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Calibration of digital SLR Nikon D3X for the use in digital photogrammetry projects

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Abstract. Results of research on calibration of high-resolution digital camera Nikon D3X have been presented. CMOS matrix stability in recording process of digital images, calculation of principle distance as well as principal point, radial distortion and tangential distortion were determined. The interior orientation parameters determined during calibration in test project were examined. All test images were obtained using three replaceable Nikkor lens of 24, 35 and 50 mm focal length. The calibration process was executed in Camera Calibration and Field Calibration modules of PhotoModeler software using convergent terrestrial images. It was also executed for single photo in DLT module of AeroSys software. For the determination of interior orientation parameters of digital camera for each lens the 2D and 3D test fields were used. Stability and repeatability of recorded digital images on CMOS matrix were examined on 25 control points which were evenly distributed on a white calibration table. Accuracy of pixel position on the image for 24 mm, 35 mm and 50 mm focal length was 0.06, 0.08 and 0.04 of image pixel, respectively. It was found that interior orientation parameters calculated using the PhotoModeler software for both calibration methods were correctly determined while when using the Aerosys software they were determined with lower accuracy. The very high accuracy of elaboration of a test photogrammetric project for each camera lens was obtained using interior orientation parameters calculated on the basis of convergent images and 3D field.

Keywords: close range photogrammetry, camera calibration, digital SLR camera, accuracy, CMOS matrix

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1. Introduction

Continuous development of professional and popular imaging sensors stimulates further research on the measurement capacity of non-metric digital cameras. Recently, reflex cameras with imaging matrixes in excess of 20 Mp appeared on the market. Such matrixes can be found in Canon EOS-1Ds Mark III, Sony Alpha900 and Nikon D3X. New high resolution matrixes enable to increase ground resolution without changing the imaging scale (in comparison with 10 megapixel previous generation cameras), and increasing the scale and scope of processing without compromising accuracy. From a photogrammetric point of view, the professional reflex digital cameras, due to instability of internal orientation elements, are considered as the non-metric cameras which, after calibration, can be used for measurement purposes. Calibrated non-metric cameras have become the popular registration tools in many applications of close range photogrammetry. They commonly replaced the expensive metric cameras because of their flexibility and considerably low price. There are many research projects, including PhD theses (Tokarczyk, 1982; Kowalczyk, 2003), MSc dissertations, and international (Torlegard, 1967; Kenefick et al., 1972; Faig, 1975; Habrouk et al., 1996; Matsuoka et al., 2003) and publications in scientific journals (e.g., Bujakiewicz et al., 1980, 2006), concerning various approaches for calibration of non-metric cameras.

Based on a study of the literature it was found that only in few publications Nikon D3X camera was used in photogrammetric projects. However, none of them relates to the important aspect of calibration of the new generation full-imaging camera matrix. This matrix is used for nadir photographs collection from UAV platform (Sauerbier et al., 2010; Aqugiaro et al., 2011) on the basis of which the accurate DSM was generated. The image data from Nikon D3X camera is used also for automatic orientation of image sequence (Roncella et al., 2011).

It was affirmed that the image sensor of Nikon D3X requires new methodology of calibration. The new very high resolution image matrix is by standards calibrated on the basis of default test field which is delivered with calibration software. In the author opinion, such test field does not provide the sufficient camera interior orientation parameters. Therefore in the following research an original 3D field calibration test adapted to the size of full-imaging matrix was designed. The camera interior model parameters obtained from calibration process based on author's 3D test field was compared with parameters obtained using standard test field. The results of the comparison confirmed the necessity of applying precise calibration test for new generation non-metric cameras.

Tests aimed at establishing the stability of digital images registered at the matrix, determining imaging distance, focal point, radial and tangential distortion and testing parameters of internal orientation of the camera. Three interchangeable lenses of 24, 35 and 50 mm were calibrated.

2. Nikon D3X specifications

The Nikon D3X (Fig. 1.) digital camera contains a CMOS matrix of 35.9 × 24 mm. The actual number of pixels at the matrix is 25.72 million, of which 24.5 Mp are effectively used.

Principle technical parameters of the camera having their impact on the image registration in photogrammetric applications include:

- autofocus modes: singular, continuous, manual;
- ISO 50÷6400 sensitivity;
- size of photographs (in pixels): 6048 × 4032, 4544 × 3024, 3024 × 2016;
- pixel size: 6 μm;
- file format: NEF (12- or 14- bit with loss or loss-free compression or without compression), TIFF, JPEG (compression 1:4, 1:8 and 1:16), NEF + JPG;
- depth of field view;
- electronically controlled resettable iris;
- electronically controlled slot shutter with vertical orientation in the focal plane;
- shutter opening time: from 1/8000 to 30s every 1/3, 1/2 or 1 EV, time B (bulb);
- photographs registration speed: 5 frames per second;
- light measurement methods: matrix, central, point;
- exposition modes: automatic control with programming flexion (P), automatic control with pre-selection of time (S), automatic control with pre-selection of iris (A), manual (M);
- live view.

Fig. 1. Non-metric digital camera NIKON D3X

The camera is provided with three interchangeable Nikkor lenses of focal lengths 24, 35 and 50 mm. The lenses are fully compatible with the tested camera which enabled the use of all functions contributing to correct registration of images.

3. Repeatability and stability of digital image registration

Following some previous research concerning examination of repeatability and stability of image registration (Boroń, 1998; Kowalczyk, 2003), all lenses applied by the author were also investigated with the use of 25 code points evenly distributed on a whiteboard. The camera was fitted to a stable tripod and during the exposure the camera's shutter was released remotely via an USB cable using DCamCapture to eliminate vibrations. Each lens was used to take a series of thirty photos each filling the whole frame with all test field points. 24 mm and 35 mm lenses were set at infinity, whereas 50 mm lens at 2 m. The photos were taken at maximum f-number of 22 for 24 mm and 35 mm lenses, and 16 for the 50 mm lens. Files were registered in the TIFF format at 6048 × 4032.

Before measuring the image coordinates, errors of automatic measurement of test field points were determined for particular series of images. To this end, a set of points at an individual image was measured ten times and standard deviations were calculated. It was confirmed that the point measurement error is statistically insignificant. Then, automatic measurement of points in the matrix was performed for each image using PhotoModeler software. An average value was determined for image coordinates of a single code point in a series of images for particular lenses, and the difference between coordinate measured at an individual image and the average value was calculated.

Testing of repeatability of data recording at the matrix aimed at defining the displacement of image details. The measure of recording repeatability was the value of standard deviation calculated on the basis of differences of pixel coordinates at particular images and their mean values from a series of images. The results are presented in Table 1.

Table 1. The results of Nikon D3X digital image acquisition stability for lenses 24, 35 and 50 mm

Lens	σ_x [pixel]	σ_y [pixel]
24 mm	0.09	0.03
35 mm	0.03	0.14
50 mm	0.05	0.02

In case of all focuses, the change of pixel coordinates of the image in the series of images did not exceed 0.14 pixel. Maximum differences for particular focuses were dx_{max} = –0.22 pixel and dy_{max} = –0.08 pixel for focal length of 24 mm, dx_{max} = –0.09 pixel and dy_{max} = 0.29 pixel for focal length of 35 mm and dx_{max} = –0.18 pixel and dy_{max} = –0.09 pixel.

As it can be seen from the results, the digital camera projected images of high repeatability and stability.

4. Test fields

In common practice, different types of two and three-dimensional test fields have been used for calibration of non-metric digital cameras. 2D fields consisting of a set of evenly spread points are usually painted on the wall or printed on paper, while 3D fields consist of a number of spatial constructions with points with 3D coordinates.

In this project two calibration test fields were used for the determination of internal orientation elements for the digital camera being tested. The first one was flat test field delivered with the PhotoModeler software. It consisted of 4 code marks and 140 points in a square of 36” × 36” (Fig. 2 – left). The test field was printed on a mat, thick paper and placed on a glass.

The second test field is a spatial one of 278 cm in width, 186 cm in height, and 90 cm in depth, developed by the author for calibration of terrestrial cameras (Fig. 2 – right). It consists of four vertical planes placed every 30 cm. Three horizontal bars are placed within each plane. Additionally, to

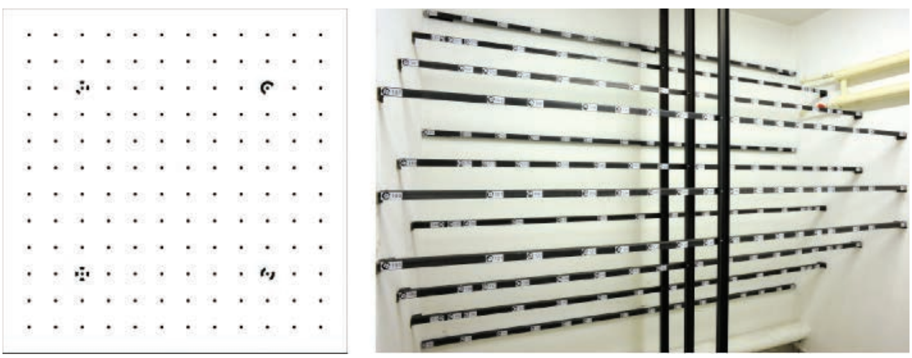

Fig. 2. 2D test field (left) and 3D test field (right)

improve stability of the construction, horizontal bars are fitted to the channel sections set between the floor and ceiling.

The construction includes 192 coded control points allowing for fully automatic measurement of images. Coordinates of those points have been determined twice using surveying measurement techniques. The control point coordinates were measured with an accuracy of ±0.3 mm.

5. Calibration

Calibration of the camera was executed with the use of two softwares: PhotoModeler (2D and 3D calibration test fields) and AeroSys (3D test field). The first calibration software involved two methods: *Camera Calibration* with the flat field delivered together with the software and *Field Calibration* which enabled to determine the internal orientation elements on the basis of the user test field. The *Direct Linear Transformation* (DLT) module of AeroSys software has been used to determine parameters of internal orientation of the reflexive digital camera.

Calibration process with the use of two softwares has differed, not only in terms of the mathematical solution but also by the number of images used for determining internal camera parameters. PhotoModeler two multi-images versions included: *Camera Calibration*, which requires from 6 to 12 images and the maximum number of images was used for calibration; *Field Calibration* based on 3D test field required 13 images. The calibration with the AeroSys DLT uses only a single photo of a 3D field, since this approach executes the photogrammetric resection solution. In both multi-images recording, additional portrait images were taken with frame rotated by 90°. The configuration of images for a flat and spatial test field is presented in Figure 3.

To obtain the peak depth, images were taken at maximum iris closure set at each of the lenses. During exposition, the camera was attached to a stable tripod, and shutter was triggered with a self-timer. Images were recorded at their top resolution in a loss free TIFF format.

PhotoModeler *Camera Calibration* is based on a free network adjustment (Luhmann et al., 2007) which allows for the determination of internal orientation elements of the camera without using control points. Calculated parameters of the camera geometrical model will thus not be affected by control point errors, however, they will depend on configuration of photogrammetric data (relations between adjustment points at images of different orientation). The calibrations involve several stages:

- automatic code point measurement in the images;
- estimation of imaging distance;
- images orientation based on code points;
- automatic matching of other homological points of the field (Stage 1);
- calculating of approximate internal orientation parameters (focal length, principal point and only one coefficient of radial distortion): c_K, x_{PP}, y_{PP}, K_1;
- automating matching of not yet determined homological points of the field (Stage 2);
- determining of internal orientation parameters: c_K, x_{PP}, y_{PP}, K_1, K_2, P_1, P_2;
- controlling of the correctness of the test field point location and internal orientation parameters.

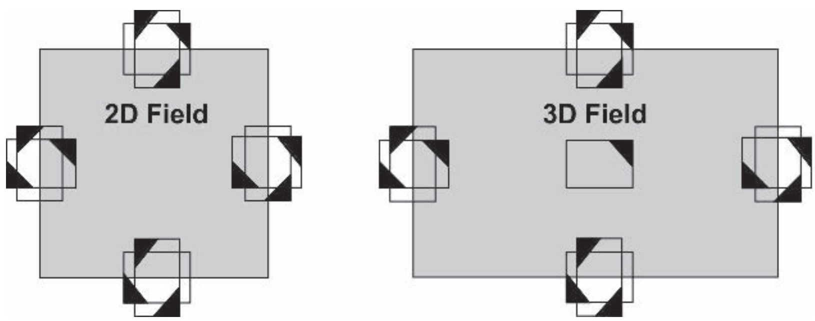

Fig. 3. Images configurations for calibration in PhotoModeler for 2D field (left) and 3D field (right)

Field Calibration was based on terra-triangulation with self-calibration approach, using all control points observed on the images and at the same time determining internal orientation parameters of the camera. The accuracy σ_X, σ_Y, and σ_Z of control points coordinates measured using surveying methods equals to 0.2 mm. The process of calibration consists of several stages:

- automatic measurement of code points in all images;
- automatic matching of control point coordinates;
- orientation of images based on known control points coordinates and orientation parameters in EXIF metadata attached to an image file;
- adjustment of observation with self-calibration of the camera.

The DLT method is based on co-linear equations. One needs at least six control points of a 3D test field to determine eleven indices of the transformation (Abel-Aziz et al., 1971). During calibration, all points of the 3D test field were used for the determination of transformation parameters.

Calibration for each replaceable lens produced models of internal orientation elements for the camera established using three different methods. Parameters and standard deviations are shown in Table 2.

When using the PhotoModeler calibration, the largest difference between calculated focal lengths was 30.6 µm at 50 mm lenses, whereas the smallest was 1.0 µm at 24 mm lenses. In the case of two wide-angle lenses, the c_K value for multiple images is similar, whereas for a regular-angle lens flat field and DLT values are similar. In the first two cases, it is caused by lower accuracy when determining parameters using DLT coefficients.

Coordinates of the principal image point, calculated during calibration using the DLT method,

Table 2. Summary of results of Nikon D3X calibration with lens 24, 35 and 50 mm (CC – *Camera Calibration,* FD – *Field Calibration*)

Lens	Calibration method	Elements of interior orientation						
		c_K [mm]	x_P [mm]	y_P [mm]	K_1	K_2	P_1	P_2
24 mm	CC	24.3873	18.0444	11.9687	1.607E-4	–2.326E-7	–1.822E-6	4.859E-6
	σ_{CC}	0.00051	0.0008	0.0008	2.300E-7	4.40E-10	4.400E-7	4.300E-7
	DLT	24.3760	18.0460	12.0570	1.669E-4	–2.701E-7	5.193E-6	1.084E-5
	σ_{DLT}	–	–	–	8.593E-7	3.695E-9	1.115E-6	7.802E-7
	FC	24.3883	18.0575	11.9920	1.640E-4	–2.521E-7	–1.393E-6	4.656E-6
	σ_{FC}	0.0010	0.0010	0.00081	2.300E-7	4.90E-10	7.200E-7	5.400E-7
35 mm	CC	36.0841	18.0945	11.8542	7.112E-5	–6.305E-8	–1.092E-5	3.465E-6
	σ_{CC}	0.00051	0.00079	0.00084	1.100E-7	2.70E-10	1.900E-7	1.900E-7
	DLT	36.0570	18.0050	12.1760	7.108E-5	–6.497E-8	6.275E-6	1.995E-5
	σ_{DLT}	–	–	–	8.704E-7	3.785E-9	1.238E-6	8.328E-7
	FC	36.0790	18.0827	11.8497	6.986E-5	–6.589E-8	–1.036E-5	4.624E-6
	σ_{FC}	0.0010	0.0010	0.0009	1.300E-7	2.50E-10	3.400E-7	2.500E-7
50 mm	CC	52.8353	18.0764	11.8936	5.055E-5	–7.965E-9	–7.472E-6	–8.539E-6
	σ_{CC}	0.0010	0.0020	0.0020	9.900E-8	2.30E-10	1.900E-7	1.800E-7
	DLT	52.8340	18.1060	12.1460	4.749E-5	–5.439E-9	–1.025E-5	–1.189E-5
	σ_{DLT}	–	–	–	5.044E-7	2.238E-9	7.399E-7	4.827E-7
	FC	52.8047	18.0654	11.8849	5.080E-5	–2.109E-8	–7.405E-6	–1.003E-5
	σ_{FC}	0.0020	0.0010	0.00074	6.400E-8	1.20E-10	1.100E-7	8.500E-8

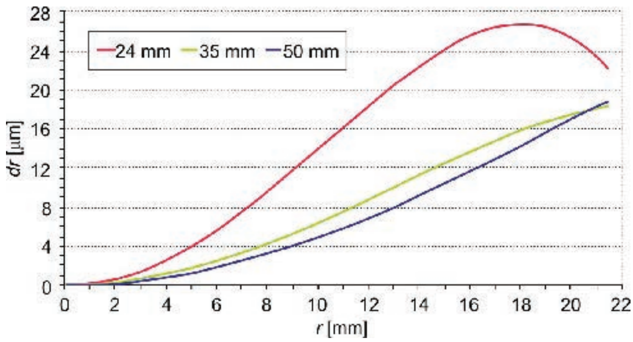

Fig. 4. Radial distortion of tested lenses obtained from the calibration using 3D test field

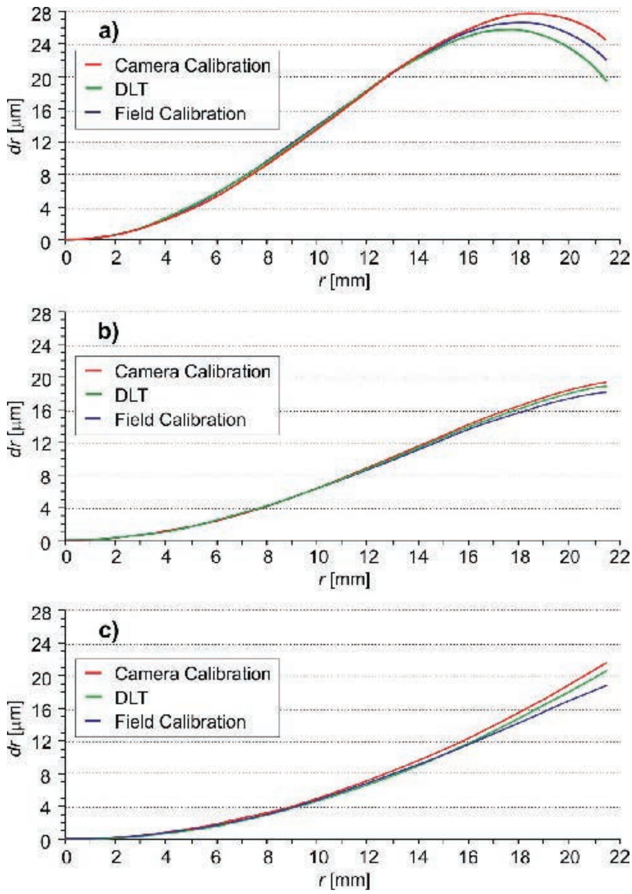

Fig. 5. Radial distortion of 25 mm lens a), 35 mm lens b) and 50 mm lens c) for three calibration methods applied

significantly differ from those obtained using other methods. This is particularly clear in the case of *Y* coordinate, where the location of the principal point centre, determined using one of the images, differ by as much as 88 µm from coordinates calculated using PhotoModeler.

When using PhotoModeler, the accuracy of c_K for all lenses was 0.7 µm and 1.3 µm for CC and

FC methods respectively, whereas the accuracy of the principal point coordinates was in average 1.2 µm and 0.9 µm for the two methods, respectively. Thus, both calibration methods exhibited similar accuracy when determining internal orientation elements at the level of 1.0 µm. When determining distortion parameters, PhotoModeler calibration provides better accuracy than DLT.

Figure 4, presenting radial distortion shows that major distortions are recorded in the case of lens of the shortest focal length. As it was expected, the largest distortion of 26.7 µm occurred at radius of 18 mm from the centre of the image. Two other lenses show much smaller distortion at the whole area of the matrix, and their maximum value is recorded at the end of a frame.

In the case of distortions calculated for all lenses examined (Fig. 5), *Camera Calibration* produced the largest values. The lowest distortion values were obtained for the DLT method with 24 mm lens and for *Field Calibration* method for all other focal lengths. The largest difference between results for particular calibrations is 2.7 µm which can be observed for 24 mm lenses at the perimeter of the frame.

Tangential distortion coefficients in both calibrations using PhotoModeler show minor differences. P_1 and P_2 calculated using DLT differ, however, by an order of magnitude.

6. Test project

All internal orientation elements determined through calibration were controlled under a test project. Each of the three calibrated lenses was used to take convergent images of the spatial field. Images were registered so that majority of field points remained within those images (Fig. 6).

Terra-triangulation of the block of images was made using 6, 10 and 14 control points. The error of measurement and identification of control points was of $\sigma_X = \sigma_Y = \sigma_Z = 0.2$ mm. Other 3D field points were used as the check points. The measure of accuracy was root mean square error determined from differences between test field coordinates of control points and points from terra-triangulation.

Based on analysis of the test project accuracy (Table 3), it can be stated that the geometrical model of the non-metric Nikon D3X camera for all the lenses is best described by the internal orientation elements set using the spatial test field and the PhotoModeler *Field Calibration* module. Parameters of wide angle lenses calculated on the basis of the flat test were determined with much lower accuracy. In the case of the 50 mm lenses, accuracy of test imaging using parameters determined with use of the 3D test is even 9-times higher that when using a geometrical model determined by *Camera Calibration* and DLT method. The accuracy

Table 3. Summary of test project errors

Lens	Number of control points	Camera Calibration		DLT		Field Calibration	
		RMS control points [mm]	RMS check points [mm]	RMS control points [mm]	RMS check points [mm]	RMS control points [mm]	RMS check points [mm]
24 mm (images scale 1:90)	6	0.30	0.48	0.63	0.74	0.19	0.33
	10	0.48	0.40	0.70	0.61	0.27	0.31
	14	0.50	0.43	0.74	0.61	0.34	0.31
35 mm (images scale 1:90)	6	0.28	0.37	1.44	1.41	0.23	0.41
	10	0.37	0.34	1.58	1.36	0.37	0.37
	14	0.37	0.35	1.57	1.38	0.43	0.38
50 mm (images scale 1:60)	6	0.57	0.99	0.53	0.60	0.07	0.13
	10	0.60	0.57	0.60	0.57	0.08	0.12
	14	0.83	0.63	0.64	0.45	0.10	0.12

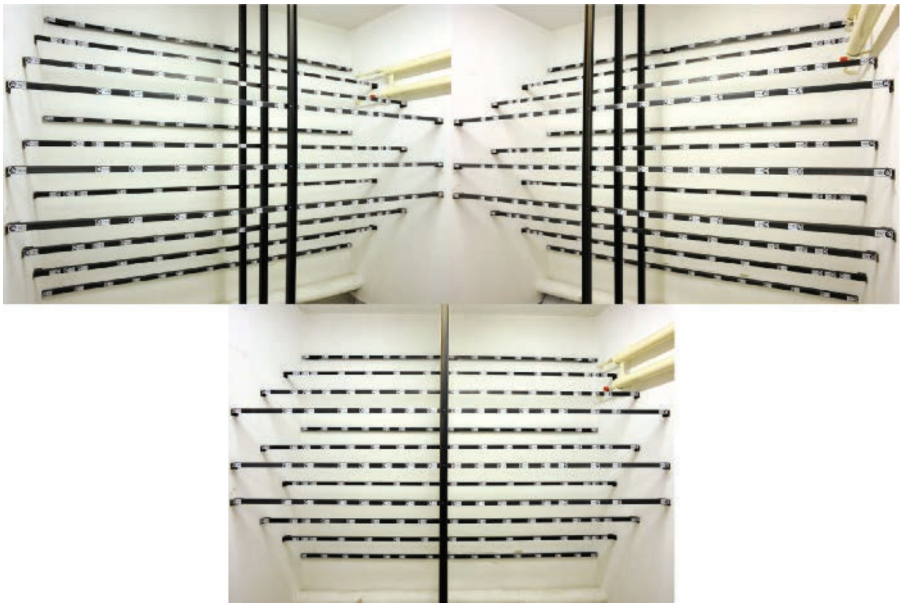

Figure 6. Example of photos series used to test project

achieved in the test project using the geometrical model of a camera determined with DLT method is several times lower than in the case of using orientation elements set by PhotoModeler. In each test project, accuracy slightly increased after adding control points, which shows the lack of gross errors in coordinates of control points selected and correctness of determining parameters of the camera's geometrical model. The summary of accuracy obtained in the test project is presented in Table 3.

7. Conclusions

The tests showed that the Nikon D3X digital camera has a stable system for registration of images and can be used for photogrammetric purposes.

Of all calibrations cases, *Field Calibration,* using multiple images for spatial testing, is the best when developing a geometrical model of the high resolution camera.

In case when the appropriate 3D test field is not available, it is advisable to calibrate using a flat test. The approach of DLT single photo, can be used to calculate the approximate values of internal camera orientation elements for cases when not high precision measurement of the objects is required.

The Nikon D3X digital camera is an excellent photogrammetric measurement tool for not necessarily small (sculptures) but also large (buildings) objects. Its 24.5 Mp matrix enables to reduce a relative accuracy of 3D coordinates measurement to 1:25 000.

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Kalibracja lustrzanki cyfrowej Nikon D3X dla celów fotogrametrycznych opracowań cyfrowych

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Streszczenie. W artykule przedstawiono wyniki badań nad kalibracją wysokorozdzielczej lustrzanki cyfrowej Nikon D3X. Badania obejmowały określenie stabilności rejestrowanych na matrycy obrazów cyfrowych, wyznaczenie odległości obrazowej, punktu głównego zdjęcia, dystorsji radialnej, dystorsji tangencjalnej oraz przetestowanie uzyskanych parametrów orientacji wewnętrznej kamery na projekcie testowym. Wszystkie etapy prac przeprowadzono wykorzystując trzy wymienne obiektywy Nikkor o ogniskowych 24, 35 i 50 mm. Proces kalibracji kamery wykonano z zastosowaniem zbieżnych zobrazowań naziemnych w oprogramowaniu PhotoModeler oraz pojedynczej sceny w module programu Aerosys. Do określenia elementów orientacji wewnętrznej aparatu z poszczególnymi obiektywami wykorzystano pole testowe płaskie oraz przestrzenne. Stabilność i powtarzalności rejestracji obrazów na matrycy sprawdzono na 25 rozmieszczonych równomiernie punktach. Uzyskane wyniki to przeciętnie: dla ogniskowej 24 mm – 0.06 piksela, 35 mm – 0.08 piksela, 50 mm – 0.04 piksela. Kalibrację wykonano wykorzystując moduły *Camera Calibration* i *Field Calibration* oprogramowania PhotoModeler oraz moduł DLT programu Aerosys. Najdokładniej dla wszystkich obiektywów opracowano przykładowy projekt fotogrametryczny, stosując elementy orientacji wewnętrznej testowanej lustrzanki, wyznaczone na podstawie zdjęć zbieżnych testu trójwymiarowego.

Słowa kluczowe: fotogrametria naziemna, kalibracja kamer, lustrzanka cyfrowa, dokładność, matryca CMOS