AN ACCURACY ANALYSIS OF LARGE RESOLUTION IMAGES CAPTURED WITH THE NIKON D810 DIGITAL CAMERA SYSTEM

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ABSTRACT
The use of commercially available non-metric camera (e.g., Canon, Nikon) for photogrammetric operations is becoming very popular. There are several reasons for their use, such as lighter payload, low cost of sensor, smaller size for limited on-board space as in the case of UAVs as the data acquisition platform, quick turnaround projects, ease of replacement, etc. All these attributes represent advantages as compared with the use of digital high resolution metric image sensors (Hexagon DMCs, Microsoft Vexcel UltraCam systems, etc.). Nevertheless, in order to achieve results approaching those obtained with the use of the metric systems, it is imperative to take into account all the systematic errors the mentioned non-metric image sensors have; to model them and to eliminate (or minimize) their impact on the acquired images. This paper includes a review of the functional and stochastical models to be used in connection with the utilization of the non-metric image sensors. Attention will be given to the sensor inner calibration parameters i.e., calibrated focal length, principal point, symmetric – asymmetric – tangential lens distortions patterns and others biases that can strongly distort the acquired images. With this purpose the photogrammetric test field area "Franklin Mills Mall" was flown with the Nikon D810 Digital Camera with 50 mm focal length for camera calibration. The field was covered with multiple flight heights resulting in images at 15 and 30 cm GSD respectively. Two perpendicular photogrammetric flight strips with high end lap and side lap were flown. The test field area possesses some 25 targeted control and check points that have been measured with an accuracy of 2 cm or better. Automatic aerial triangulation using the above described imagery was conducted using PIX4Dmapper, a software package created specifically for images acquired from a UAV or terrestrially. The image observation results were exported (ASCII) and the corresponding Bundle Block Adjustments were conducted using the Leibnitz University of Hannover program system BLUH that is able to perform self-calibration through Additional Parameters (twelve standard plus different distortion patterns of mid-size format digital non-metric cameras). Varying numbers and distribution of Ground Control Points (GCPs) and Check Points (ChkPts) were used in the investigation. The results are presented herein.

1. INTRODUCTION

The main objective of aerial photogrammetry is to reconstruct 3-Dimensional objects from 2-Dimensional imagery. For this reason, it is highly important to know beforehand the values of the interior orientation parameters of the imagery acquisition sensor. The accuracy of the derived positional information from imagery depends on the validity of the available (or to be determined) Interior Orientation Parameters (IOP) of the implemented camera. For this purpose there are two possible approaches towards the so called sensor calibration, i.e., 1. "Laboratory Sensor Calibration" and 2. "The test Field Area Sensor/Camera Calibration". As it is well known by the photogrammetric community, the lab calibration is carried in especially designed laboratories. In

these specially designed labs and using highly precise optical instrumentation (e.g., optical multi-collimators, optical-electronic Goniometers, etc.), the IOPs of a "metric" camera are measured and validated. Specially designed procedures conduct to the determination of the principal point of the camera, the calibrated focal length and the values of the symmetric lens distortion parameters and in some cases those of the tangential distortion as well. The laboratory calibration is such that the derived IOPs are valid for the environmental conditions (atmospheric pressure, temperature, humidity, etc.) existing in the laboratory at the time of calibration. At the time of aerial photography, the atmospheric conditions are completely different than those of the lab at the calibration time. There are invariably mechanical-geometric distortions of the camera that invalidates the lab calibrated IOP for a precise 3-dimensional reconstruction of the object at hand. Table 1 shows distortions on a metric camera that resulted in large differences between the actual and the calibrated focal length. (Source: Prof. Dr. Ing. H.H. Mayer 1978).

	Pressurized cabin, cover glass		Lens in free atmosphere $7 = 7°C$		Lens in free atmosphere t like air	
Flying Altitude	6 Km	14 km	6 Km	14 KM	6 Km	14 Km
Wide Angle f=153 mm	-20µm	-38µm	-36µm	-58µm	-47µm	-80µm
Normal Angle f= 305 mm	+12µm	-17µm	-33µm	-28µm	-110µm	-172µm

Table 1: Effects of atmosphere and temperature on focal length of metric cameras

The second approach requires control information that is usually available in the form of a calibration test field area. The acquired imagery over the calibration test field area is integrated in a simultaneous least squares bundle block adjustment procedure that includes self-calibration through additional parameters, whose main aim is the determination of the IOP of the camera system but in normal flying atmospheric conditions. In these traditional camera calibration activities, the control information takes the form of distinct and specifically marked points and targets. These targets are established and precisely measured in the test field using highly accurate field surveying techniques. The number and distribution of these targets are vital for the recovery of the IOP of the camera as well as the metric effects of the biases and systematic deformation and mechanical-geometric distortions of the sensor.

In the present study the above mentioned field test calibration approach was attempted. For acquisition, a Nikon D810 with a 50 mm nominal focal length was used with and a proprietary flight management system and data storage software. The collection was performed over the Franklyn Mills Mall Test Field Area located in the vicinity of the Northeast Philadelphia Airport. The test field contains new control targets selected at the intersection of parking strips and painted traffic lines on the streets that were field survey measured with a final accuracy of ± 2 cm or better. A total of 25 control points were field surveyed and photogrammetrically observed during the process of aerial triangulation. For this test, two flights were done a two different GSD (15 and 30 cm) each transversal to each other to help in the precise determination of the principal point of the camera by eliminating the effect of the residual image shift produced while opening the shutter for photography acquisition. The longitudinal overlap resulted in 80% (or higher) and the lateral overlap was planned to be 60%. Due to the high overlap and the resulting high correlation between images and lines, the relative accuracy of the Exterior Orientation Parameters (EOPs) is extremely strong and maximizes correlation between the IOP and EOP. Figure 1 shows some

topographical details of the test field area, while Figure 2 shows the individual image footprints from the lower (15cm GSD) flight.

Figure 1: Imagery Mosaic Overview

Figure 2: East/West flight image footprints

2. CAMERA USED

During this investigation, Keystone Aerial Surveys, Inc. flew the Nikon sensor in a configuration to collect nadir imagery from altitudes of approximately 5000 feet (1525 m) for the 15 cm GSD imagery and 9000 feet (2740 m) for the 30 cm GSD.   The system platform is not as significant as the camera itself. It is a camera that is relatively inexpensive, can be mounted on any aircraft and most unmanned aerial vehicles, and can easily be configured to automatically capture imagery.   The Nikon D810 used has the specifications of: 36 Megapixels, a pixel size of 4.88 microns, 7360 x 4912 (cross x long) pixels, sensor size of 35.9 x 24 (mm), Dimensions (w x h x l) 146 x 123 x 82 (mm). A Nikkor AF lens with a Nominal Focal Length of 50 mm was used.

3. THE FRANKLIN MILLS MALL TEST FIELD AREA

Located near the Northeast Philadelphia airport, the large Franklin Mills Mall maintains a huge parking lot with plenty of parking stripes that can be used as targets at intersecting lines. It is surrounded by neighborhoods of family houses with streets having plenty of painted traffic lines with intersections and other features easily used as target control points. The total area of the test field is approximately 7 sq. miles and with a difference in height of about 75 feet, it incorporates 25 targeted ground control points (GCP) that were field surveyed with an accuracy of 2 cm or better. The area has plenty of details and is suitable for many sensor calibration purposes. Figure 4 shows a typical detail of a GCP and Figure 3 shows the distribution of such points.
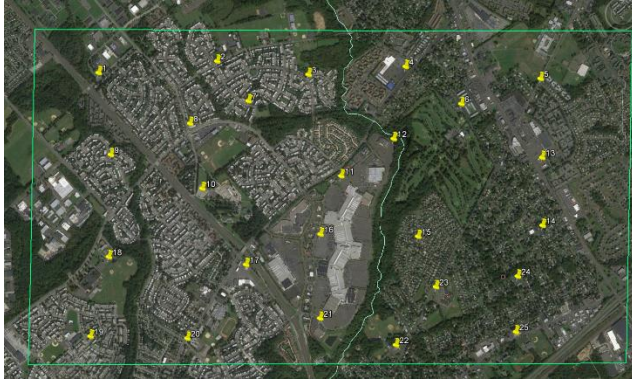
Figure 3: Overview of the Test Field Area and GCP

Figure 4: Typical detail of GCP

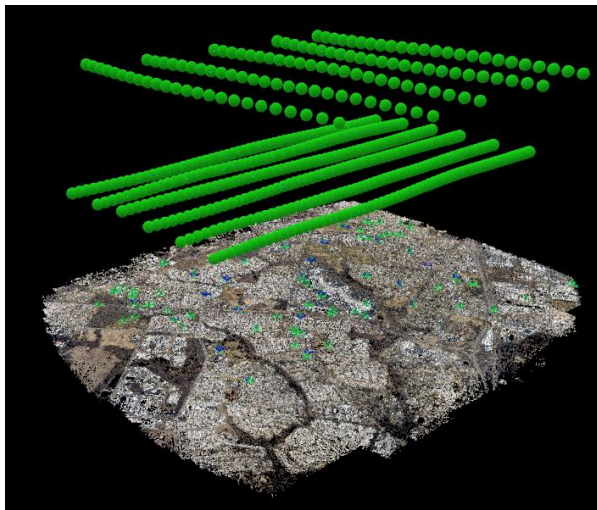## 4. AERIAL TRIANGULATION DATA ACQUISITION

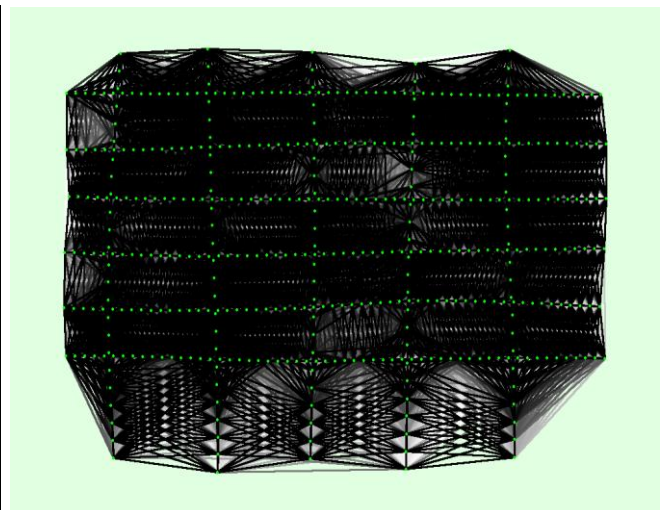*Figure 5: Projection centers with match points*

Figure 6: Density of intersected homologous intersected rays

As mentioned above, AT data acquisition was done with the software package Pix4Dmapper, specifically created for aerial images taken from any kind of platform (including UAS) and any sort of digital frame cameras. The Automatic Triangulation process produced more than 40 million matched points between the two flights. All ground control points (as shown in Figure 3 above) and different LS Bundle Block Adjustment with self-calibration were conducted using the Hannover Bundle Block Adjustment Package BLUH. Herein a brief description of the calibration it is given. Figure 5 shows the projection centers of the two transversal flights with an image of the cloud of matched points portrayed as surface points. Figure 6 shows the density of intersected homologous intersected rays. It is worth mentioning that a multiplicity of up to 72 photos/rays/points were matched resulting in high redundancy during LS Bundle Block Adjustment which creates high internal and external reliability in the block.
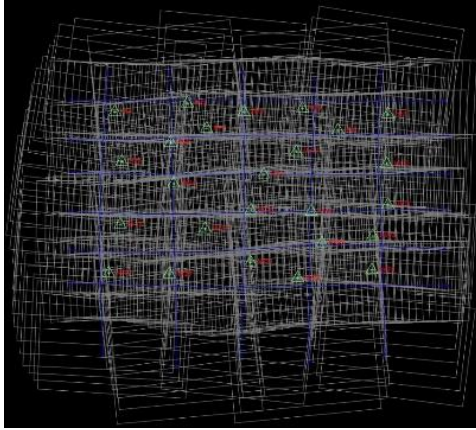
5. BUNDLE BLOCK ADJUSTMENT RESULTS

Figure 7: Image footprints of both high and low flights with Ground Control Displayed

Cameras like the Nikon D810 were not originally intended to be used for aerial photography for the production of geospatial products. The camera's cone is such that it is easily deformed with varied atmospheric conditions (difference of pressure between MSL and aerial photography altitude). The system of lenses has a very strong radial distortion that is compounded by to other geometric distortions such as tangential, asymmetric, etc.

Because of the lens configuration of 50mm and the altitude of the flight (especially the 30cm GSD), the radiometric characteristics are not as ideal as with traditional metric systems. The atmospheric issues and variation between images is a challenge for AT software packages' matching algorithms that expect less variability in the color balance between images. While large format, metric digital sensors record detailed metadata about the sensor, atmospherics, sun angle and exposure at the time of image capture, these values are not available for off the shelf systems. Additionally, many large format manufacturers offer post production software to ease the balancing of imagery, while Adobe Photoshop and other techniques must be used for DSLR cameras such as the Nikon. Additionally, the imagery was formatted as JPEG files that may sacrifice image detail (texture, color, detail definition, etc.) in favor of compression. Meanwhile, RAW images or RAW images converted to TIFF format are not compressed, hence they preserve the original image quality by not introducing compression artifacts. Moreover, they can have a bit depth of as much as 16-bits per channel and multiple layered images can be stored in a single TIFF file. With the wide spread use of this type of camera, the use of JPEG imagery has become acceptable for most geospatial uses, but is not to as geometrically stable as RAW/TIFF formats in rigorous test such as this.

These two factors made it difficult to achieve optimum results (matching quality) during AT, but were overcome with the manual color correction of the imagery. This image enhancement likely introduced additional image deformation to the already existing values resulting from the above mentioned camera characteristics.

Nevertheless, once matching results were acceptable, several different LS Bundle Block Adjustment (LS BBA) were carried out.

Least Squares Bundle Block Adjustment Summary															
No self-calibration				12 Standard Add. Param				12 St. + Mid Format CCD Cam.				1 - 9, 12, 27-28, 81-88			
σ_o	RMX	RMY	RMZ	σ_o	RMX	RMY	RMZ	σ_o	RMX	RMY	RMZ	σ_o	RMX	RMY	RMZ
14.0	0.53	0.39	2.43	3.3	0.12	0.19	0.68	2.89	0.12	0.19	0.30	2.7	0.08	0.09	0.25

Table 2: Initial results of LS BBA attempts on Nikon imagery

Table 2 above summarize the results of the LS BBA adjustment in terms of Overall Standard Deviation (μm) and Root Mean Square Discrepancies (m) on Ground Control Points for the following cases:

1. LS BBA with no self-calibration
2. LS BBA with self-calibration using 12 standard additional parameters
3. LS BBA with 12 standard additional parameters plus add. Param. for typical Mid Format CCD Cameras

4. LS BBA with additional Parameters 1 to 9, 12, 27 to 28 and add. Param. for typical Mid Format CCD Cameras

From the results, it is easy to see the strong effect of the large lens distortion of the camera. Simply adding the industry standard 12 additional parameters improved the standard deviation by 23.6%, a large improvement on the RMSZ of more than 200% was achieved. These improvements were accentuated when Mid Format CCD Camera Specific Additional Parameters are incorporated (parameters 81 to 88 in BLUH Program Systems). A closer look at the data and results reveals the existence of systematic residuals. To remove their effects it was decided to perform an LS BBA using additional parameters 1 to 9 (most significant part of the 12 standard), 12, 27 to 28 and the Mid Format CCD Camera Specific. Parameters 9, 27 and 28 correspond to the Brown-Corradi distortion model which removes large distortion caused by the camera lens system. With this combination of additional parameters it was possible to achieve a standard deviation of 2.7 micron, RMSXY of 0.09 m and a RMSZ of 0.25 m.

The radial distortion patterns for case 4 of the LS BBA is shown in Figure 8a and the systematic residual distribution pattern is depicted in Figure 8b. Notice the enormous effect of the radial distortion.
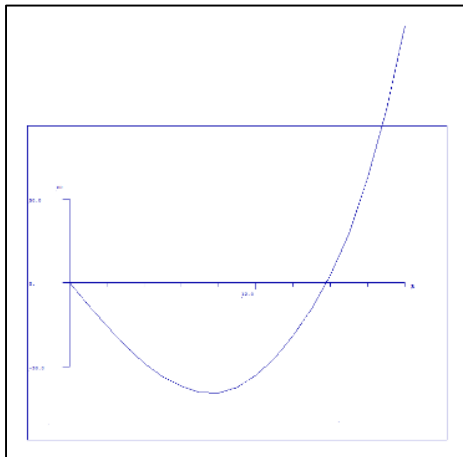

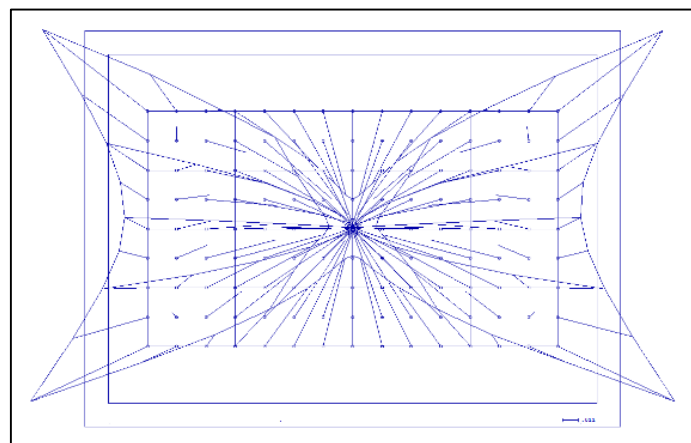*Figure 8a: Radial Distortion Curve*

Figure 8b: Systematic errors of the camera

Figure 9 below shows the systematic image residuals correction grid out of the LS BBA with self-calibration corresponding to the case 4 above. (Additional Parameters 1 to 9, 12, 27 to 28 and 81 to 88)
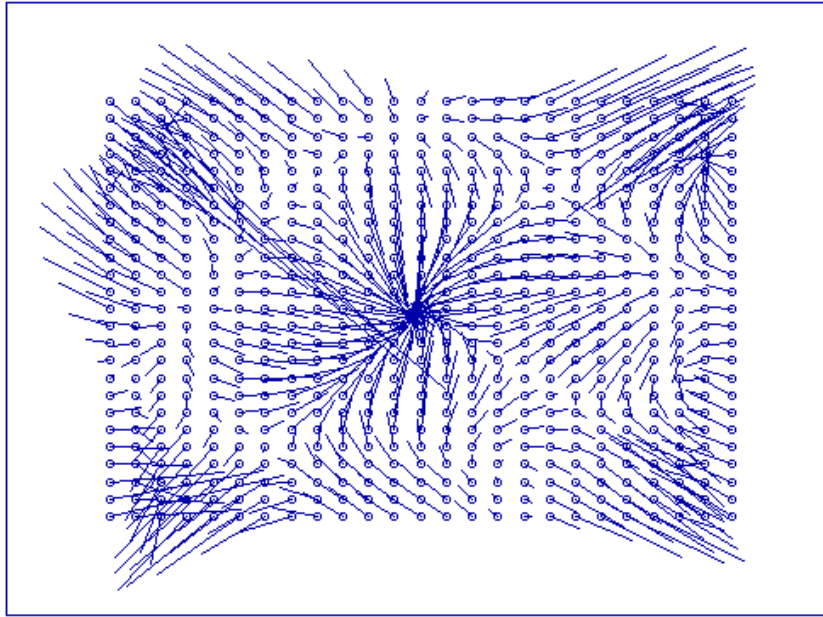
Figure 9: Systematic image residuals/correction grid resulting from self-calibration with add. Param. 1 to 9, 12, 27 to 28 and 81 to 88.

6. CALIBRATION

Using the correction grid (out of self-calibration case 4 above) and with the intent to generate calibrated IOPs, The image observations were corrected to remove the major effects due to the strong lens distortion.

Another adjustment was carried out with BLUH using additional parameters 13, 14 and 15 (parameter 14 is associated with correction to the nominal focal length to obtain a calibrated focal length, whereas parameters 14 and 15 are associated with calibrated principal point of the camera. The results were as follows:

X-COORDINATES SHIFTED   LEFT= -0.274 mm   RIGHT= 0.274
Y-COORDINATES SHIFTED   LEFT= -0.119   RIGHT= 0.119 mm
CHANGE OF FOCAL LENGTH= 0.089 mm

From the above values, one can conclude that such major changes are due to the unaccounted for systematic effects remaining. Nevertheless, using the above shifts, the image coordinates were updated once more and a LS BBA took place with zero iterations (meaning direct intersection). The results are shown in Table 3 below

Direct Intersection				12 St. + Mid Format CCD Cam			
σ_o	RMX	RMY	RMZ	σ_o	RMX	RMY	RMZ
5.34 µm	0.25 m	0.28 m	1.88 m	2.75 µm	0.10 m	0.15 m	0.38 m

Table 3: Further LS BBA results

The left side of Table 3 reveals the remaining systematic errors on the pass/tie points, especially those related to the Z-component. Once the full self-calibration with the 12 Standard Additional Parameters was conducted, the accuracy improved dramatically, especially on the Z-component.

With the use of the parameters applied to corrected points, sub pixel accuracy was attained in the horizontal axis.   Further improvement was not possible with this data set due to the following:
1. The use of JPEG images with image enhancements limits the maximum accuracy that can be obtained from an image (metric or non-metric).
2. The difference in altitude between the GCPs within the Boresight area is too small to compute an accurate calibrated focal length.
3. There are still systematic errors in the camera/acquired images due to the nature of the camera.

7. CONCLUSIONS
After a deep analysis of the results the following conclusions were drawn:
1. Despite the flight being conducted at GSDs not intended for this system and using JPEG imagery, the results were excellent: sub pixel accuracy for horizontal and 1 or 2 pixel (depending on GSD) for the vertical.
2. Image enhancement techniques performed on the JPEG imagery increased the matching performance significantly but added more pixel shift to the shift created by the lens distortion.
3. For highest possible accuracy with this lens configuration, it is best to capture with lower flying heights and RAW imagery formats. This will minimize any radiometry based matching failures and eliminate some increased image distortion.
4. As expected, the digital camera NikonD810 has very large radial distortion that it is also combined with tangential and asymmetric distortion (See above used additional parameters).
5. To achieve better reliability when calculating the PPA, a flight with all lines flown in both forward and reverse directions should completed.   An area with greater GCP height variation should also be explored as this will allow for focal length calculation to be performed.
6. It has been proven that if used properly it is possible to achieve very acceptable results with off the shelf cameras.
7. Due to the large radial (and other) lens distortion, the images of the camera must be corrected using the additional parameters to eliminate (or minimize) the effects of the systematic effects on the images themselves. This is the case of using the imagery acquired by this type of camera for purposes of texture in 3D models

8. ACKNOWLEDGEMENT

9. REFERENCES
1. Passini, R.; Jacobsen, K. (2008). Geometric Analysis on Digital Photogrammetric Cameras. ASPRS. Annual Conference. Portland – Oregon (USA)
2. Passini, R.; Dor Yalon, Airik Nir (2009). An accuracy analysis on large resolution images exposed by with the Icaros Digital Camera System. ASPRS. Fall Conference. Tampa 2009
3. Passini, R.; Jacobsen, K. (2008). Accuracy Analysis of Large Size Digital Aerial Cameras. ISPRS. Beijing – China. International Congress for Photogrammetry and Remote Sensing. Beijing 2009.

4. Passini, R.; Jacobsen K. (2008). Analisis de Precision geometrica y cualidades radiometricas de las camaras fotogrametricas de alta resolucion. Congreso Nacional de Fotogrametria y sciencias afines. Buenos Aires, Argentina 2008
5. Passini, R.; Jacobsen, K. (2010). Accuracy and Radiometric Study of two very high resolution digital camera Images. ASPRS. Annual Convention 2010
6. Passini, R.; Jacobsen, K.; Day David. (2011). Photogrammetric Orientation of the UltraCam Eagle using Airborne GPS and IMU Readings. System Calibration. System Calibration. ASPRS. Fall Convention. Tampa 2011
7. Passini, R.; Jacobsen, K.; Day David. (2012). Accuracy and Radiometric Study on Latest Generation Large format Digital Frame Cameras. JACIE 2012. Fairfax, VA, April 2012