

Mobile Photogrammetry

ARMIN GRUEN¹ AND DEVRIM AKCA¹

Abstract:

This paper examines the potential of mobile phones to be used as a front-end sensor for photogrammetric procedures and applications. For this purpose we are currently calibrating various mobile phones over our indoor 3D testfield, using self-calibration. In some systems we have diagnosed substantial systematic errors. We are currently also in the process of checking the stability of the interior orientation over time.

Using the same testfield we are performing accuracy tests in order to evaluate the metric performance. This paper reports about first experiences in calibration and accuracy validation of mobile phone cameras. We believe that with a proper performance these devices can be used for many photogrammetric tasks in the future.

1 Introduction

With the availability of very affordable and good resolution CCD/CMOS cameras and other off-the-shelf devices, including compact computers (of laptop type) the potential of building efficient mobile, low-cost, high-performance systems has substantially improved. Among various hardware and software components mobile phones constitute an interesting component for image data acquisition for obvious reasons: They are very inexpensive, light and handy and have CMOS cameras integrated of currently up to 10 Mpixels image format.

Their usability for many applications has recently been realized. One of the most prominent applications is the character/text recognition in a flexible and portable fashion (Watanabe et al., 2003; Koga et al., 2005; Parikh, 2005). Rohs (2004) realizes a scenario where camera phones are used to recognize the visual codes in the scene. By recognizing a code tag, the device determines the code value, the targeted object or image element. The phone's wireless communication channel is used to retrieve online content related to the selected image area or to trigger actions based on the sensed code.

As a facial animation study for mobile phones, Riegel (2005) creates a specific 2D head model using the generic 3D MPEG-4 face and portrait images. The model is animated via voice or text. Al-Baker et al. (2005) uses a GPRS and WAP enabled PDA or mobile phone for human face identification. The system allows the user to send an image of a human face, acquired through a mobile phone with a built-in camera, to remotely perform automatic face recognition. The user will then instantly receive details of the person, if a match is found. The system can be useful especially for the instant face identification and authentication tasks.

Clemens et al. (2005) develop a panoramic image application suit for handy cameras. The image stitching is carried out in real-time. Pittore et al. (2005) implement an image-based context awareness engine specifically for archeological sites and museums. Visitors can "ask" information about an unknown monument by simply taking a picture of it with a camera integrated mobile phone and send it to the system for recognition. Ueda et al. (2004) use mobile

¹ Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland, www.photogrammetry.ethz.ch

phones, equipped with a camera and a GPS chip, as a content provider to a Geographical Information System (GIS). Users can annotate objects in the environment by sending text, picture and location information via mobile phone to a central data base.

Chung et al. (2004) correct the radial lens distortion of a mobile phone camera applying a calibration procedure from Lenz and Tsai (1988). However, their experiment lacks numerical results and analysis. In spite of the availability of a broad diversity of applications, the metric capabilities and characteristics of mobile phone cameras have not been investigated so far.

In 2004, Sharp Corporation developed a 2 Mpixel CCD camera module with 2X optical zoom and auto-focus function (Figure 1a) intended for use in mobile phones (Physorg, 2004). In 2005, they released two new camera modules (Figure 1b) with a 3 Mpixel CCD chip (Physorg, 2005). One year after, Samsung announced a 10 Mpixel camera phone (Figure 1c) at CeBIT exhibition in Hannover (Williams, 2006). These examples show the rapid progress in the technology of mobile phone cameras.

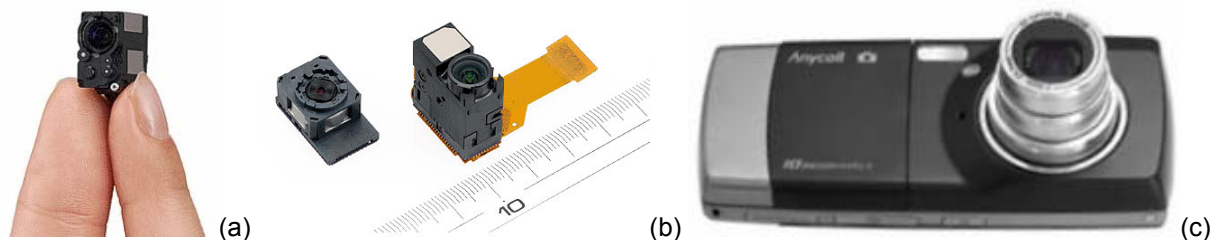


Figure 1. (a) Sharp's 2 Mpixel CCD camera module LZP0P3738, (b) Sharp's 3 Mpixel CCD camera modules LZ0P3751 and LZ0P3758, (c) Samsung's 10 Mpixel camera integrated handy SCH-B600.

Due to very limited size and restricted material and equipment costs, the production of mobile phone cameras is a challenge (Myung-Jin, 2005; Chowdhury et al., 2005). The impact of their production specifications on the stability of interior orientation and 3D object reconstruction capabilities has not adequately been studied in the literature. This work investigates the accuracy potential of two recent mobile phone cameras and compares them with respect to two off-the-shelf digital still video cameras.

The next chapter introduces the cameras and the calibration/validation testfield. The third chapter gives the results of the accuracy test for all four cameras and a test, which analyses the effect of JPEG compression. The fourth chapter discusses the results.

2 Cameras and the testfield

2.1 Cameras

Four cameras are used (Figure 2). Two of them are mobile phone cameras (Sony Ericsson K750i and Nokia N93) and two of them are off-the-shelf digital still video cameras (Sony DSC W100 and Sony DSC F828). The mobile phone cameras have CMOS sensors of smaller size than the CCD chips in the off-the-shelf cameras and partly much smaller lenses. The technical specifications of all four cameras are given in Table 1.



Figure 2. Cameras used in our tests: (a) Sony Ericsson K750i, (b) Nokia N93, (c) Sony DSC W100, (d) Sony DSC F828.

Table 1: Technical specifications of the cameras.

	K750i	N93	W100	F828
Sensor	CMOS 1/3.2" 4.5 x 3.4 mm	CMOS 1/3.2" 4.5 x 3.4 mm	CCD 1/1.8" 7.2 x 5.3 mm	CCD 2/3" 8.8 x 6.6 mm
Pixel size	2.8 micron	2.2 micron	2.2 micron	2.7 micron
Image format	1632 x 1224 2 Mpixel	2048 x 1536 3.2 Mpixel	3264 x 2448 8 Mpixel	3264 x 2448 8 Mpixel
Lens	No information	Carl Zeiss Vario-Tessar	Carl Zeiss Vario-Tessar	Carl Zeiss T Vario-Sonnar
Focal length	4.8 mm	4.5 – 12.4 mm	7.9 – 23.7 mm	7.1 – 51.0 mm
Optical zoom	No	3X	3X	7X
Auto focus	Yes	Yes	Yes	Yes
Aperture	F2.8 (fixed)	F3.3 (fixed)	F2.8 – 5.2	F2.0 – 8.0
Output format	Only JPEG	Only JPEG	Only JPEG	JPEG and TIFF

2.2 Testfield

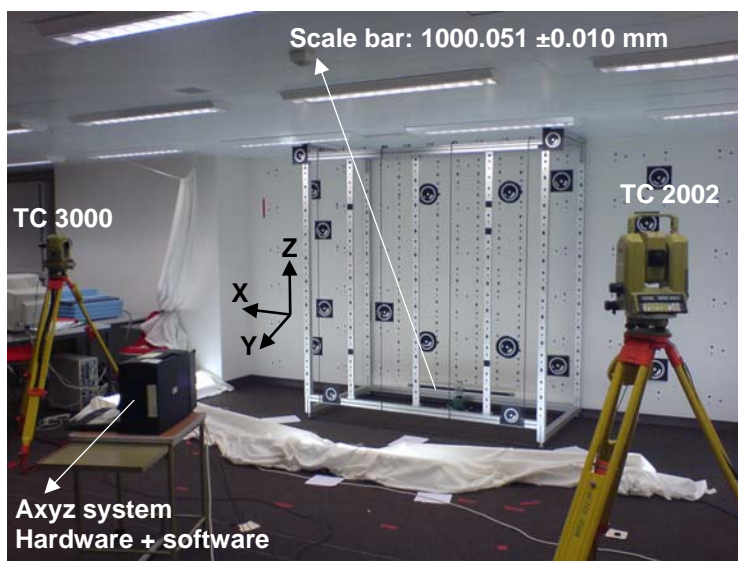


Figure 3. The 3D testfield and the Axyz system.

The photogrammetric calibration field at the Institute of Geodesy and Photogrammetry (HIL C57.3, ETH Zurich) was used. It is 3.4 x 2.0 x 1.0 m³ in size. The 3D coordinates of 87 well distributed control points (GCP) were measured using a Leica Axyz system. The Leica Axyz system consists of two Leica total stations (TC 3000 and TC 2002) and one processing computer unit, which is connected to them. After an initialization step, two operators simultaneously measure the vertical angles and horizontal directions of

the targeted point. The system calculates the 3D coordinates (by spatial intersection) and the precision values in real-time. The scale of the object space was given by measuring a bar whose length was accurately defined by interferometry. The average precision values of the GCPs are ± 0.03 , ± 0.05 and ± 0.03 mm for X, Y and Z axes, respectively.

3 Accuracy tests

For the calibration of the K750i, eighteen images from three locations (each of which has three stations, i.e., down, middle and up) were taken in a convergent geometry mode (Figure 4a). Nine images are taken in normal mode (image no. 1-9) and each three of the rest nine images are -90° (image no. 10-12), $+90^\circ$ (image no. 13-15) and 180° (image no. 16-18) rotated, respectively.

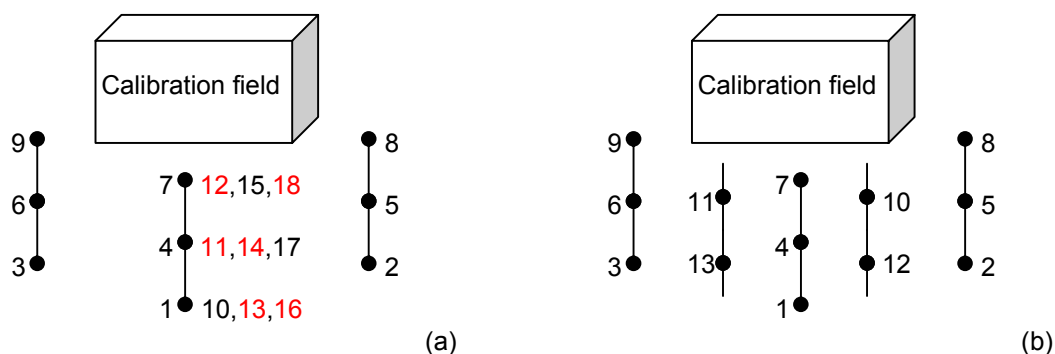


Figure 4. (a) Image acquisition geometry for the calibration of K750i, and (b) for N93, W100 and F828. Black circles stand for the image stations.

For the calibration of the N93, W100 and F828 cameras an image acquisition geometry with thirteen images (Figure 4b) was used. Images no. 1-9 are in normal mode and no. 10-13 are the rotated ones. However, different rotated image versions were used. For the camera N93 the images no. 10 and 11 are -90° and no. 12 and 13 are $+90^\circ$ rotated, for W100 no. 10-13 are all $+90^\circ$ rotated, and for F828 no. 11 and 13 are -90° and no. 10 and 12 are $+90^\circ$ rotated.

The image measurements were performed with the Least Squares template matching (Gruen, 1985) using the in-house developed software BAAP. Another in-house developed software SGAP (Beyer, 1992) was used for the bundle block adjustment with self-calibration.

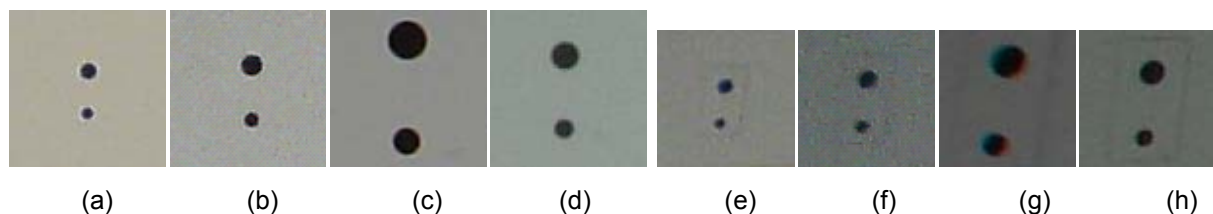


Figure 5. Image quality of the cameras. (a), (b), (c) and (d) are cropped images at station 4 from K750i, N93, W100 and F828, respectively. The signalized point approximately locates at the centre of the image. Image scales are $1/863$, $1/829$, $1/460$ and $1/513$ for (a), (b), (c) and (d), respectively. (e), (f), (g) and (h) are cropped images at station 1 from K750i, N93, W100 and F828, respectively. The signalized point approximately locates at the upper left part of the full image. Image scales are $1/977$, $1/961$, $1/550$ and $1/583$ for (e), (f), (g) and (h), respectively.



Figure 6. 3X zoom-in of the upper left part of Figure 5f. JPEG artifacts are visible.

The imaging quality differs among the cameras. In Figure 5a, 5b and 5c, low-level image enhancement effects are strongly visible at the edges of the points. The F828 has the best overall image quality considering all images from all stations. On N93 images (Figure 5b and 5f) strong JPEG artifacts are visible (Figure 6).

The K750i, N93 and W100 have only the JPEG output option. Their image measurements were carried out on their original JPEG images. For the F828, TIFF output images were used for the image measurements.

3.1 Accuracy test of K750i

The 18 images version gives a sigma0 value of about half a pixel (version 10 in Table 2) and highly systematic residual patterns at some images (Figure 7, 1. row), even after self-calibrating bundle adjustment with block-invariant additional parameters.

The six most deteriorated images among the rotated ones were then excluded (images no. 11, 12, 13, 14, 16 and 18). These reduced twelve images versions (versions 11, 12, 13, 14 and 15 in Table 2) give better sigma0 and precision values. However, a systematic pattern of the image coordinate residuals still remains, varying from image to image. Note that version 15 stands for the free network adjustment.

Table 2: Absolute accuracy test of K750i.

Ver	GCP	CHK	TIE	APs	Rej	Sigma0 (μm) (pixel)	STD-X of CHK+TIE points (mm) of only GCP points (mm)	STD-Y	STD-Z	RMSE-X at CHK points (mm) at GCP points (mm)	RMSE-Y	RMSE-Z
10	87	0	90	10	0	1.20 0.43	0.291 0.109	0.558 0.182	0.251 0.107	N.A. 0.086	N.A. 0.125	N.A. 0.053
11	87	0	80	10	26 ⁽¹⁾	0.65 0.23	0.187 0.026	0.307 0.039	0.161 0.026	N.A. 0.006	N.A. 0.008	N.A. 0.005
12	87	0	80	44	26 ⁽¹⁾	0.64 0.23	0.185 0.025	0.304 0.038	0.159 0.025	N.A. 0.006	N.A. 0.008	N.A. 0.005
13	44	43	80	10	25 ⁽¹⁾	0.64 0.23	0.188 0.025	0.312 0.038	0.163 0.025	0.280 0.007	0.498 0.010	0.201 0.006
14	10	77	80	10	27 ⁽¹⁾	0.61 0.22	0.196 0.024	0.318 0.036	0.173 0.024	0.499 0.008	1.048 0.012	0.501 0.005
15	167 free	--	--	10	30 ⁽¹⁾	0.59 0.21	0.174 N.A.	0.283 N.A.	0.151 N.A.	N.A. N.A.	N.A. N.A.	N.A. N.A.

Ver : Version number
 GCP/CHK/TIE : Number of control points / independent check points / tie points, respectively
 APs : Number of additional parameters
 Rej : Rejected rays by data-snooping, rejection rule for ⁽¹⁾ : reject all residuals $\geq 4 \times \text{Sigma0}$
 Sigma0 : Standard deviation of image observations a posteriori
 STD : Average theoretical precision values of CHK/TIE/GCP coordinates
 RMSE : Empirical accuracies of CHK/GCP coordinates.

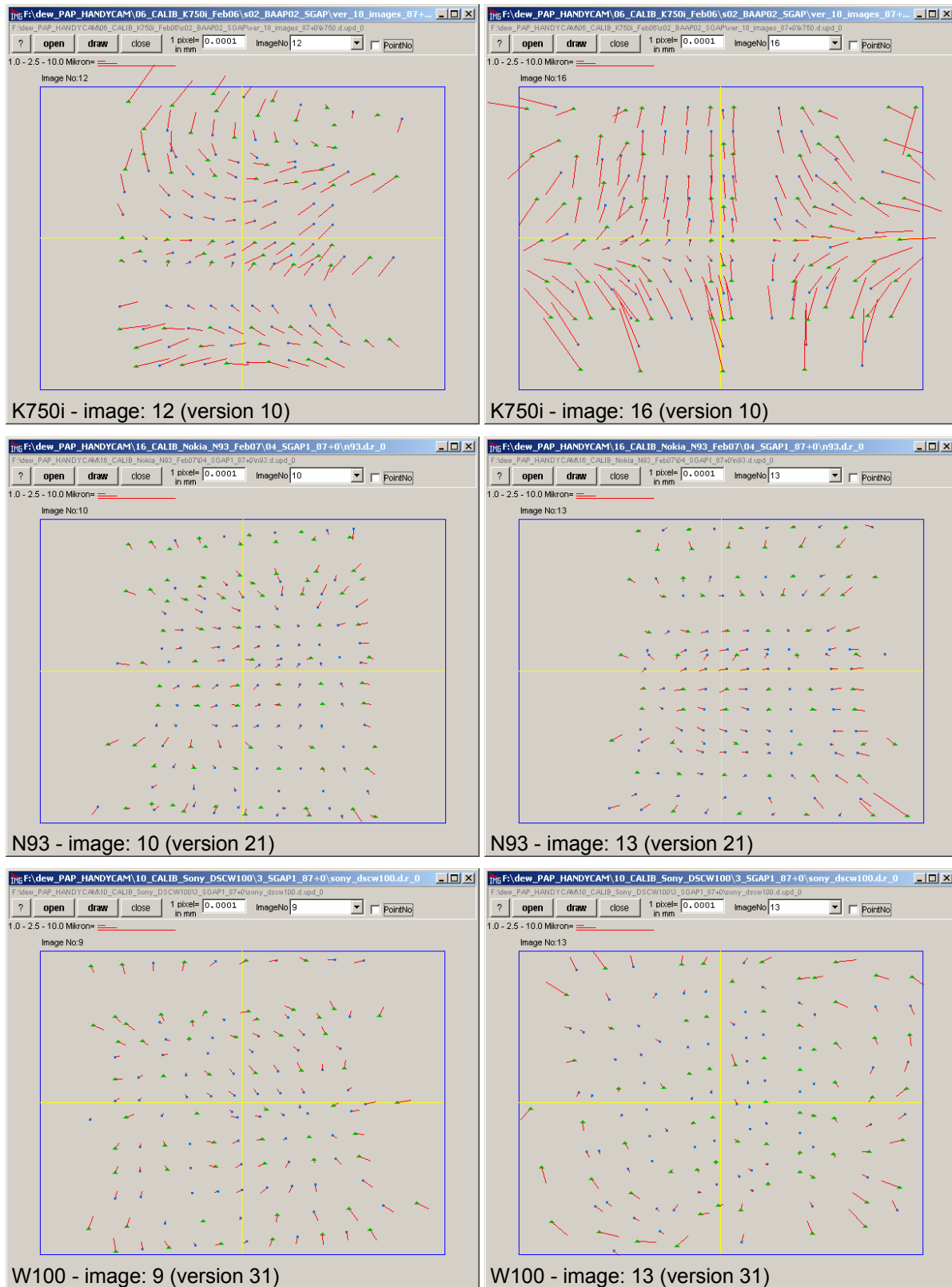


Figure 7. Systematic residual patterns after self-calibrating bundle adjustment.

After Brown's 10 additional parameter set, Gruen's (1978) 44 additional parameter set was applied. The block-invariant 44 additional parameters did not compensate the systematic errors as well (version 12).

3.2 Accuracy test of N93

The accuracy test of N93, also based on block-invariant APs, apparently gives better results. The sigma0 is a quarter of a pixel. A systematic error pattern still remains in the residuals (Figure 7, 2. row), however, the magnitude is much less than in K750i's case. It has clearly achieved sub-millimeter accuracy in object space (versions 22 and 23 in Table 3) in all coordinate directions.

Table 3: Absolute accuracy test of N93.

Ver	GCP	CHK	TIE	APs	Rej	Sigma0 (μm) (pixel)	STD-X of CHK+TIE points (mm) of only GCP points (mm)	STD-Y	STD-Z	RMSE-X at CHK points (mm) at GCP points (mm)	RMSE-Y	RMSE-Z
21	87	0	99	10	0	0.55 0.25	0.165 0.051	0.312 0.084	0.139 0.050	N.A. 0.044	N.A. 0.074	N.A. 0.028
22	44	43	99	10	0	0.52 0.24	0.157 0.049	0.286 0.080	0.133 0.048	0.449 0.045	0.617 0.084	0.225 0.029
23	10	77	99	10	0	0.50 0.23	0.161 0.047	0.284 0.077	0.140 0.046	0.701 0.036	0.816 0.101	0.203 0.030
24	186 free	--	--	10	0	0.47 0.21	0.144 N.A.	0.250 N.A.	0.120 N.A.	N.A. N.A.	N.A. N.A.	N.A. N.A.

3.3 Accuracy test of W100

The W100 gives slightly better theoretical precision and empirical accuracy values than the N93 (Table 4). The standard deviation of image observations is in the same range with the N93, i.e. one quarter of a pixel. The W100 reveals similar residual errors like the N93 regarding the magnitude (Figure 7, 3. row).

Table 4: Absolute accuracy test of W100.

Ver	GCP	CHK	TIE	APs	Rej	Sigma0 (μm) (pixel)	STD-X of CHK+TIE points (mm) of only GCP points (mm)	STD-Y	STD-Z	RMSE-X at CHK points (mm) at GCP points (mm)	RMSE-Y	RMSE-Z
31	87	0	92	10	0	0.59 0.27	0.114 0.030	0.203 0.050	0.094 0.030	N.A. 0.036	N.A. 0.052	N.A. 0.029
32	44	43	92	10	0	0.55 0.25	0.104 0.028	0.181 0.046	0.084 0.028	0.298 0.043	0.369 0.061	0.221 0.034
33	10	77	92	10	0	0.47 0.21	0.100 0.022	0.168 0.035	0.085 0.021	0.501 0.049	0.421 0.078	0.443 0.050
34	179 free	--	--	10	0	0.44 0.20	0.083 N.A.	0.140 N.A.	0.067 N.A.	N.A. N.A.	N.A. N.A.	N.A. N.A.

3.4 Accuracy test of F828

The F828 gives the best performance and remarkably superior numbers compared to the other cameras (Table 5). Sigma0 goes down to 1/10 of a pixel. Also, the empirical RMSEs are here in much better agreement with the theoretical standard deviations.

Table 5: Absolute accuracy test of F828.

Ver	GCP	CHK	TIE	APs	Rej	Sigma0 (μm) (pixel)	STD-X of CHK+TIE points (mm) of only GCP points (mm)	STD-Y	STD-Z	RMSE-X at CHK points (mm) at GCP points (mm)	RMSE-Y	RMSE-Z
41	87	0	81	10	0	0.27 0.10	0.048 0.022	0.084 0.037	0.041 0.022	N.A. 0.026	N.A. 0.032	N.A. 0.023
42	44	43	81	10	0	0.27 0.10	0.047 0.022	0.082 0.036	0.040 0.022	0.076 0.034	0.125 0.033	0.058 0.028
43	10	77	81	10	0	0.26 0.10	0.049 0.022	0.084 0.036	0.043 0.022	0.097 0.055	0.144 0.033	0.134 0.022
44	168 free	--	--	10	0	0.25 0.09	0.043 N.A.	0.074 N.A.	0.037 N.A.	N.A. N.A.	N.A. N.A.	N.A. N.A.

3.5 JPEG test with F828

The use of JPEG images for the image measurements of K750i, N93 and W100 raised the question whether the JPEG compression has an effect on the results. The original TIFF images of the F828 were converted to quality level 100 (maximum quality) and 70 JPEG images, using the free software IrfanView (version 3.98, <http://www.irfanview.com/>). Table 6 gives the results. The loss of empirical accuracy due to ~ 42 times JPEG compression is only 12 microns in depth (version 51 and 53 in Table 6). The other coordinates are of the same accuracy. Our results are controversial to those results given in Lam et al. (2001), Li et al. (2002) and Shih and Liu (2005). However, their tests are on aerial images, while we have a close-range test object under good illumination conditions.

Table 6: JPEG compression test with F828 (GCP/CHK/TIE are 44/43/81 respectively).

Ver	Compression	APs	Rej	Sigma0 (μm) (pixel)	STD-X of CHK+TIE points (mm) of only GCP points (mm)	STD-Y	STD-Z	RMSE-X at CHK points (mm) at GCP points (mm)	RMSE-Y	RMSE-Z
51	Original TIFF / 23,410 KB	10	0	0.26 0.10	0.047 0.022	0.082 0.036	0.040 0.022	0.077 0.034	0.120 0.033	0.059 0.028
52	5.5 Q100 / 4,265 KB	10	0	0.26 0.10	0.047 0.022	0.082 0.036	0.040 0.022	0.078 0.034	0.124 0.033	0.059 0.027
53	41.6 Q70 / 562 KB	10	0	0.26 0.10	0.047 0.022	0.082 0.036	0.040 0.022	0.077 0.033	0.132 0.033	0.060 0.028

4 Analysis of results

In spite of giving the worst results in the test, the K750i still can offer sub-millimeters accuracy in the object space. Both block-invariant 10 and 44 additional parameter sets cannot compensate the systematic errors fully.

The first three cameras of the test K750i, N93 and W100 give identical standard deviation values for the image observations (between 1/4 - 1/5 pixel). They all apply a chip level image enhancement for sharpening the images. This effect is visible in Figures 5a, 5b and 5c. This low level image enhancement, while improving the visual quality, is probably reducing the geometric quality of the cameras. They show noticeably block-variant systematic errors after the self-calibrating bundle adjustment with block-invariant additional parameters.

The N93 and W100 have same lens systems (Zeiss, Vario-Tessar). The W100 has a CCD sensor of larger size with 8 Mpixels. It is 2.5 times larger than the CMOS sensor of N93. According to theoretical expectations, the N93 should give an accuracy of factor 1.6 ($\sqrt{2.5}$) worse compared to the W100. The N93 almost strictly meets this expectation by giving 1.7-1.9 times worse numbers than the W100. On the other hand, there is a large difference between those two cameras, considering the size of the imaging system and the cost of the materials used in the construction. In this respect, the accuracy performance of the N93, as compared to the W100, is noteworthy.

Although the W100 and F828 have the same image format with 8 Mpixels, the expectation of equal accuracy does not hold here. The W100 gives substantially worse accuracy numbers (almost 3 times) than the F828. This is mainly due to a better lens system of the F828 and (possibly) the degrading chip level image enhancement operation of the W100.

5 Conclusions

We have metrically calibrated and we have tested the metric accuracy of four consumer-grade imaging devices: Two mobile phone cameras (Sony Ericsson K750i and Nokia N93) and two still video cameras (Sony DSC W100 and Sony DSC F828). The tests were performed by using our in-house 3D testfield. We have found unwanted effects from image enhancement (sharpening) in the K750i, N93 and W100 cameras and JPEG compression artifacts in the N93. In all four cases we have used (more or less) the same imaging geometry, and imaging conditions in order to make the results comparable.

With the given strong geometrical set-up of course all parameters for the interior orientation could be calibrated reliably.

The accuracy tests showed that in all cases the theoretical expectations, as defined by the average standard deviations of the object space coordinates, could not be achieved by the empirical RMSEs, computed from checkpoints. The deviations range from factor 3.3 (K750i) to factor 1.7 (F828). While the σ_0 values of the K750i, N93 and W100 are all at a 1/5 pixel level, they drop down to 1/10 pixel with the F828. This improvement in σ_0 is matched by the better behaviour of the post-adjustment image residuals. Only in case of the F828 do we get an almost random distribution. The other cameras, in particular the K750i, suffer from strong image-variant systematic errors. Since we have used in our self-calibration only block-invariant additional parameters these errors could not be compensated. The error patterns are also not in agreement with what we are used to in photogrammetry. Therefore, our standard additional parameter functions cannot compensate these defects. So far we cannot explain the reasons for these errors. Could they lie in the image enhancement procedure or any other shortcomings in the electronic circuits?

Nevertheless, and despite these problems, we could reach relative accuracies of 1:8 000 in-plane and 0.03% of average depth with the K750i and 1:34 000 in-plane and 0.005% of average depth with the F828, using in both cases 10 control points. This superior behaviour of the F828 can only partly be explained by the larger image format (8 Mpixels versus 2 Mpixels), which theoretically should only lead to an improvement of factor 2.

If we apply to both cameras a free network adjustment by minimizing the trace of the covariance matrix for the object space coordinates we get the following values: 1:25 000 and 0.009% for the K750i and 1:99 000 and 0.0025% for the F828. This shows roughly the same relationship between both cameras, it gives however a better indication of the potential system accuracy. It is worthwhile to note that, compared to the film-based large format aerial photogrammetric block adjustment accuracy, we can achieve here the same and better accuracies in height and almost the same in planimetry, if we consider for the aerial case an object area of one image coverage only (like in our close-range case). This definitely indicates the great potential of consumer-grade and even mobile phone cameras for photogrammetric processing. The main remaining problem is to find a convincing explanation for the image-to-image varying systematic error pattern in some of the mobile phone cameras.

In a final test we also checked the effect of JPEG compression on the metric system accuracy for the F828 camera. Even when going up to a factor of 42 compression rate we did get only a small reduction in accuracy (9% in depth direction). This can be considered harmless.

Our future plans are to spread these tests over a longer time period in order to check the temporal stability of the calibration and also invest some more work into image quality studies.

In conclusion we can state that mobile cameras do give us a very interesting option for doing “mobile photogrammetry”, in terms of accuracy, costs and flexibility.

The integration of GPS receivers and motion sensors will further broaden their applicability.

6 Acknowledgements

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