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Evaluation of the geometric stability and the accuracy potential of digital cameras — Comparing mechanical stabilisation versus parameterisation

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ABSTRACT

Recent tests on the geometric stability of several digital cameras that were not designed for photogrammetric applications have shown that the accomplished accuracies in object space are either limited or that the accuracy potential is not exploited to the fullest extent. A total of 72 calibrations were calculated with four different software products for eleven digital camera models with different hardware setups, some with mechanical fixation of one or more parts. The calibration procedure was chosen in accord to a German guideline for evaluation of optical 3D measuring systems [VDI/VDE, VDI/VDE 2634 Part 1, 2002. Optical 3D Measuring Systems – Imaging Systems with Point-by-point Probing. Beuth Verlag, Berlin]. All images were taken with ringflashes which was considered a standard method for close-range photogrammetry. In cases where the flash was mounted to the lens, the force exerted on the lens tube and the camera mount greatly reduced the accomplished accuracy. Mounting the ringflash to the camera instead resulted in a large improvement of accuracy in object space. For standard calibration best accuracies in object space were accomplished with a Canon EOS 5D and a 35 mm Canon lens where the focusing tube was fixed with epoxy (47 μm maximum absolute length measurement error in object space). The fixation of the Canon lens was fairly easy and inexpensive resulting in a sevenfold increase in accuracy compared with the same lens type without modification. A similar accuracy was accomplished with a Nikon D3 when mounting the ringflash to the camera instead of the lens (52 μm maximum absolute length measurement error in object space). Parameterisation of geometric instabilities by introduction of an image variant interior orientation in the calibration process improved results for most cameras. In this case, a modified Alpa 12 WA yielded the best results (29 μm maximum absolute length measurement error in object space). Extending the parameter model with FiBun software to model not only an image variant interior orientation, but also deformations in the sensor domain of the cameras, showed significant improvements only for a small group of cameras. The Nikon D3 camera yielded the best overall accuracy (25 μm maximum absolute length measurement error in object space) with this calibration procedure indicating at the same time the presence of image invariant error in the sensor domain. Overall, calibration results showed that digital cameras can be applied for an accurate photogrammetric survey and that only a little effort was sufficient to greatly improve the accuracy potential of digital cameras.

1. Introduction

Working with cameras that are not designed for the special needs of photogrammetry is common practise in close range applications. While it is established knowledge that high precision can be accomplished with regular digital cameras (Peipe and Schneider, 1995; Fraser et al., 1995), the geometric stability of these cameras is often the limiting factor for the accuracy that can be achieved (Gruen et al., 1995; Shortis et al., 1998; Chandler et al., 2005; Shortis et al., 2006). Mechanical problems are held responsible for the most significant problems regarding geometric stability of cameras (Gruen et al., 1995; Tecklenburg et al., 2001; Mills et al., 2003; Miyatsuka, 1996; Habib and Morgan, 2005; Rieke-Zapp and Peipe, 2006; Haig et al., 2006) besides

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thermal effects (Gülch, 1984) and influences caused by the signal processing chain (Beyer, 1992). Unstable camera geometry may be tackled either by means of parameterisation or mechanical camera stabilisation. Parameterisation includes for instance the calculation of an image variant interior orientation (Maas, 1999; Hastedt et al., 2002), the modelling of image variant sensor deformations within a finite-element correction grid (Tecklenburg et al., 2001) or the calculation of a parameter depicting the impact of the gravitational force on camera geometry (Haig et al., 2006). Mechanical stabilisation includes the fixation of the sensor inside the camera (Shortis et al., 1998; Rieke-Zapp and Nearing, 2005), but poses the disadvantage that such stabilisation measures will typically void the manufacturer's warranty. As high-end digital cameras cost only a fraction of their price ten years ago, warranty concerns are less pressing today, allowing even for the total loss of a camera in the quest for optimum geometric stabilisation. Best candidates for stabilisation measures are cameras that show good accuracy potential without stabilisation and revealing a possible improvement when working with the parameterisation of unstable camera geometry. Like that, parameterisation can be applied to disclose the accuracy potential of a camera while mechanical stabilisation is utilized to exploit this potential. Parameterisation can often account for symptoms of unstable camera geometry, but cannot depict the actual cause for the instability. Working with an image variant interior orientation for instance, it is not clear if sensor, lens, lens tube or the lens mount cause the instability. It is unknown what factors affect the geometric stability the most, which would aid in identification of the weakest link or the place where stabilisation measures should be most effective. Parameterisation of unstable camera geometry is implemented in some software products such as Aicon 3D Studio (Aicon, 2005), AXIOS Ax.Ori (Axios, 2008) or FiBun (Tecklenburg et al., 2001), but is not accepted as a standard set of additional parameters such as lens distortion, affinity or shear parameters. Mechanically stable cameras are easier to use on the job as they provide optimum accuracy without extra parameterisation degrading the degrees of freedom in the adjustment unless the network geometry is sufficient to support a stable and well conditioned solution for the parameter set.

Testing the geometric stability of several cameras in recent years has shown that the accomplished accuracies in object space are either limited (Mills et al., 2003; Peipe and Schneider, 2003; Chandler et al., 2005; Habib and Morgan, 2005; Peipe, 2006; Shortis et al., 2006; Peipe et al., 2007; Wackrow et al., 2007) or that the accuracy potential is not exploited to the fullest extent (Rieke-Zapp and Nearing, 2005; Rieke-Zapp and Peipe, 2006). At the same time, the camera industry added features to the latest digital camera models which counteract their usefulness for photogrammetry. These features include sensor vibration for removal of dust particles or sensor movement to reduce the effect of camera shake during image acquisition. In both cases the sensor position needs to be flexible which equates to possible instability of the sensor position. Auto focus lenses require low friction gears in the lenses for quick focus action, stabilisation of lens elements to reduce camera shake and other features reduce the geometric stability of the camera system and can hardly be avoided as only a few cameras are left in the market lacking these features.

In this manuscript we (a) investigate the accuracy in object space of several digital cameras, (b) explore the accuracy potential of the same cameras extending the model of interior orientation with image variant additional parameters, and (c) evaluate the effectiveness of mechanical stabilisation on accuracy in object space.

2. Materials and methods

2.1. Investigated cameras

Several cameras were evaluated covering a wide range of brands and sensor formats (Table 1). Mechanical fixes of the investigated cameras were explicitly noted. Several Nikon cameras were available for the tests. D2X, D200 and D80 shared a common sensor size. Working with the same 2.8/24 mm AiS Nikkor manual focus lens allowed comparison of results between the most rugged model aimed at professional photographers (D2X), the semi-professional model (D200) and the amateur model (D80). The Nikon D3 with a larger sensor size than the other Nikon cameras was released quite recently to replace the current model aimed at professional photographers and was added to the test at later stage. It was tested with the same 24 mm lens mentioned before. A different Nikon D2X with similar AiS 24 mm Nikkor lens was examined in a second test cycle. The same camera lens combination was first tested without any modification and then with the focusing tube of the lens fixed with two screws and the lens glued to the camera mount. These tests were carried out on a testfield in Brunswick, Germany.

A Canon EOS 5D camera was tested with two Canon EF 2/35 mm lenses and a Leica Summicron-R 2/35 mm. One of the Canon EF lenses was fixed at infinity by placing epoxy between the focusing tube and the outer lens tube. The Leica lens was adapted to Canon EOS via a Novoflex mount adapter.

Furthermore a Leica M8 with Summicron-M 2.8/28 mm ASPH was tested as well as a Sigma SD14 using a 2.8/24 mm Sigma manual focus lens. On the Sigma camera the lens was available in M42 screw mount and was mounted to the camera via a Dörr adapter. The manual focus lens was used as previous tests with the Sigma (Peipe et al., 2007) revealed low accuracy in object space with autofocus lenses.

All of the aforementioned cameras were based on camera systems dating back to the 35 mm film format. In order to complete the evaluation, two cameras based on medium format camera systems complemented the group of cameras to be tested. A Mamiya ZD camera was used in combination with a 3.5/35 mm auto focus lens. An Alpa 12 camera was evaluated with a Schneider Kreuznach Apo-Digitar 5.6/47 mm lens and an interchangeable Leaf Aptus 75 digital camera back. Based on previous experiences with Alpa 12 cameras (Rieke-Zapp and Nearing, 2005; Rieke-Zapp and Peipe, 2006), camera back and lens were fixed to the camera body with screws (Fig. 1). Only the camera was altered, lens and digital back were still exchangeable. The Alpa setup was evaluated on two testfields (Oldenburg/Wolfsburg).

The lenses for all cameras, except the Nikon D3 and the Mamiya ZD, were chosen to yield a similar angle of view and thus a similar perspective (Table 1). Therefore, the cameras with smaller sensors were used in combination with lenses of short focal length and the cameras with the larger sensors were used with the longer focal lengths. While this resulted in the same perspective for most images, the depth of field was narrower for lenses with longer focal length. The lenses were stopped down to an aperture number of 16. The Canon EF lens with epoxy in the lens tube was fixed at infinity. For this camera the aperture was stopped down to 22 to increase depth of field as the actual distance between the camera and the centre of the testfield was approximately 3 m.

2.2. Testfields

The majority of all tests were performed using a testfield at the University of Applied Sciences in Oldenburg, Germany (Table 1). The testfield (Fig. 2) was designed according to a German guideline for evaluation of optical 3D measuring

Table 1
Technical specifications of all cameras in this test.

Test site Camera	Oldenburg Alpa 12 WA	Leica M8	Canon EOS 5D			Mamiya ZD	Nikon				Sigma SD14	Wolfsburg Alpa 12 WA	Brunswick Nikon D2X
							D3	D2X	D200	D80			
Lens manufacturer	Schneider Kreuznach	Leica	Canon	Canon	Leica	Mamiya	Nikon	Nikon	Nikon	Nikon	Sigma	Schneider Kreuznach	Nikon
Lens nominal focal length (mm)	47	28	35	35	35	35	24	24	24	24	24	47	24
Diagonal field of view (°)	65	60	63	63	63	99	84	61	61	61	55	65	61
Ring flash mounted to lens	yes	no[b]	yes	yes	yes	yes	yes/no[a]	yes/no[a]	yes	yes	yes	no	yes
Sensor (mm^2)	36 × 48	18 × 27	24 × 36	24 × 36	24 × 36	36 × 48	24 × 36	15.7 × 23.7	15.8 × 23.6	15.8 × 23.6	13.8 × 20.7	36 × 48	15.7 × 23.7
Sensor Pixel	4992×6666	2630×3936	2912×4368	2912×4368	2912×4368	4000×5328	2832×4256	2848×4288	2592×3872	2592×3872	1760×2640	4992×6666	2848 × 4288
Pixel pitch[c] (mm)	0.0072	0.0061	0.00825	0.00825	0.00825	0.009	0.0085	0.0055	0.0061	0.0061	0.00686	0.0072	0.0055
Stabilisation measure	Fixation of digital back and lens with screws	-/-	-/-	Fixation of lens tube with epoxy	Lens fitted via mount adapter	-/-	-/-	-/-	-/-	-/-	Lens fitted via mount adapter	Fixation of digital back and lens with screws	None/fixed focusing tube & lens fixed in lens mount

[a] LED ringlight fixed to camera's tripod mount.
[b] Ringflash taped to camera body not affecting the lens.
[c] Used for calibration.

Fig. 1. Alpa 12 WA with the digital back and the lens fixed to the camera with screws. Four clamps in the front and four clamps in the back of the standard camera were replaced with screws. In addition to that, an aluminium plate was connected with screws to the camera providing extra support for the digital back.

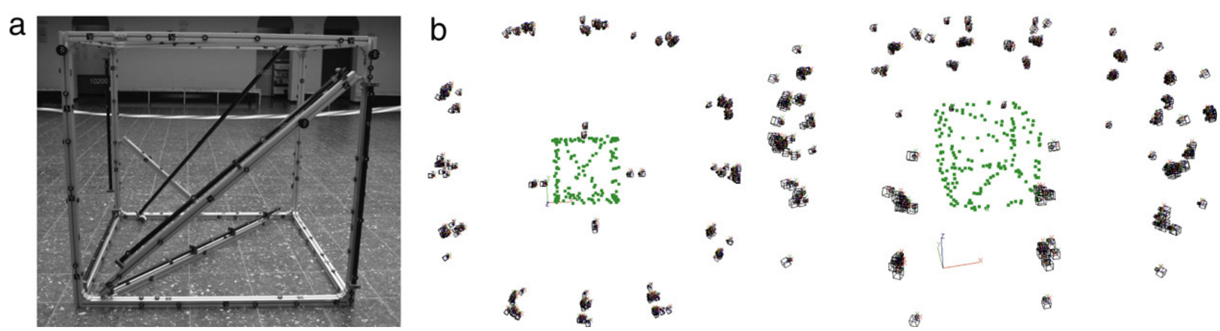

Fig. 2. (a) Testfield at the University of Applied Sciences in Oldenburg, Germany. (b) Image exposure stations around the testfield.

systems (VDI/VDE 2634 Part 1, 2002). The measuring volume was approximately 2000 mm × 2000 mm × 1500 mm (length × width × height). Seven measuring lines were placed in the volume, the longest was approximately 2039 mm. A total of 57 distances on the measuring lines were available calibrated to an accuracy of 10 μm and better (one sigma). The measuring lines were initially calibrated by Deutscher Kalibrierdienst (DKD) and were later checked and recalibrated at the University of Applied Sciences in Mainz, Germany (i3Mainz). Approximately 170 retroreflective photogrammetric targets were placed in the measuring volume as well as a scale bar in the centre to scale the object coordinate system.

All images were taken with a ring flash that was mounted to the lens of the camera as this was considered a standard technique for image acquisition. In case of the Leica M8 the flash was taped to the camera as the diameter of the lens was too small to fix the flash in the filter thread. In order to preclude the influence of a ring flash pulling on the front tube of the lens, two datasets (Nikon D3, D2X) were acquired with a specialised LED ring flash that was fixed solely to the cameras tripod mount (Fig. 3). The Alpa camera was evaluated on a testfield in Wolfsburg, Germany, to quantify the influence with (Oldenburg) and without (Wolfsburg) ringflash fixed to the lens. Furthermore, a second Nikon D2X was evaluated on a testfield in Brunswick, Germany. The performance of the camera was evaluated before and after mechanical stabilisation. The testfields in Brunswick and Wolfsburg had similar specifications as the one in Oldenburg. All testfields were in compliance with VDI/VDE 2634 Part 1 (2002).

2.3. Test procedure

More than 120 images were acquired with each camera setup of the measuring volume in Oldenburg (Fig. 2) and Wolfsburg; more than 80 images were taken for tests in Brunswick. The camera under investigation was rotated about the camera axis for more than a third of all images. The testfield was covered by images from all directions and at different heights (Fig. 2). Images were acquired with the best in-camera JPEG compression and in raw format. The two medium format cameras did not allow saving JPEG images in the camera. Raw image data was converted to TIFF with the software of the camera manufacturer — in case of the Alpa with the software of the back manufacturer (Leaf). Since this software was only supported under Macintosh computers at the time of the testing, Alpa/Leaf raw imagery was also developed with Adobe Photoshop Camera Raw 3.4 software on a Windows computer. Raw and JPEG imagery was processed without sharpening or other image enhancement options. In-camera settings for JPEG generation were also set to discard any image enhancements.

Object coordinates and camera parameters of the testfield were calculated for each set of images individually using Aicon 3D Studio

Fig. 3. LED ringlight mounted to Nikon D2X.

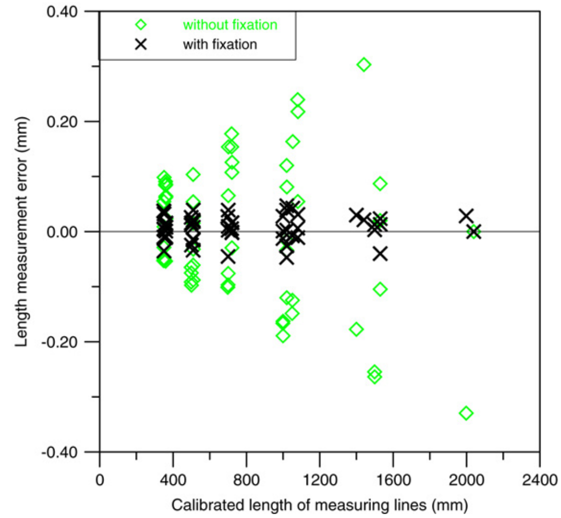

Fig. 4. Calibration results of Canon EOS 5D with EF 2/35 mm lens using the standard calibration with Aicon 3D Studio software. The camera was calibrated with a lens where the lens tube was fixed with epoxy and without fixation. Maximum absolute LMEs were 330 and 47 μm for the non-modified and the modified lens, respectively.

(version 7.5; Aicon, 2005) as well as FiBun (Tecklenburg et al., 2001; Hastedt et al., 2002) software. In case of the Aicon software the interior orientation of the cameras was calibrated with the position of the projection centre in image space (c, x'_0, y'_0) along with additional parameters for lens distortion $(A_1, A_2, A_3, B_1, B_2)$ as well as affinity and shear (C_1, C_2). The cameras were once calibrated applying a single parameter set for all images in the block and then with the same set of parameters, but calculating an image variant interior orientation for each image to account for unstable camera geometry. Calibrating an image variant interior orientation follows the same approach in Aicon and in FiBun software. While Aicon 3D Studio applies a common parameterisation for distortion, affinity and shear, FiBun merely considers the balanced form of parameters describing the radial symmetric distortion (A_1, A_2, A_3); the remaining image errors in sensor space were modelled using a finite elements correction grid (Tecklenburg et al., 2001). In this calibration model the correction grid covers, for instance, unflatness of the imaging sensor and other invariant errors in the sensor domain which are usually not taken into account by conventional calibration models (Tecklenburg et al., 2001).

Only the length of the scale bar in the centre of the measuring volume was introduced in the bundle adjustment for camera calibration and calculation of object coordinates. The three-dimensional length measurement error (LME) was obtained from the difference between the measured and the calibrated distances between two target points. The maximum absolute deviation of all distances was the maximum absolute length measurement error in the system (Table 2). In addition to the maximum absolute LME the range of the LME from the smallest to the largest deviation was reported (Table 2).

3. Results and discussion

3.1. Oldenburg testfield

Most cameras were evaluated on the testfield in Oldenburg. The results of three different adjustment methods with self-calibration (Tables 2 and 3, Fig. 4) revealed that parameters describing the internal precision of the adjustment did not reflect accuracy in object space represented by the maximum absolute LME. The root mean square error (RMSE) of object coordinates estimated in the adjustments was too favourable and underestimated the actual length measurement accuracy by more than an order of magnitude for most calibrations with Aicon 3D Studio (standard) and at least by a factor of four for calibration with the same software and image variant calibration of the interior orientation. A posteriori sigma$_0$ was also not a useful predictor of accuracy in object space. The Canon EOS 5D for instance reached the same a posteriori sigma$_0$ with the fixed 35 mm Canon lens and the 35 mm Leica lens, but the maximum absolute LME of the latter setup was approximately three times worse than for the first setup. Another example was the Nikon D2X where a posteriori sigma$_0$ for the setup with the ringflash mounted on the lens and the LED ringflash fixed to the cameras tripod mount was approximately the same, but the maximum absolute LME was three times smaller for the setup with the LED ringflash.

The system scale bar was placed in the middle of the testfield. Comparing maximum absolute LME and the range of the absolute LME indicated no significant skew of the LME in positive or negative direction. Only in case of the Canon EOS 5D in combination with the Leica lens, the maximum absolute LME accounts for approximately two thirds of the total range of absolute LME in case of the standard calibration (Table 2) revealing a significant trend away from unity that may be attributed to configuration of image acquisition. The trend disappeared with image variant calibration of the camera.

Calibration with the standard parameter set in Aicon 3D Studio showed rather disappointing results. Only for camera setups where the ringflash was not mounted to the lens (Leica M8; Nikon D2X and D3 with LED ringflash) as well as for the Canon EOS 5D with the fixed focusing tube, a maximum absolute LME of less than 100 μm was accomplished. Other camera setups such as the Alpa or the Nikon D2X with a ringflash mounted to the lens fell below values experienced in previous tests. Comparison of the standard calibration and the image variant calibration with Aicon 3D Studio revealed that the force that the ringflash exerted on the focusing tube resulted in unstable camera geometry in all cases, except for the Canon lens where the focusing tube was fixed with epoxy. The Nikon D3 and D2X accomplished 59 and 52 μm in maximum absolute LME, respectively, for standard calibration with the flash not fixed to the lens. Testing the Alpa camera on a different testfield in Wolfsburg (under adverse, less controlled conditions) with the flash not fixed to the lens yielded a maximum absolute LME of 61 μm which was more than twice as good as with the flash pulling on the focusing tube in the Oldenburg test.

Fixation of the focusing tube in the Canon EF lens was a very successful mechanical stabilisation measure, as the accomplished accuracy with standard and image variant calibration in Aicon 3D

Table 2
Results of camera calibration on the testfield in Oldenburg based on calculation with Aicon 3D Studio software. The ringflash was mounted to the lens unless otherwise noted.

Camera/lens	Image format	Point measurement accuracy in images (μm)	Calculation with Aicon 3D Studio (standard)				Calculation with Aicon 3D Studio (image variant)			
			Root mean square error of object coordinates (μm)	A posteriori $sigma_0$ of bundle adjustment (μm)	Max. absolute LME[a] (μm)	LME range (μm)	Root mean square error of object coordinates (μm)	A posteriori $sigma_0$ of bundle adjustment (μm)	Max. absolute LME (μm)	LME range (μm)
Alpa 12 WA/ Schneider 47 mm	TIFF, raw data TIFF, PSCS2[b]	0.20–0.34 0.17–0.28	8.2 8.1	0.44 0.41	124 125	210 211	7.3 6.7	0.34 0.30	29 35	57 69
Canon EOS 5D/Canon 35 mm	TIFF, raw In camera JPEG	0.21–0.30 0.16–0.27	22.8 22.9	0.76 0.80	330 324	633 622	10.3 10.1	0.32 0.33	46 48	68 74
Canon EOS 5D/Canon 35 mm, focus tube fixed with epoxy	TIFF, raw data In camera JPEG	0.17–0.33 0.18–0.29	12.7 12.2	0.40 0.40	47 58	94 116	10.6 11.2	0.30 0.35	66 47	104 93
Canon EOS 5D/Leica 35 mm	TIFF, raw data In camera JPEG	0.14–0.30 0.14–0.31	12.3 13.1	0.41 0.44	201 193	275 288	10.1 11.0	0.31 0.34	35 42	65 79
Leica M8/Leica 28 mm	TIFF, raw data In camera JPEG	0.11–0.23 0.14–0.24	11.8 13.8	0.31 0.35	78 80	127 130	11.3 13.3	0.28 0.32	78 72	133 134
Mamiya ZD/Mamiya 35 mm	TIFF, raw data	0.28–0.36	26.7	1.13	132	238	14.0	0.57	66	111
Nikon D3/Nikkor 24 mm, ringflash fixed to lens	TIFF, raw data In camera JPEG	0.19–0.28 0.16–0.25	15.5 17.6	0.56 0.60	213 225	342 388	10.7 13.1	0.35 0.41	46 51	71 86
Nikon D3/Nikkor 24 mm, ringflash fixed to tripod mount	TIFF, raw data In camera JPEG	0.20–0.31 0.16–0.23	14.0 14.3	0.46 0.45	52 57	93 105	11.0 11.3	0.34 0.32	39 44	67 79
Nikon D2X/Nikkor 24 mm, ringflash fixed to lens	TIFF, raw data In camera JPEG	0.13–0.23 0.10–0.20	12.6 13.3	0.29 0.30	166 190	320 342	12.0 12.4	0.26 0.26	83 102	123 142
Nikon D2X/Nikkor 24 mm, ringflash fixed to tripod mount	In camera JPEG	0.11–0.18	20.1	0.25	59	92	-/-.	-/-	-/-	-/-
Nikon D200/Nikkor 24 mm	TIFF, raw data In camera JPEG	0.13–0.23 0.14–0.25	14.8 14.3	0.32 0.32	208 225	354 390	13.3 13.4	0.27 0.28	81 100	126 145
Nikon D80/Nikkor 24 mm	TIFF, raw data In camera JPEG	0.13–0.22 0.11–0.23	15.0 14.6	0.33 0.32	191 209	348 392	13.1 13.3	0.27 0.27	93 145	131 190
Sigma SD14/Sigma 24 mm	TIFF, raw data	0.10–0.20	18.7	0.32	185	301	17.7	0.27	117	174

[a] Length measurement error.
[b] Converted with Photoshop CS2 Camera Raw 3.4.

Table 3
Results of camera calibration on the testfield in Oldenburg based on calculation with FiBun software. The ringflash was mounted to the lens unless otherwise noted.

Camera/lens	Image format	Calculation with FiBun		
		A posteriori sigma$_0$ of bundle adjustment (μm)	Max. absolute LME[a] (μm)	LME range (μm)
Alpa 12 WA/ Schneider 47 mm	TIFF, raw data	0.26	29	50
	TIFF, PSCS2[b]	0.23	33	59
Canon EOS 5D/Canon 35 mm	TIFF, raw	0.24	118	172
	In camera JPEG	0.23	118	182
Canon EOS 5D/Canon 35 mm, focus tube fixed with epoxy	TIFF, raw data	0.23	61	114
	In camera JPEG	0.24	49	91
Canon EOS 5D/Leica 35 mm	TIFF, raw data	0.22	40	77
	In camera JPEG	0.23	37	72
Leica M8/Leica 28 mm	TIFF, raw data	0.19	64	111
	In camera JPEG	0.20	59	98
Mamiya ZD/Mamiya 35 mm	TIFF, raw data	0.33	45	78
Nikon D3/Nikkor 24 mm, ringflash fixed to lens	TIFF, raw data	0.25	41	73
	In camera JPEG	0.28	48	84
Nikon D3/Nikkor 24 mm, ringflash to tripod mount	TIFF, raw data	0.26	25	46
	In camera JPEG	0.25	42	82
Nikon D2X/Nikkor 24 mm, ringflash fixed to lens	TIFF, raw data	0.20	89	120
	In camera JPEG	0.19	99	129
Nikon D2X/Nikkor 24 mm, ringflash to tripod mount	In camera JPEG	0.19	63	96
Nikon D200/Nikkor 24 mm	TIFF, raw data	0.20	79	114
	In camera JPEG	0.20	99	133
Nikon D80/Nikkor 24 mm	TIFF, raw data	0.20	104	134
	In camera JPEG	0.19	140	171

[a] Length measurement error.
[b] Converted with Photoshop CS2 Camera Raw 3.4.

Studio was the almost the same. This result also indicated that the lens mount of the Canon camera was not affected by the lens and the flash pulling on it. Slightly better maximum absolute LME was accomplished with the normal, not fixed, Canon and Leica 35 mm lenses with the image variant calibration in Aicon 3D Studio. The Leica lens produced slightly better maximum absolute LME in this case which was attributed to the better photographic quality of the images compared with images taken with the Canon lenses. Working with an image variant calibration improved the results gained with the unaltered Canon lens by almost an order of magnitude indicating the low geometric stability of this lens (Fig. 4). Fixing the lens tube with epoxy resulted in a six-fold improvement of maximum absolute LME for standard calibration allowing the Canon lens to excel from the worst (324 μm) to the best accuracy in object space (47 μm) (Fig. 4). Leica M8, Nikon D2X and Nikon D3 were the only other cameras to reach a maximum absolute length measurement error of less than 100 μm for standard calibration when the ringflash was not fixed on the lens. The best results for non-modified cameras were accomplished by the Nikon D3 and Nikon D2X with a maximum absolute LME of 52 and 59 μm, respectively, with the LED ringflash.

Comparing the performance of the four Nikon cameras (D3, D2X, D200, D80) in combination with the same 24 mm lens and the ringflash fixed to the lens, showed no significant difference in maximum absolute LME between consumer (D80), prosumer (D200) and professional (D2X, D3) camera models for standard calibration with Aicon software. In case of the image variant calibration with Aicon as well as calibrating with FiBun software, the Nikon D3 went ahead of its three competitors. The accuracy accomplished with the Nikon D80 lagged behind the other models when working with JPEG images. Considering the great influence of the ringflash when mounted to the lens, the accuracy accomplished with the Nikon camera models was probably mostly affected by the stability of the lens with the ringflash pulling on it rather than the camera model.

Working with the image variant calibration in Aicon 3D Studio, more cameras revealed a good accuracy potential of less than 100 μm (Table 2). The best accuracy potential with the image variant calibration was accomplished with the Alpa camera (29 μm maximum absolute length measurement error; Fig. 5) closely followed by the Canon with the Leica lens (35 μm maximum absolute length measurement error). The Nikon D3 in combination with the LED ringflash fixed to the tripod mount of the camera was able to excel to a maximum absolute LME of 39 μm (Fig. 6) — a similar improvement was expected for the Nikon D2X, but no data was available for this calibration.

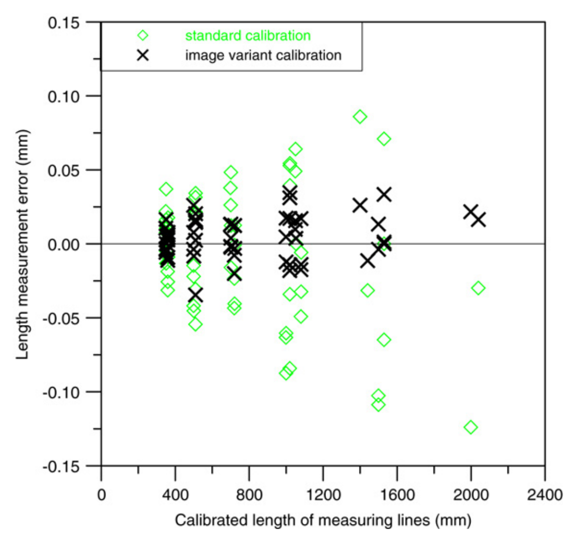

Fig. 5. Calibration results of the Alpa 12 WA with fixations and the ringflash mounted to the lens. Maximum absolute LMEs were 124 and 29 μm for the standard and image variant calibration, respectively..

The system scale and the measuring lines had a certified accuracy of 10 μm and better (one sigma). The maximum length measurement error that may be tested with this setup is five times the certified accuracy (VDI/VDE 2634 Part 1 , 2002) which equates to 50 μm for the described testfield. Maximum absolute

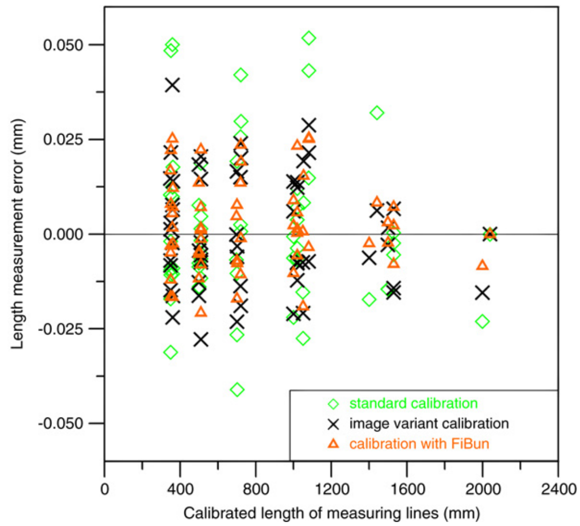

Fig. 6. Calibration results for the Nikon D3 with LED ringflash mounted to the camera. Maximum absolute LMEs were 52, 39 and 25 μm for the standard, image variant and FiBun calibration, respectively.

LME values less than 50 μm surpassed this accuracy limit that can be verified by the setup and must be regarded excellent results for the respective cameras.

The Nikon D2X did not reach the same level of accuracy with the ringflash mounted to the lens in the case of the image variant calibration as for the setup where the ringflash was mounted to the tripod mount (Table 2). This indicated that the image variant calibration was only useful to reveal the accuracy potential of a camera to a limited degree and that more favourable values may be accomplished by further fixation or relieving the focusing tube of the ringflash load. The image variant calibration was not able to compensate for all effects of unstable camera geometry. This was also obvious for the Alpa camera. In a previous test under similar conditions, an Alpa camera (Rieke-Zapp et al., 2005) without fixation revealed an accuracy potential (based on calibration with image variant interior orientation) of 57 μm. This was approximately twice of what was accomplished here after fixation of lens and digital back to the camera (29 μm; Table 2, Fig. 5).

Results of calibration with FiBun software were quite similar to the image variant approach with Aicon software. Only the Leica M8, Mamiya ZD and Nikon D3 showed a significant improvement for the maximum absolute LME (Table 3). The Nikon D3 with the LED ringflash marked here the best accuracy of all tested cameras with a maximum absolute LME of 25 μm (Fig. 6), an improvement of more than 35% compared with the image variant calibration with Aicon software. The major difference of FiBun to Aicon software was the calculation of a finite element grid to detect and correct errors such as unflatness of the sensor plane and other invariant errors in sensor space. The results indicated that errors in the sensor domain were present for the three cameras that showed improvements when calibrated with FiBun. Nevertheless, all three cameras revealed very good accuracy potential in object space even without parameterisation of image invariant errors in the sensor domain (Tables 2 and 3). In case of the Nikon D3 the best maximum absolute LME of all cameras was accomplished with this approach. Sensor size and pixel pitch of these three cameras were similar to the sensors in the Canon EOS 5D or the Leaf Aptus 75 digital back on the Alpa camera which did not reveal errors in sensor space that can be detected with FiBun software.

Working with TIF-files generated from raw imagery resulted in more favourable maximum absolute LME values (Tables 2 and 3). A gain in accuracy between 5% and 10% was possible which was considered a significant improvement over analysis of the JPEG files. Only the Canon EOS 5D in combination with the fixed 35 mm lens revealed slightly better results with JPEG imagery for image variant calibration. In this particular case, raw and JPEG imagery correspond to different data sets taken three months apart, representing the repeat accuracy rather than the difference between different image processing of the same raw data. Comparison of different raw development software for images taken with the Alpa camera indicated significant differences for the image variant calibration with Aicon software. In this case, images developed with the Leaf (manufacturer of the digital back) software yielded approximately 18% better accuracy than images developed with Adobe Photoshop Camera Raw software (Table 2).

The Mamiya ZD revealed a maximum absolute LME for the image variant calibration that was similar to the better group of small format cameras, but did not match the accuracy of the Alpa, the other camera in the test based on a medium format camera system. Both cameras had a large sensor with 22 or 33 mega pixel which was more than twice the pixel count of most small format cameras in the test. Only the Alpa camera met the expectations of the performance of a great number of pixels yielding better accuracy than the other cameras in case of the image variant calibration, but the advantage was much smaller than the pixel count or the price tag would have suggested. Even the Alpa camera was surpassed by the Nikon D3 when the sensor domain was modelled with FiBun software.

The Sigma SD14 could not deliver any favourable LME values and was listed mostly for completeness. It was not clear if the performance of the Sigma was due to geometric instability or to the small number of pixels as this camera employs less than half the number of physical pixels than any other camera tested here. On a per pixel basis the Sigma camera performed well, but in absolute terms a maximum absolute LME of 117 μm for calibration with image variant interior orientation puts it in last place of the tested cameras.

3.2. Tests in Brunswick and Wolfsburg

The Alpa 12 WA (Table 1) was also tested in Wolfsburg on a similar testfield as present in Oldenburg. The test was performed with a flash mounted to the camera instead of the lens. The calibration was calculated only for the standard parameter set of GOM Tritop software (GOM, 2008) which corresponds closely to the parameterisation employed in the standard calibration model of Aicon 3D Studio software. The maximum LME was 61 μm and the range of the LME was 99 μm. This implied that the ringflash in the Oldenburg test increased the maximum absolute LME of the Alpa camera by approximately 60 μm or, in other words, the ringflash degraded the accomplished accuracy by approximately 50%. Although the maximum absolute LME improved significantly over the Oldenburg test, the image variant calibration with Aicon 3D Studio of the Oldenburg data set still showed a more than twofold increase towards 29 μm, compared with the 68 μm accomplished with the standard GOM software calibration. Therefore, an additional 39 μm must be attributed to a not completely stable camera geometry of the Alpa.

In addition to the Nikon D2X tested in Oldenburg, a second Nikon D2X with 24 mm AiS Nikkor manual focus lens was evaluated on a testfield in Brunswick which was similar to the Oldenburg testfield. Calibration was calculated with Aicon 3D Studio software for the standard parameter set as well as an image variant calibration (Table 4). Two tests were performed with the same camera. At first, the camera was calibrated without any stabilisation, then the focusing ring of the lens was fixed with two small screws, and the lens was glued permanently to the camera mount. All images were taken with a ringflash mounted to the

Table 4
Results of the Nikon D2X evaluated on a testfield in Brunswick, Germany, calculated with Aicon 3D Studio software. The ringflash was mounted to the lens for all tests.

Camera/lens		Calculation with Aicon 3D Studio (standard)		Calculation with Aicon 3D Studio (image variant)	
		Max. absolute LME[a] (μm)	LME range (μm)	Max. absolute LME (μm)	LME range (μm)
Nikon D2X with Nikkor 24 mm	No fixation	99	138	60	118
	Focusing tube fixed, lens glued to camera mount	90	133	94	155

[a] Length measurement error.

Table 5
Torque in the lens mount for selected cameras.

Camera	Lens	Weight (N)	Distance[a] (m)	Max. Torque[b] (N m)
Alpa	Schneider 47 mm with ringflash	5.10	0.067	0.34
Alpa	Leaf Aptus 75 digital back	6.38	0.028	0.18
Canon EOS 5D	Canon EF 35 mm with ringflash	3.53	0.028	0.10
Canon EOS 5D	Canon EF 35 mm w/o ringflash	2.06	0.022	0.05
Canon EOS 5D	Canon EF 35 mm w/o ringflash	5.68	0.039	0.22
Nikon D2X	Nikkor 24 mm with ringflash	4.12	0.037	0.15
Nikon D2X	Nikkor 24 mm w/o ringflash	2.65	0.023	0.06

[a] From the lens' center of gravity to the lens mount.
[b] Maximum torque is produced when the camera is held with the optical axis perpendicular to the plumb line.

filter thread of the lens. The stabilisation measures showed no improvement of camera stability, actually maximum absolute LME increased with stabilisation (for image variant calibration) which was an unexpected outcome. While simple fixation measures in case of the Canon EOS 5D had a very positive effect on the accomplished accuracy, the D2X tested in Brunswick appeared immune to any stabilisation measure and performed at the same level of accuracy as the D2X in Oldenburg when a ringflash was fixed in the filter thread of the lens (Table 2). For the Nikon D2X mechanical fixation was less successful than calibrating the camera without the ringflash mounted on the lens (Table 2). Possible causes for this behaviour may be that either the focusing tube of the lens or the connection between camera and lens was not completely fixed, or some internal instability was present in the camera or the lens body.

Calculating the torque on the lens mount with the ringflash mounted to the lens showed that the focusing tube of the lens rather than the lens mount was the weak link in this setup. The extra torque of the ringflash mount to the lens should not deform the lens mount. The torque produced in the lens mount is the product of the weight of the lens multiplied with the distance of the lens' centre of gravity from the lens mount (Table 5). The maximum torques produced in the lens mount of the Nikon D2X were 0.15 and 0.06 Nm, respectively, with and without mounting the ringflash on the 24 mm Nikon lens. In both cases with and without ringflash the torques were not significantly larger than for other cameras presented in Table 5. This indicated that the force on the mount of the D2X was not excessive and well within the limits that should be handled by a camera advertised to have an extra rigid mount. Therefore it was more likely that the lens tube or some other part besides the lens mount caused the geometric instability of the D2X. This interpretation was also supported by comparison of calibration results of different Nikon cameras with the same lens. No significant difference in calibration accuracy of Nikon cameras was found for standard calibration (Table 2) and major improvements were present when the ringflash was not exerting extra force in the lens tube — tested only for the Nikon D2X and D3 models (Table 2). The largest torque values in Table 5 were calculated for the Alpa camera. The large sensor size required a longer focal length lens than for the other cameras to cover the same field of view. Although the weight of the lens including the ringflash was less than for the Canon EOS 5D with the Leica lens, the comparatively long focal length resulted in a longer distance from the centre of gravity to the lens mount, leading to large torque values. At the same time, the digital camera back produced an additional torque of 0.18 N m at the back of the camera. This clearly indicated that working with larger format cameras requires careful attention and good fixation to constrain the forces acting on the different connections present in such cameras.

4. Conclusion

Calibrating a wide variety of cameras with different calibration models and testing several measures to improve the geometric stability of some cameras revealed some interesting insights. Mounting a ringflash on the filter thread of lenses as is often done for close range applications had the largest negative effect on the accuracy in object space (Tables 2 and 3, Figs. 4 and 5). The ringflash should either be fixed directly onto the camera or in the tripod mount as indicated by the results of the Nikon D2X and D3 which showed a significant improvement in accuracy advancing from average performance to reach some of the best accuracy values when the ringflash was not mounted to the lens. Fixation of the focusing tube with epoxy was quite successful for the Canon EOS 5D with the 35 mm Canon EF lens which yielded the best accuracy for standard calibration even with the ringflash attached to the lens (Table 2, Fig. 4). The accuracy accomplished with fixation of the focusing tube as well as preventing gravitational loads on the lens or the lens mount yielded accuracies suitable for high-precision surveys even in case of standard calibration with Aicon software.

The best accuracy for calibration with Aicon 3D Studio was accomplished with the Alpa 12 WA with digital camera back and lens fixed to the camera (29 μm maximum absolute LME) (Table 2, Fig. 5). This value was only surpassed by the Nikon D3 with LED ringlight fixed to the tripod mount of the camera and parameterisation of the sensor domain with Fibun software (Table 3, Fig. 6). Stabilisation of problems in the sensor domain will be much more difficult to fix by mechanical means than unstable focusing tube or lens mount. Modelling the sensor domain in FiBun software significantly improved results for the Leica M8, Mamiya ZD and Nikon D3 only. This finding indicated that image invariant sensor deformations like unflatness were present that can be parameterised with FiBun software. Such errors were not present for the other cameras as calibration with FiBun did not result in a significant accuracy improvement.

The Canon EOS 5D with the Leica lens (35 μm maximum absolute LME) fell just short of the Alpa and Nikon results for image variant calibration. The latter two cameras yielded their best result with image variant calibration in Aicon 3D Studio. These results were considered excellent as the calibrated accuracy of the measurement lines was 10 μm and better (one sigma). Both, mechanical fixation of digital cameras as well as parameterisation did significantly improve the accuracy that can be accomplished in object space. Mechanical fixation is often straightforward and allows utilizing the accuracy potential of digital cameras even with the standard parameter set. Extended sets of parameters are not optimal in production environments unless the network geometry is sufficient to support a stable and well conditioned solution for the parameter set. Not all software products can work with extended parameter sets making it sometimes cumbersome or impossible to pass on calibration parameters from one software product to the other. Extended parameter sets may also be employed to identify mechanical weak points of digital cameras. Since mechanical fixation of weak camera components does not exclude parameterisation for further improvements, a combined approach should yield best accuracy in object space under most conditions.

Working with TIF-format files generated from raw imagery improved accuracy by approximately 5%–10%. Even utilising different raw converter software had an effect on the accuracy in case of the Alpa camera.

The pixel count of the two medium format cameras was at least two to three times larger than for the other cameras. This advantage could not be transferred to an advantage in accuracy for the two cameras. The Alpa camera with fixation of lens and camera back yielded an accuracy that was among the best of all cameras exceeded only by the Nikon D3 with the FiBun parameterisation. Weak points regarding geometric stability of medium format cameras are not only the weight of individual components, but also the number of interfaces for detachable camera backs and lenses. The geometric fixation of a medium format camera requires more effort than needed for smaller format cameras. Fixation of lens and digital back with screws improved the accuracy accomplished with the Alpa camera compared to previous tests significantly. The medium format cameras did not allow saving images in JPEG format. Image acquisition of raw data was advisable for best accuracy. This process was fairly time-consuming and may be impractical for industrial applications.

Stabilisation measures of Canon and Alpa camera did not inhibit the usefulness of camera or lens. The fixed Canon lens would still communicate with the camera body for metering and auto aperture — only the auto focus would not function anymore which can not be considered a drawback for photogrammetric applications. The screws of the Alpa camera allowed the utilisation of all lenses and backs of the Alpa 12 system. Fitting lenses via an adapter to a camera with a different mount (M42 lens on Sigma camera, Leica lens on Canon camera) had the disadvantage that the camera would only work in stop down metering mode and did not significantly improve the accuracy accomplished with the cameras.

A slightly altered version of the Alpa 12 WA with fixation screws and a pressure plate for digital camera backs and lens mounting is now commercially available as Alpa 12 Metric. The focusing distance of lenses can be fixed on customer request. Thorough evaluation of this new camera will be quite interesting as well as further investigation of the other camera models presented here. At the time of writing this manuscript only five of the eleven cameras tested are still in production, representing most if not all cameras without sensor cleaning and image stabilisation features that could be suitable for photogrammetric applications.

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Appendix. Alaphbetical list of web links to companies and brand names listed in the text

Adobe: www.adobe.com
Aicon: www.aicon.de
Alpa: www.alpa.ch
Axios: www.axios3d.de
Canon: www.canon.com
Dörr: www.doerrfoto.de
GOM: www.gom.com
Leaf: www.leafamerica.com
Leica: www.leica-camera.com
Mamiya: www.mamiya.com
Nikon: www.nikon.com
Novoflex: www.novoflex.com
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