STUDY OF STABILITY ANALYSIS OF THE INTERIOR ORIENTATION PARAMETERS FROM THE SMALL-FORMAT DIGITAL CAMERA USING ON-THE-JOB CALIBRATION

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ABSTRACT:

Small and medium format digital cameras are widely used in Photogrammetric applications due to their accessibility, availability and quick image acquisition and processing. In addition, the resolution of these cameras has significantly increased while their prices decreased. Generally, a small-format digital camera does not have a pre-definition of the internal geometric characteristics, commonly known as the interior orientation parameters (IOPs), which are computed by a bundle adjustment with a self-calibration procedure that uses a set of images, geometrically acquired over the calibration test field. However, to extract precise and reliable 3D metric information from images, an important condition should be considered: are the interior orientation parameters accurate enough for photogrammetric applications? Usually, the camera calibration procedure is performed using a target or a linear test field, regardless of the photogrammetric project that will be performed later. For photogrammetric applications, the camera should be stable and the interior orientation parameters should not vary over time. Considering airborne photogrammetric mapping, the digital camera is exposed to different conditions from the ones registered during the terrestrial calibration procedure. Two aspects should be discussed: Do the interior orientation parameters change? Do the changes modify the quality of the derived information? In this paper we try to answer these questions. The digital camera Kodak DCS Pro 14n is calibrated under different conditions to determine the geometric stability of the Interior Orientation Parameters. Using traditional terrestrial calibration and airborne (on-the-job) calibration procedures, the camera is calibrated in two different situations. Mathematic correlations of interior orientation parameters within themselves and with exterior orientation parameters are examined and discussed. Two external target test fields are used to perform all experiments. The geometric stability for the camera is presented and discussed. Airborne photogrammetric experiments, using different sets of interior orientation parameters, are performed to verify the precision of 3D object position at different calibration process. Finally some conclusions are drawn from the experimental results, and future recommendations are proposed.

1. INTRODUCTION

Nowadays, small format digital cameras have been applied in many photogrammetric applications. Frequently, these cameras do not have information about their internal geometric characteristics, commonly known as the interior orientation parameters (IOPs). Without this information, the systematic errors in the image measurements can not be modeled, and therefore the derived metric information in the object space is degraded in terms of accuracy. So, to qualify these cameras for the photogrammetric application, a calibration procedure must be applied to compute the interior orientation parameters. The most common calibration method uses a set of images, geometrically acquired over a calibration test field and a bundle adjustment with a self-calibration to estimate the IOPs.

Camera calibration, using self-calibration procedure and small-format digital camera, is a research topic with an extensive number of papers written by photogrammetric and computer vision researchers. Fraser (1997) reviewed the mathematical formulation of self-calibration procedure and discussed the main sources of image deviations from collinearity model. Mitishita et al. (2003) used a set of aerial convergent video images over a target test field and bundle adjustment with self-calibration to compute the IOPs of the video camera HITACHI onboard the Robinson R-44 Newscopter helicopter to perform photogrammetric applications. Habib et al. (2002), Habib & Morgan (2005) and Tommaselli & Telles (2006) used object space straight lines in a bundle adjustment with self-calibration, considering that any deviations from a straight line projected in the image space are modeled by distortions parameters. Cronk et al. (2006) showed a methodology to calibrate color low-cost digital camera using bundle adjustment with self-calibration. Additionally, a procedure to measure targets and an approach to compute initial values for the parameters of the exterior orientation parameters of the camera stations, without human intervention, were developed.

Together with the quality of IOPs estimation, their temporal stability should be considered for photogrammetric application. Regarding this subject, there is a small number of papers about the stability analysis of the small-format digital cameras. This reduced number of literature can be attributed to the lack of standards for quantitative analysis of camera stability (Habib And Morgan, 2005). Commonly, a statistical test is used to verify if two IOPs sets are equivalent or not. Having some

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uncertainty to perform the statistical test, Habib et al. (2006) proposed three methodologies for testing camera stability based on the degree of similarity between the reconstructed bundles using two sets of IOPs. In the first, called Zero Rotation Method (ZROT), two bundles of rays in the same position and orientation were fixed. It is analogous to direct geo-referencing procedure. The second is called Rotation Method (ROT), which consists of bundles rotating relative to each other to achieve the best solution. This method is similar to indirect geo-referencing procedure. In the last, called the Single Photo Resection Method (SPR), the bundles can rotate and shift in order to assure the best fit at the object space, similarly to conventional bundle adjustment.

Machado et al. (2003) performed the stability analysis of the Sony DSC-F717 digital camera that was calibrated three times over two months of regular use. The analysis from three sets of IOPs concluded that they are approximately equal, so the camera was considered stable over the test period. In Habib & Morgan (2005) the Sony DSC-F707 digital camera was calibrated two times over ten months of regular use to perform the stability analysis, resulting in almost identical IOPs from two calibrated sessions. Wackrow et al. (2007) verified the stability and manufacturing consistency of seven Nikon Coolpix 5400 digital cameras over a year, that were calibrated four times over this period. The temporal stability was performed by comparing 3D coordinates of check-points determined by photogrammetric intersection and DEM generation, using different sets of IOPs. To assess the manufacturing consistency, the same methodology was used, but the photogrammetric processes were performed using images from one camera with IOPs from another. Using images of a test field that were taken from 1.5 m of distance, the performed experiments yield millimetric accuracy, whichever combination of image sets and IOPs was used. Rieke-Zapp et al. (2009) reported that latest digital camera types have included some features such as sensor vibration for removal of dust particles and sensor movement to reduce the effect of camera shaking during the image acquisition. These features cause possible instability of the sensor position, which is not allowed in photogrammetry. The authors mentioned before analyzed the performance of eleven digital cameras to derive measurements in the object space. In the calibration process, the parameterization of geometric instabilities using a model of an image variant for interior orientation improved the results for most cameras. Mitishita et al. (2009) verified the stability of the Sony DSC-F828 digital camera when it was exposed to a variation of environmental temperature. In two calibrations the temperature was close to zero degrees Celsius, and in four calibrations the temperature was close to twenty-five degrees Celsius. The values of IOPs from the six performed calibration were not similar, so the Sony digital camera was considered geometrically unstable and the experiment performed did not prove if a great variation of environmental temperature changes significantly the values of IOPs.

According to Habib et al. (2006), photogrammetric processes, using exterior orientation parameters (EOPs) from direct geo-referencing procedure, have strict requirements regarding the stability of the internal characteristics of the camera. In such a case, slight changes in the IOPs will have a negative effect on the quality of the reconstructed object space. On the other hand, using EOPs from indirect geo-referencing procedure, the inaccuracy in IOPs can be compensated by EOPs estimation. Considering airborne photogrammetric mapping, the digital camera is exposed to different conditions from the one registered during the calibration procedure. Two aspects should be discussed: Do the interior parameters change? Do the changes modify the quality of the derived information? In the paper we try to answer these questions. A digital camera Kodak DCS Pro 14n is calibrated under different condition to determine the geometric stability of the Interior Orientation Parameters. Using traditional terrestrial calibration and airborne (on-the-job) calibration procedures, the camera is calibrated in two different situations. Mathematic correlations of interior orientation parameters within themselves and with exterior orientation parameters are examined and discussed. Two external target test fields are used to perform all experiments. The geometric stability for Kodak camera is presented and discussed. Airborne photogrammetric experiments, using different sets of interior orientation parameters, are performed to verify the precision of 3D object position at different calibration process. Finally some conclusions are drawn from the experimental results, and future recommendations are proposed.

The following four sections present a small discussion about on-the-job-calibration, the used camera in this research and procedures used for evaluation of geometric stability of the Kodak digital camera through on-the-job-calibration. Finally, in the last two sections, the obtained results from the performed experiments are shown and discussed, as well as the conclusions and recommendations for future work.

2. ON-THE-JOB-CALIBRATION

Merchant (1980) classifies the calibration procedures as a Component and System method; he also defines calibration as a procedure to compute a set of parameters which describes the metric character of the measurement system, related with the quality of its performance. Furthermore, Merchant summarizes the concept of measurement system calibration according to Eisenhart (1963). Using calibration data acquired while performing the job (*in situ*), the Camera Calibration method is close to the concept defined by Eisenhart for the system calibration. Traditionally, in close range or terrestrial applications, a system calibration is used when a testfield is fixed in the job area and a set of convergent images are taken in the same epoch and job circumstances. On the other hand, for aerial applications due to linear dependency, which exists between three paired elements of interior and exterior orientation in case of vertical images and flat terrain, the *in situ* calibration was not easy to apply (see Merchant, 1979). Today, the facilities established to connect cameras with **GPS** System to determine 3D coordinates of the exposure station's position have allowed a system calibration (*in situ)* for aerial photogrammetric application. The experiments performed in this work showed that the Bundle Adjustment using 3D coordinates of the exposure station's position from GPS survey requires *in situ* calibration to get the same precision of the traditional Bundle Adjustment.

3. USED CAMERA

The Kodak pro DCS-14n digital camera, mounted with 35 mm Nikon lens was used to carry out this research. The CMOS sensor has 14 million effective pixels. The type is 2/3" with the size: diagonal equal 43 mm; width equal 36 mm and height equal 24 mm. The pixel size is 0.0079 mm. The images used on this research have 4500 x 3000 pixels. The camera was connected with the Optech Airbone Laser Scanner ALTM 2050 to direct extraction of the position and orientation of the images. More detail about this adaption can be found in Martins, 2010.

4. CAMERA CALIBRATION

Two target testfields were used to perform the proposed research. The first is a two-dimensional testfield with forty-five targets that were precisely surveyed using a total station. This testfield was established on a large wall on the side of a building. The accuracy of the 3D target coordinates is close to one millimeter. The second testfield area, approximately 4 km^2 in size, lies within the suburban area of the city of Curitiba (State of Paraná – Brazil). Before the aerial surveys, 70 pre-signalized control points were painted on the streets within the testfield area. The target was a circle with a 60 cm diameter, marked with PVA paint (Poly-Vinyl Acetate). White color was chosen to yield a better contrast against the black background of the asphalt. The three-dimensional coordinates of the 70 points were acquired through precise GPS surveying techniques. The accuracy of the 3D target coordinates acquired from GPS survey is close to one centimeter.

Using both testfields, the Kodak camera was calibrated by bundle adjustment with self-calibration. The principal distance, the coordinates of the principal point, and the parameters of radial and decentring lens distortions are the Interior Orientation Parameters (IOPs) considered in this work. The multi-camera convergent method is used in the terrestrial calibration and a procedure is used in the aerial calibration to minimize the linear dependency between the interior and exterior orientation parameters.

5. STABILITY ANALYSIS

The stability analysis aims to verify if the internal characteristics of a camera, over different methods of calibration, change significantly to modify the accuracy of derived information from the images. Generally, the analysis is carried out by comparing the performance of two sets of IOPs to find out if they are similar at the moment of exposure, by using them to reconstruct the bundle of light rays that was measured on the image. In this research, the bundle adjustment aided by 3D coordinates of the exposition station position and conventional bundle adjustment, using different sets of IOPs, are used to perform the IOPs stability analysis. The aerial image block covering urban region (the second testfield) is used to perform the stability analysis experiments. From the experiments results that were performed with different sets of IOP, the stability of the camera over a terrestrial and aerial calibration is evaluated

6. RESULTS AND DISCUSSIONS

6.1 Terrestrial Calibration

The principal distance was fixed manually at infinity focus and twelve convergent images were acquired in 2009 from three different camera stations with four roll angles each (0°, ±90° and 180°). The target images were measured by manual monocular process. The self-calibration was performed, using half of one pixel (0.00395 mm) for the standard deviation of the image coordinates and one millimeter for the standard deviation of the targets coordinates on the object space. The main results from the performed calibrations are shown in Tables 1, 2, 3 and 4.

c (mm)	**σ_c (mm)**	**x_p (mm)**	**σ_{xp} (mm)**	**y_p (mm)**	**σ_{yp} (mm)**
35.506	0.012	-0.123	0.005	-0.098	0.006

k_1 (mm^{-2})	**σ_{k1} (mm^{-2})**	**K_2 (mm^{-4})**	**σ_{k2} (mm^{-4})**
-7.0631e^{-5}	1.0635 e^{-6}	6.5727 e^{-8}	2.3956 e^{-9}

(**c**)= Principal distance

(**x_p ,y_p**)= Coordinates of principal point;

(**k_1, K_2**)= Radial lens distortion; (**σ**)= Standard deviation

Table 1. The interior orientation parameters (IOPs) computed in the terrestrial calibration that were significant on the variance-covariance matrix

c	1.0000				
x_p	-0.1945	1.0000			
y_p	0.2754	-0.0874	1.0000		
k_1	-0.4646	0.1806	-0.1759	1.0000	
k_2	0.4064	-0.0508	0.0828	-0.8973	1.0000

Table 2. Correlation matrix between IOPs computed in the terrestrial calibration

	c	**x_p**	**y_p**	**k_1**	**k_2**
Omega	0.1333	0.2201	0.3021	0.0989	0.0747
Phi	0.2547	0.2727	0.2589	0.1420	0.0589
Kappa	0.1222	0.2238	0.3395	0.0955	0.0391
Xo	0.5510	0.1623	0.1750	0.1124	0.1198
Yo	0.1069	0.1204	0.1271	0.0467	0.0613
Zo	0.7976	0.1028	0.2126	0.1709	0.2014

Table 3. Mean absolute correlation matrix between the IOPs and EOPs computed in the terrestrial calibration

Measurements				
Image coordinates residuals		Object coordinates residuals		
Rmse x (mm)	**Rmse y** (mm)	**Rmse X** (m)	**Rmse Y** (m)	**Rmse Z** (m)
0.003	0.002	0.001	0.001	0.003

A posteriori variance (**$\sigma_{o)}$**) : 0.5353

Rmse: Root mean square error

Table 4. Main values computed from the observation residuals in the terrestrial calibration

The obtained results from the performed calibration revealed that the IOPs were computed according to the expected precision. The computed values of the root mean square errors from the residuals, shown in Table 4, are very close to the measurements precisions assumed in this calibration. The parameters of the lens distortion, that were insignificant in the variance and covariance matrix from the previous adjustment, were set to zero and a new adjustment was performed to compute the significant parameters. In the final results, only the parameters k_1 and k_2 were deemed significant for the model of radial lens distortion. The values of k_1 and k_2 reveal that the Kodak camera has big radial lens distortion on the image borders, close to 0.4 mm. A high correlation was found with k_1 and k_2 parameters. This high correlation is normal for radial lens distortion model and it demonstrates that the radial lens distortion can be modeled by only one parameter. In this work, the k_1 and k_2 parameters were used due to their significance in the variance and covariance matrix. A non favourable correlation was found with the principal distance and Z coordinates of the exposure station (Zo) because the maximum roll convergent angle found with two images was close to 73°. Therefore, convergent images with orthogonal roll angles must be applied to fix this correlation when the flat testfield is used.

6.2 Aerial Calibration

The aerial image block used in this research, has twenty-three images acquired in two strips, using opposite flight directions (approximate West-East and East-West). The flight height was close to 1,000 meters, resulting in a ground sample distance (GSD) close to 23 centimeters. Using the large side of the image, the forward and side overlaps were close to 60% and 40% respectively. The urban area of the second testfield was covered by the aerial survey. All images in the block have the 3D coordinates of the exposure station's positions computed via precision GPS survey.

The 3D coordinates of the exposure station's positions were fixed in the aerial calibration to minimize the high correlation between IOPs and EOPs. This procedure was considered, in this work, as system calibration to estimate the IOPs inside the same work circumstances.

In this calibration the 3D coordinates of the exposition stations' positions, computed via GPS survey, were fixed in the self-calibration process. The image block acquired in 2006 has forty-five pre-signalized points and one hundred and fifty-three natural image pass points. All the pre-signalized points have 3D coordinates determined via precise GPS survey and were used as ground control points in the experiment. The self-calibration was performed, using half of one pixel (0.00395 mm) for the standard deviation of the image coordinates and one centimeter for the standard deviation of the ground control points coordinates on the object space. The value of one centimeter was the estimated precision of the GPS 3D coordinates. The main results from the performed calibrations are shown in Tables 5, 6, 7, 8, 9, 10 and 11.

c (mm)	**σ_c** (mm)	**x_p** (mm)	**σ_{xp}** (mm)	**y_p** (mm)	**σ_{yp}** (mm)
35.534	0.002	-0.166	0.002	-0.171	0.003

k_1 (mm^{-2})	**σ_{k1} (mm^{-2})**	**K_2 (mm^{-4})**	**σ_{k2} (mm^{-4})**
- 7. 1015 e^{-5}	5.4759 e^{-7}	6. 4643 e^{-8}	1.3363 e^{-9}

(**c**)= Principal distance
(**x_p ,y_p**)= Coordinates of principal point;
(**k_1, K_2**)= Radial lens distortion; (**σ**)= Standard deviation

Table 5. The interior orientation parameters (IOPs) computed in the aerial calibration that were significant on the variance-covariance matrix

c	1.0000				
x_p	0.0734	1.0000			
y_p	0.0218	-0.0493	1.0000		
k_1	-0.8770	-0.1051	-0.0124	1.0000	
k_2	0.7943	0.1416	-0.0401	-0.9748	1.0000

Table 6. Correlation matrix between IOPs computed in the aerial calibration

	c	**x_p**	**y_p**	**k_1**	**k_2**
Omega	0.0329	0.1432	0.9434	0.0322	0.0128
Phi	0.0424	0.7441	0.5784	0.0742	0.1296
Kappa	0.0126	0.0285	0.0692	0.0135	0.0126
Xo	0.0011	0.0077	0.0017	0.0012	0.0013
Yo	0.0005	0.0030	0.0039	0.0007	0.0008
Zo	0.0068	0.0062	0.0047	0.0028	0.0034

Table 7. Mean absolute correlation matrix between the IOPs and EOPs computed in the aerial calibration

	c	**x_p**	**y_p**	**k_1**	**k_2**
X	0.0190	0.0158	0.0164	0.0212	0.0231
Y	0.0192	0.0104	0.0260	0.0153	0.0131
Z	0.0371	0.0266	0.0562	0.0284	0.0302

Table 8. Mean absolute correlation between the IOPs and pass points coordinates computed in the aerial calibration

Measurements				
Image coordinates residuals		Object coordinates residuals		
Rmse x (mm)	**Rmse y** (mm)	**Rmse X** (m)	**Rmse Y** (m)	**Rmse Z** (m)
0.003	0.003	0.003	0.002	0.001
A posteriori variance (**σ_o**) : 0.644				
Rmse: Root mean square error				

Table 9. Main values computed from the observation residuals in the aerial calibration

Image (4) in the strip 1 – Flight direction: East-West					
Omega= 1.326°; Phi= 2.917° ; Kappa= 197.532°					
	c	**x_p**	**y_p**	**k_1**	**k_2**
Omega	-0.0297	-0.1086	-0.9534	0.0320	0.0114
Phi	0.0416	0.7828	-0.5109	-0.0900	0.1450
Kappa	0.0265	0.0217	0.0562	-0.0235	0.0208

Table 10. Correlation between the IOPs and orientation parameters of the image (4) computed in the aerial calibration

Image (15) in the strip 2 – Flight direction: West-East					
Omega= 0.236°; Phi= -1.683° ; Kappa= 22.572°					
	c	**x_p**	**y_p**	**k_1**	**k_2**
Omega	0.0218	0.1606	0.9550	-0.0267	-0.0156
Phi	-0.0452	-0.7483	0.6145	0.0925	-0.1507
Kappa	0.0069	0.0531	0.0434	0.0054	-0.0060

Table 11. Correlation between the IOPs and orientation parameters of the image (15) computed in the second aerial calibration

Comparing the IOPs values computed in this calibration with those from the terrestrial calibration, a small variation on the principal distance and the principal point coordinates was verified. The different values for these parameters were expected due to the fact that in the aerial calibration procedure the positions of the exposition stations were fixed. On the other hand, the results from this calibration associated with measurements precisions and the parameters of the radial lens distortion are much similar to those computed in the terrestrial calibrations. The Figure 01 shows a small variation of the radial lens distortion in the performed calibrations. Another similarity with the two performed calibrations is related to a correlation between the k_1 and k_2 parameters in each calibration, which kept their values approximately equal. However, there are different large correlations between parameters that occurred in this calibration. The notable large correlation, showed in Table

6, happened between the principal distance and parameters of the radial distortion. Due to the fact that the principal distance was estimated with high precision and the radial lens distortion was the same in both calibrations, this large correlation only shows the relationship that the parameters of radial lens distortion have with the principal distance. It is well-known that the values of radial lens distortion change, without alteration of the projective ray, when the principal distance has a small alteration. Other large correlations, showed in Table 7, happened between the principal point coordinates and two parameters of image orientation (Omega and Phi). These correlations indicate that the position of principal point becomes highly correlated with the Omega and Phi parameters when the horizontal position of the image (Xo, Yo) was fixed. The variation of the four involved parameters happens together with same or opposite direction as showed in Tables 10 and 11. Even having such a high correlation, the parameters that represent the coordinates of principal point ($\mathbf{x_p}$,$\mathbf{y_p}$) were estimated precisely as can be seen Table 5. The non-correlation between the Kappa parameter and principal point coordinates is expected since this rotation does not change the position of principal point in the image coordinate system. The values of correlations parameters between the pass points coordinate (X, Y, Z) and IOPs, shown in Table 10, were deemed insignificant, even having a large number of pass points planned in the block and their 3D coordinates (X, Y, Z) computed simultaneously with the IOPs.

6.3 Stability analysis

The stability experiments were performed using the aerial image block with the same set of ground control points and precision values for image and ground coordinates, which were applied in the aerial calibration. For each experiment, using different sets of IOPs from the performed calibration, the image measurements are previously corrected from the principal point displacement and the radial lens distortion. Afterward, the photogrammetric bundle adjustments are performed and the obtained residuals were analyzed to verify the level of the precision quality. Finally, the photogrammetric pass points coordinates, computed in the aerial calibration, are compared from the pass points coordinates calculated in the bundle adjustment experiments. The obtained results are analyzed to perform the IOPs stability from terrestrial and aerial calibrations as well in photogrammetric bundle adjustments. The main analysis results are shown in Tables 12 and 13.

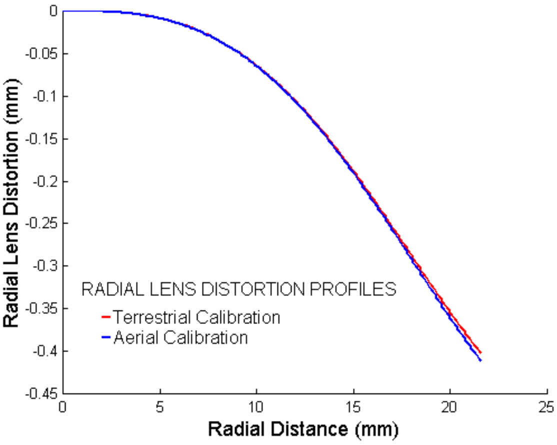

Figure 01. Radial lens distortion profiles from terrestrial and aerial calibration

RESIDUALS ANALYSIS						
Experiment	Image coordinates residuals (mm)		Object coordinates residuals (m)			A posteriori variance
	Rmse x	**Rmse y**	**Rmse X**	**Rmse Y**	**Rmse Z**	**(σ_0)**
1	0.003	0.003	0.003	0.002	0.001	0.6473
2	0.005	0.004	0.004	0.003	0.002	1.9449
3	0.003	0.003	0.003	0.002	0.001	0.7064
4	0.003	0.002	0.003	0.002	0.001	0.6547

Table 12. Main results of the residuals analysis performed in bundle adjustment experiments

DISCREPANCIES ANALYSIS						
Experiment	Mean Values of the Discrepancies (m)			Root Mean Square Error of the Discrepancies (m)		
	µ (DX)	**µ (DY)**	**µ (DZ)**	**Rmse (DX)**	**Rmse (DY)**	**Rmse (DZ)**
1	0.000	-0.001	-0.003	0.005	0.005	0.017
2	-0.023	-0.001	-0.626	0.074	0.048	0.720
3	-0.004	-0.005	0.069	0.039	0.031	0.153
4	0.002	-0.007	0.007	0.028	0.021	0.095

Table 13. Main results of the discrepancies analysis performed in bundle adjustment experiments

The Table 12 shows results from the photogrammetric bundle adjustment, performed with the combination of two sets of the IOPs and four configurations. In the experiments 1 and 2, the bundle adjustment aerotriangulation procedures used weight constraints to fix the 3D coordinates of the images exposition stations' positions. They use IOPs, respectively, from the aerial and terrestrial calibration. The 3D coordinates of the exposition stations positions were fixed with the same precisions that were applied in the calibration process. In the experiments 3 and 4, the conventional bundle adjustment aerotriangulation procedures were performed; they use the IOPs, respectively, from the terrestrial and aerial calibration.

The Table 13 shows results from the analysis of discrepancies that were yielded by the subtraction of the 3D coordinates of the pass point from the aerial calibration with those 3D coordinates computed in bundle adjustment aerotriangulation experiments.

The stability analysis experiments were conducted to verify the precision or internal precision of the bundle adjustment aerotriangulation procedures only, using two sets of IOPs. The four experiments performed in this research did not use check points to analyze the external precision or accuracy.

The obtained results in the experiment 1 are evident since it uses the same conditions and IOPs applied in the aerial calibration. This experiment was accomplished to evidence the importance of the system calibration to perform the bundle adjustment aerotriangulation aided by 3D coordinates of the exposition station's position. The lower precision results from the experiment 2, when the IOPs from terrestrial calibration were used, confirm this conclusion.

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The experiments 3 and 4 were conducted to analyze the stability of the IOP sets, computed in the calibration procedures, to perform the conventional bundle adjustment. The precision results from these experiments are very close to each other, proving the well-known conventional bundle adjustment property "the small inaccuracies in the values of IOPs can be compensated by the variation EOPs values". So, the conventional bundle adjustment, using IOPs from terrestrial or aerial calibration procedures, produced similar precision results.

7. CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

The stability analysis of the interior orientation parameters from the on-the-job calibration of the small format digital camera has been studied, discussed and shown. Terrestrial and aerial testfields were used to perform the calibration procedures and photogrammetric stability analysis. One aerial image block from the aerial testfield was captured by a Kodak DCS Pro 14n digital SLR camera in 2006. It was used in the performed system calibration method and stability analysis experiments. The image block has the positions of the exposure stations computed via precise GPS survey and a large set of the pre-signalized points with a GPS 3D coordinates. The bundle adjustment aerotriangulation aided by 3D coordinates of the exposition station's position and a conventional bundle adjustment aerotriangulation were applied to perform the IOPs stability analysis. Considering the results from the performed calibration procedures and carried out experiments, the following conclusions are drawn:

The system calibration, using data acquired while performing the job (*in situ*), was a fundamental procedure to compute IOPs necessary to perform the bundle adjustment aerotriangulation aided by 3D coordinates of the exposition station's position. Accurate values of IOPs are the prerequisite to perform this type of the aerotriangulation with same level of the horizontal and vertical precisions, which have been yielded in the conventional bundle adjustment aerotriangulation. On the other hand, aerial or terrestrial calibration procedures can be used to compute IOPs necessaries to perform the conventional bundle adjustment aerotriangulation with similar horizontal and vertical precisions. Conventional bundle adjustment does not require accurate IOPs because its inaccuracies are compensated by the changes in the EOPs' values.

The IOPs values that were computed in the terrestrial and aerial calibrations are too similar, although the calibration methods using too different procedures to minimize the correlation between IOPs and EOPs. The values of radial lens distortion parameters from both calibrations are too similar, as can be seem the radial lens distortion profiles in Figure 1. Moreover, the values of principal distance and principal point coordinates from both calibrations have a small difference. The parameters correlation remained in the calibration methods can be the probable cause of these differences.

Considering the calibration procedures performed in this research, it was impossible to eliminate completely every high correlation between IOPs or between IOPs and EOPs. The correlation problem is a well-known topic in the calibration process. Generally, the calibration methods are classified according to the procedure used to fix the linear dependency between IOPs and EOPs. However, other non-severe correlations remain in the mathematical process, making it difficult to calculate the correct value of the parameters that represents the real physical effects.

Important correlations were found in the aerial system calibration procedure used in this research. They are associated with EOPs, principal point position and the principal distance. When the planimetric position of the exposition stations (Xo, Yo) was fixed, the correlations between principal point position ($\mathbf{x_p}$,$\mathbf{y_p}$) and two orientation parameters of the exposition station (Omega and Phi) increase in the process. Addition, when the vertical position of the exposition station (Zo) was fixed a significant large correlation happened between radial lens distortion parameters and the principal distance value. These correlations can produce difficulties to compute the correct values of the IOPs in the calibration process. The instabilities in the values of the principal point's position and principal distance from two calibrations can be directly related with these correlations. Additionally, any inaccuracies in the 3D coordinates of the exposition station's position (Xo, Yo, Zo) can reflect directly in the IOPs values.

For the aerial calibration method, performed in this research, the correlations between the principal point position and two orientation parameters of the exposition stations (Omega and Phi), discussed before, disable the real determination of the principal point coordinates since they are dependent of the flight conditions or the image block properties. On the other hand, when the terrestrial calibration method was applied, significant correlations between IOPs and EOPs remained in the process, making it difficulty to calculate the real IOPS values. So, these correlations reveal the importance of the on-the-job calibration to perform the bundle adjustment aerotriangulation aided by 3D coordinates of the exposition station's position.

In the aerial calibration procedures performed in this research, the values of correlations parameters between the pass points coordinate (X, Y, Z) and IOPs were deemed insignificant and they demonstrate the non-correlations with these parameters

Future work will concentrate on a verification of the quality and performance of the IOPs from different methods for aerial system calibration to perform the bundle adjustment aerotriangulation aided by 3D coordinates of the exposition station's position and conventional bundle adjustment, using image blocks captured in different scales, flight orientations and epoch. Additionally, the study for the definition of the excellent number of ground control points in the block and accuracy analysis for the obtained results will be conducted

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REFERENCES

CRONK, S., FRASER. C.S. AND HANLEY, H.B., 2006. Automated Metric Calibration of Colour Digital Cameras. *Photogrammetric Record*, Vol. 21, No. 116, pp. 355-372.

EISENHART, C. S., 1963. Realistic Evaluation of the precision and accuracy of instrument calibration systems. *Journal of research of the national bureau of standards*, vol. 67c, No 2, pp. 161-187. April/June, 1963.

FRASER, C. S., 1997. Digital camera self-calibration. *ISPRS Journal of Photogrammetry and Remote Sensing*, 52(4): 149–159.

HABIB, A., MORGAN, M., LEE, Y., 2002. Bundle Adjustment with Self-Calibration using Straight Lines, *The Photogrammetric Record*, 17(100):635–650.

HABIB, A. AND MORGAN, M., 2005. Stability analysis and geometric calibration of off-the-shelf digital cameras. *Photogrammetric Engineering & Remote Sensing*, 71(6): 733–741.

HABIB, A., PULLIVELLI, A., MITISHITA, E., GHANMA, M. and EUI-MYOUNG KIM, 2006. Stability analysis of low-cost digital cameras for aerial mapping using different Georeferencing Techniques. *Photogrammetric Record Journal*, 21(113): 29-43.

MACHADO, A. M. L., MITISHITA, E., SANTOS JR, R. L., BARBOSA, F. P., 2003. Verificação da estabilidade geométrica dos parâmetros de calibração de uma câmera digital de pequeno formato Sony-F717. In: Mitishita, Edson Aparecido. (Org.). *Série em Ciências Geodésicas – Novos desenvolvimentos em Ciências Geodésicas*. Curitiba, v. 3, p. 292-309. ISBN: 85-88783-04-5.

MARTINS, M, A, R, 2010. Geração de ortoimagem a partir de georreferenciamento direto de imagens digitais aéreas de pequeno formato com dados lidar. 2010. 131 páginas, Dissertação (Mestrado *em Ciências Geodésicas)* – Setor de Ciências da Terra - Universidade Federal do Paraná – Curitiba – Paraná.

MERCHANT, D, C, 1979. *Analytical Photogrammetry – Theory and Practice – Part I*. Department of Geodetic Science – The Ohio State University.

MERCHANT, D, C, 1980. *Analytical Photogrammetry – Theory and Practice – Part II*. Department of Geodetic Science – The Ohio State University

MITISHITA, E., MACHADO, A. M. L., SILVA, V. F., TREVIZAN, S. J., SIKORSKI, J, 2003. Desenvolvimento de técnica de mapeamento planimétrico cadastral de rodovias utilizando-se de monorrestituição, imagens digitiais provenientes de câmera de vídeo e helicóptero. In: Mitishita, Edson Aparecido. (Org.). *Série em Ciências Geodésicas – Novos desenvolvimentos em Ciências Geodésicas*. Curitiba, v. 3, p. 227-245. ISBN: 85-88783-04-5.

MITISHITA, E., CÔRTES, J., CENTENO, J.,MACHADO, A, M., 2009. Small-Format digital camera: a study into stability analysis of the interior orientation parameters through temperature variation, In: *MMT09 2009 6th International Symposium on Mobile Mapping Technology*, Presidente Prudente, Brazil, 21-24 July. (proceedings on CD-ROM)

WACKROW, R., CHANDLER, J. H., BRYAN, P., 2007. Geometric consistency and stability of consumer-grade digital cameras for accurate spatial measurement. Photogrammetric Record 22 (118), 121_134.

RIEKE-ZAPP, D., TECKLENBURG, W., PEIPE, J., HASTEDT, H., HAIG, C., 2009. Evaluation of the geometric stability and the accuracy potential of digital cameras- Comparing mechanical stabilisation versus parameterisation. *ISPRS Journal of Photogrammetry and Remote Sensing*, 64(2009): 248–258.

TOMMASELLI, A. M. G., S., TELLES, S. S. S., 2006. A Mathematical model for camera calibration using straight lines, In: *EuroCOW 2006 International Calibration and Orientation Workshop*, Castelldefels, Spain, 25-27 Jan. (proceedings on CD-ROM).