly less accurate in comparison with the other methods, but their accuracies are still acceptable. Therefore, by adding more tie points we can reduce the required number of GCPs while still attaining acceptable accuracies, for LFAC.
- The effect of the bias on the LFAC simulation results in a decrease in accuracy by around 0.3-0.75m.

Test 3

- The overlap was defined as: 60% overlap, sidelap increased to 60%
- The tie point distribution: 7x7 grid, for each image in the block

The Root Mean Squared Errors (RMSE) were computed between the estimated and actual ground point coordinates for 5 scenarios, and the results are summarized in Table 7 and Table 8.

Table 7. RMSE of derived ground coordinates, for MFDC

	Direct with GPS only		Direct with GPS/INS			Indirect (4GCP)		Indirect (5GCP)		Indirect (10GCP)		Expected accuracy
	No bias	IOP bias	No bias	IOP bias	Bias in ω, ϕ, κ	No bias	IOP bias	No bias	IOP bias	No bias	IOP bias	
X(m)	0.0890	0.2514	0.0768	0.1772	0.8210	0.0792	0.0807	0.0789	0.0795	0.0783	0.0790	0.075
Y(m)	0.1064	0.4268	0.0895	0.1408	0.9892	0.0807	0.0813	0.0788	0.0793	0.0789	0.0792	0.075
Z(m)	0.2771	1.0913	0.2674	1.1177	0.5623	0.3585	0.3542	0.3099	0.3134	0.2998	0.2988	0.331

Table 8. RMSE of derived ground coordinates, for LFAC

	Direct with GPS only		Direct with GPS/INS			Indirect (4GCP)		Indirect (5GCP)		Indirect (10GCP)		Expected accuracy
	No bias	IOP bias	No bias	IOP bias	Bias in ω, ϕ, κ	No bias	IOP bias	No bias	IOP bias	No bias	IOP bias	
X(m)	0.0808	0.2070	0.0857	0.1897	0.5013	0.0885	0.0892	0.0852	0.0860	0.0792	0.0797	0.075
Y(m)	0.1093	0.2138	0.1049	0.1883	0.8771	0.1059	0.1065	0.0916	0.0916	0.1105	0.1105	0.075
Z(m)	0.1326	0.6512	0.1336	0.6407	0.8634	0.1834	0.1842	0.1311	0.1334	0.1641	0.1628	0.173

The results from the simulations performed in Test 3, where the sidelap was increased to 60%, can be summarized as follows.

- Table 7 reveals that, for this test scenario for MFDC, all methods yield similar accuracies which are all close to the expected accuracies.
- In particular, it should be noted that the inclusion of INS, in this test case, has not had a significant impact on the accuracy. This is an interesting observation, and agrees with the results found in Test 2 for the MFDC. That is, that INS does not contribute for georeferencing using MFDCs when there are sufficient tie points (7x7 in this case) or significant side lap.

- Another conclusion that can be drawn from this test is that when sufficient side lap exists in the images, the number of GCP that are required is reduced. This is seen in the RMSE Table 7, where the accuracy values for 4, 5 and 10 GCPs are all very similar, in comparison to Test 2, where the sidelap was 20% and the Indirect Georeferencing with 4 and 5 GCP produce 10cm deterioration in vertical accuracy.
- It is concluded that, for a 7x7 DEM with 60% endlap and sidelap, the inclusion of INS data for georeferencing with a MFDC does not significantly improve the ground coordinates estimation, and less GCP are required to achieve acceptable ground point accuracy.
- The effect of the IOP biases degrades the derived object space accuracy for this test case as well. The effect, however, is less significant in comparison to the Test 1 and Test 2 results, in terms of horizontal positional accuracy. For the case of MFDC, seen in Table 7, the error in derived ground coordinates due to the effect of the IOP bias has improved by around 30-60cm in horizontal positioning in comparison to Test 1 and Test 2. Therefore, the extension of the sidelap has mitigated the effect of the IOP bias on the derived ground coordinates. The effect from the attitude bias, however, is for the most part unchanged, as can be seen in Table 7, column 5.
- Table 8 shows the RMSE for the various georeferencing methods from this simulation for a LFAC with a 7x7 DEM and 60% overlap and sidelap. The RMSE for the various methods are all quite similar, and all methods yield accuracies that are consistent with the expected accuracies
- The results from LFAC for direct georeferencing with GPS only is very similar to the results for direct with GPS/INS, and thus the conclusion for this test case is that the inclusion of INS data is not required.
- For the LFAC, the IOP bias degrades the positional accuracy, although the horizontal effect for direct georeferencing has improved in comparison to the results from Test 1 and Test 2. The error in the derived horizontal ground coordinates have improved by around 30cm. There is, however, no change in vertical accuracy. The effect of the attitude bias has not changed from previous test results, and thus is still significant for direct georeferencing with GPS/INS.
- It can also be noted, that the results from the Indirect Georeferencing with 4, 5 and 10 GCPs are similar, and thus for this scenario we do not require a large number of GCP to achieve acceptable accuracy of the ground points.
- Therefore, similar conclusions are draw for both MFDC and LFAC under this test situation

CONCLUSION

Camera calibration is an important procedure, and new users of any camera systems 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 reduces the required number of point features necessary for in-situ or indoor calibration. From personal experience, the calibration process can be long and tiresome when performed manually. The procedures outlined 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 insure that the IOP of the selected camera(s) are stable over time. Three methods for the determination of camera stability have been outlined. In addition to the procedures described 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 Surveys, was 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.

The final area of investigation, once camera calibrated and validation are completed, is to perform pre-flight analysis to determine the appropriate equipment and ground information required, based on the desired product accuracy. The accuracy of the derived ground coordinates has been shown to be a function of tie point density and ground control point quantity and distribution, as well as the percentage of sidelap between flight strips. The attainable accuracies for various flight configurations were presented, and from these results several comparisons can be made between MFDC and LFAC. It has been determined that when there is a limited number of available tie points; the incorporation of INS in georeferencing provides significant accuracy improvement in the case of MFDC and has little effect for LFAC, yet the number of available GCPs has an impact on the derived object space accuracy (in particular the vertical accuracy) for both MFDC and LFAC. When the tie point density is increased it was found that; the addition of INS is no longer critical for accuracy (offers an improvement of a few cm) for the MFDC, while the amount of GCPs continues to affect the MFDC and LFAC accuracy,

although the achievable accuracy has improved through the increase in tie points used. Finally, when the sidelap is increased from 20% to 60%; in the case of the MFDC, good accuracies can be achieved using less GCPs, which is also seen in the case of LFAC, where the number of GCPs no longer has a significant impact on the accuracy of the derived object space.

The tests and analysis described in this paper present the preliminary work being conducted by the DPRG group at the University of Calgary, in collaboration with the USGS and the BMGS, in the joint effort to produce definite standards and specifications for digital camera calibration and stability analysis, in addition to outlining achievable accuracies for various integrations of sensor data and ground control for airborne mapping. Once clearly defined standards are accepted, the accuracy of the final product will be definite thus ensuring high quality work, customer satisfaction, and offering well-founded encouragement for the use of digital imaging systems in current and emerging markets.

ACKNOWLEDGMENTS

The authors would like to acknowledge the collaboration and financial support provided by the British Columbia Base Mapping Geomatic Services, the U.S. Geological Surveys, and NSERC.

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