GEOMETRIC STABILITY OF LOW-COST DIGITAL CONSUMER CAMERAS

Thomas Läbe and Wolfgang Förstner

Institute for Photogrammetry, University of Bonn, Nussallee 15, 53115 Bonn, Germany
laebe@ipb.uni-bonn.de, wf@ipb.uni-bonn.de

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ABSTRACT:

During the last years the number of available low-cost digital consumer cameras has significantly increased while their prices decrease. Therefore for many applications with no high-end accuracy requirements it is an important consideration whether to use low-cost cameras. This paper investigates in the use of consumer cameras for photogrammetric measurements and vision systems.
An important aspect of the suitability of these cameras is their geometric stability. Two aspects should be considered: The change of calibration parameters when using the camera's features such as zoom or auto focus and the time invariance of the calibration parameters. Therefore laboratory calibrations of different cameras have been carried out at different times. The resulting calibration parameters, especially the principal distance and the principal point, and their accuracies are given. The usefulness of the information given in the image header, especially the focal length, is compared to the results of the calibration.

1 INTRODUCTION

During the last years the number of available low-cost digital consumer cameras has significantly increased while their prices decrease: digital cameras with 2000×3000 pixels cost below 1000 Euro, while the additional price for cameras in mobile phones having up to 640×480 Pixels is significantly below 100 Euro, similar to web cameras. Parallel to these hardware developments tools for geometric processing digital images become part of the software delivered with the cameras: prominent examples are tools for warping images, e. g. for morphing or for generating plane or cylindrical panoramas.

Photogrammetry has to face the fact: all basic image processing techniques are already in the hands of students when they start learning. Though the awareness of lens distortion, especially of short focal length cameras is present, geometric precision seems to be of no concern.

Aiming at ultimate precision is a classical goal in geodetic and photogrammetric applications for two reasons: efficiency, by exploiting the potential of the measuring device 'image', and the statistical properties of optimal solutions are well understood, easing the evaluation with respect to all kinds of errors in the assumed models. Close range photogrammetry partly follows this paradigm.

However, accuracy requirements vary tremendously: from relative accuracies 1 : 200, e.g. when measuring sizes of windows at facades to 1 : 100 000 e.g. when determining forms of airplane wings. In order to exploit the full potential of photogrammetric techniques, especially in those application areas with no high-end accuracy requirements it is important whether use low-cost cameras is feasible.

There is a large body of literature on the calibration of cameras in general, cf. the review in (Fraser, 1992). A historical review on the development of consumer cameras is given in (Clarke and Fryer, 1998). However, only few investigations of low-cost cameras exist, e.g. (Kunii and Chikatsu, 2001), however not treating the stability. The interior orientation of zoom cameras has been investigated, e.g. in (Burner, 1995) and (Wiley and Wong, 1995), e.g. demonstrating the principal point not varying linearly with zoom. On of the few investigations into the stability of cameras over time is (Peipe and Stephani, 2003), however, for a camera which is partly designed for the use in photogrammetry, and therefore turned out to be quite stable, cf. also (Shortis and Beyer, 1997).

In the computer vision area many of the classical models for calibration, e.g. (Brown, 1966), (Brown, 1971) have been adapted, cf. (Hartley and Zisserman, 2000). However, the dramatic changes of interior orientation when exploiting zoom cameras lead to a different view on the role of calibration. First, there are two sets of parameters of interior orientation (1) those five, which still guarantee a straight line preserving mapping and (2) all others, which lead to non-linear distortions. Second, starting from images with a straight line preserving camera model, the 3D-reconstruction is performed in a projective coordinate system, including the self-calibration of the five parameters of the interior orientation of all images, and in a second step, called *stratification*, an absolute orientation using control points is performed to obtain an Euclidean 3D-reconstruction. The loss in precision, especially due to the assumption of a totally varying interior orientation, usually is accepted. However, methods - similar to the plumb-line method of D. C. Brown (Brown, 1971) have been developed to correct only for the non-linear distortions (Devernay and Faugeras, 2001). No information on the time-stability of these non-linear distortions appears to be available.

This paper investigates in the use of consumer cameras for photogrammetric measurements and vision systems. An important aspect of the suitability of these cameras is their geometric stability. Two aspects should be considered: The change of calibration parameters when using the camera's features such as zoom or auto focus and the time invariance of the calibration parameters. Therefore laboratory calibrations of different cameras have been carried out at different times. The resulting calibration parameters, especially the principal distance and the principal point, and their accuracies are given. The usefulness of the information given in the image header, especially the focal length, is compared to the results.

The paper is organized as follows: After characterizing the cam-

Camera	Chip size (pixel)	lens	price (Euro)
Logitech Quick Cam Zoom	640x480	manual focus, fixed zoom	64
Terratec 2move 1.3	1280x1024	fixed focus, fixed zoom	79
HP Photosmart 435	2069x1560	fixed focus, fixed zoom	139
Sony DSC V1	2592x1944	autom. + manual focus, optical zoom 4x	550
Kodak DSC 460	3060x2036	autom. + manual focus, 24mm lens	1000-5000

Table 1: Data of the different cameras used in this study. Note that the Kodak DCS 460 is not available any more. The costs of comparable cameras may be in the given range (1000-5000 Euro).

eras selected for our investigation and the achievable measuring accuracy we discuss temporal variations of image distortions modeled by various additional parameters for the interior orientation, the effect of changing resolution of the images, the effect of zooming, the effect of change in focus and the effect of changing the aperture. The paper closes with a short comparison with the results achieved with the calibration tool contained in MATLAB and recommendations.

2 SETUP OF INVESTIGATION

2.1 Description of the Cameras

We selected five cameras for our investigation which cover the spectrum of consumer cameras. As most cameras allow to select the resolution or the compression rate we distinguished altogether 10 different 'cameras'.

Two web cams represent the low end. The web cam LOGITECH QUICK CAM ZOOM is a fixed zoom camera which only allows to change focus. Only VGA modus with 640×480 pixels is investigated, with the implemented low compression rate. The TERRATEC 2MOVE 1.3 has fixed settings, but a larger sensor, compensated by a strong compression ratio. We investigated the camera in two versions: VGA resolution with 640×480 pixels, with a compression ratio of 11.3 and the full resolution with 1 Mega-pixel with an even higher compression ratio of 15.9.

Two digital cameras represent the moderate price range. The HP PHOTOSMART 435 also has fixed setting, however a much larger sensor than the Terratec web cam. We investigated the VGA mode and the high resolution mode with 3 Mega-pixels with the *'better'* and *'optimal'* compression. The SONY DSC V1 has been selected due to its features, namely automatic and manual focus and optical zoom. Also here we investigate the VGA mode and two resolutions, namely with 1 Mega-pixels and with 5 Mega-pixels.

For comparison, the well known Kodak DCS 460, a 6 Megapixel-camera, has been investigated. Here no compression takes place. The used lens has a focal length of 24 mm.

The naming of the 10 different 'cameras' and their basic features are given in table 2.

All cameras have the possibility to work with a fixed focus setting.

2.2 Description of the Calibration Process

We used our tool TCC for calibrating digital cameras, cf. (Abraham and Hau, 1997),(Abraham and Förstner, 1997), (Abraham, 2000), consisting of a 3D-test field (cf. figure 1) and software for self-calibration.

The automatic detection and location of the points of the 3D-test field lead to image coordinates, which in a self-calibrating bundle adjustment with blunder detection and elimination lead to estimated values of the exterior and interior orientation and coordinates of the 3D points, which a priori are only known approximately. Details are given in (Abraham and Hau, 1997).

Code	Camera	format/size	compr. ratio
1	Logitech	VGA	2.9
2V	Terratec	VGA	11.3
2M		1 Mbyte	15.9
3V	HP	VGA	5.2
3MB		3 Mbyte	'better': 6.7
3MO		3 Mbyte	'optimal': 5.1
4V	Sony	VGA	2.2
4_1M		1 Mbyte	2.5
4M		5 Mbyte	2.8
5	Kodak	6 Mbyte	-

Table 2: Code of investigated cameras. The compression ratios are determined from the file sizes.

The calibration of all cameras was performed as a test field calibration. In all cases 24 images were taken in different orientations in order to capture all types of distortions. All camera parameters, such as zoom, focus, aperture, white balance, etc. were kept constant during data capture as far as possible.

All calibrations were performed indoor. The calibrations were performed 3 to 7 times within a time period of four months, always with the same calibration setup.

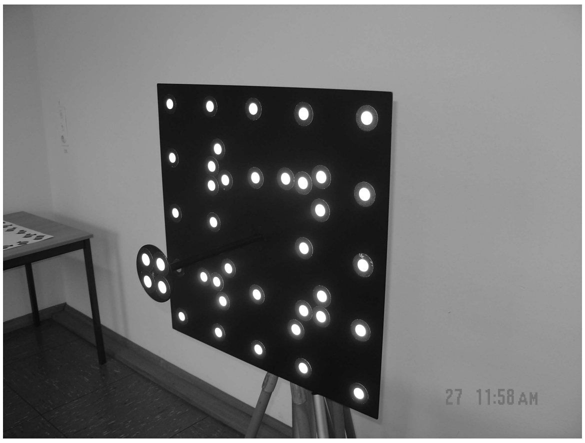

Figure 1: The used test field for calibration. The coordinates of the marks are known only approximately.

In all cases we have the principal distance, the coordinates of the principal point and the scale difference in x' and y'-image coordinates as parameters. Five different sets of additional calibration parameters for compensating for non-linear distortions are used:

O no additional distortion parameters, only principal distance and principal point additional physically motivated parameters:

A One radial-symmetric distortion parameter A_1

B A_1 and two tangential distortion parameters B_1, B_2 (cf. (Brown, 1966))

C Three radial-symmetric distortion parameters A_1, A_2, A_3, two tangential distortion parameters B_1, B_2 and one affine shear parameter C_1

T additional modeling of distortion with Chebychev polynomials with maximum degree of 3, cf. (Abraham and Hau, 1997).

3 RESULT OF INVESTIGATIONS

3.1 Accuracy of Measurements

We first compare the precision obtainable with the different cameras. This can be evaluated with the mean precision of the image coordinates of the points. The automatic point location procedure yields an individual internal estimate for the covariance matrices for the image coordinates, and the chosen camera model influences the residuals, thus the estimated $\widehat{\sigma}_0$ and therefore the estimated standard deviation of the image coordinates. Therefore we give the mean value of the internal estimates for the individual standard deviations of the image coordinates corrected by the best achievable variance factor, implicitly assuming the smallest variance factor most realisticly reflects the achievable measuring accuracy. In nearly all calibrations the Chebychev polynomials model delivers the best $\hat{\sigma_0}$ in the bundle adjustment.

The results are shown in figure 2. The mean standard deviations $\overline{\sigma}_{x'}$ in nearly all cases are around 0.1 pixels. The bad results with the Terratec web cam certainly result from the large compression rates, whereas the standard deviation of 0.25 pixels with the large images with the Sony camera can be explained by non-modeled distortions.

The relative accuracy (not shown in the figure) which can be achieved can be characterized by the mean standard deviation related to the width w [pixel] of the image, being the length of the larger side. Except for the web cams, a relative precision of better than 1 : 10 000 can be reached, indicating a high accuracy potential achievable with consumer cameras.

No dependency between accuracy of mark detection and compression ratio could be observed regarding HP, Sony and Logitech cameras (compression ratio from 1.0 to 6.7). The huge compression ratios of 11. 3 and 15.9 of the Terratec camera seem to have a strong influence on the accuracy of mark detection and as a result of that on the calibration.

The maximal estimated distortion within an elliptic image region with semi-major axis $a = 97.5\%$ of image width and semi-major axis $b = 97.5\%$ of image height is: Logitech: 1.8 Pixel (VGA resolution), Terratec: 2.3 Pixel (1MB resolution), HP: 0.4 Pixel (3MB resolution), Sony: 23.7 Pixel (5M resolution, Zoom 1x), Kodak: 15.1 Pixel (6MB resolution).

3.2 Temporal Variations of Calibration Parameters

The calibration of cameras was repeated between 3 and 7 times within a period of 4 months. We did not observe any systematic temporal increase or decrease of calibration parameters.

Only random variations could be observed. In the following we show and discuss the range of change of different parameters in the mentioned time period.

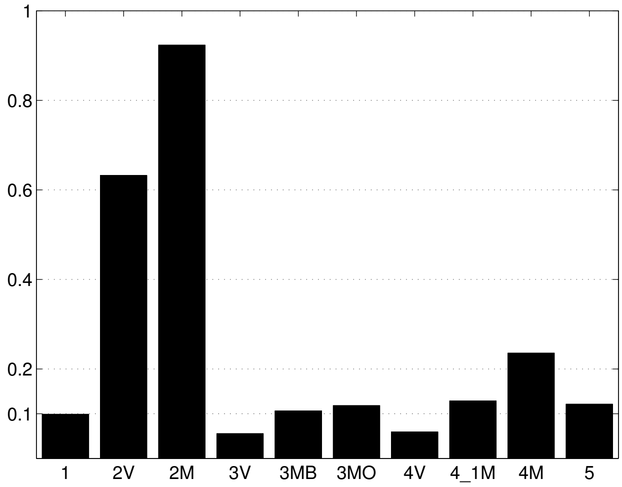

Figure 2: Mean precision of image coordinates of marks of test field: $\overline{\sigma}_{x'}$ in pixels.

3.2.1 Temporal changes in principal distance.

The changes in principal distance c are shown in figure 3. They again refer to the image width: $(c_{\max} - c_{\min})/w$. This ratio in principle depends on the used calibration model. Therefore we give the values for all five calibration models.

We find the following:

1. For the Sony camera (4) we investigated four zoom factors. The largest variation can be found for a zoom factor between 2x and 4x: Here the control of the lens is not be performed accurately. Choosing zoom factor 1x leads to a stable principal distance, because it's the limit of the zoom. The zoom factor 4x also is more stable.

2. The highest stable in principal distance shows the Kodak DCS 460 (5), as to be expected. No differences could be found between the situation when leaving the lens mounted or unmounted lens between two calibrations. The variations are less than 3 pixels, thus appear to be much smaller than those reported in (Maas and Niederöst, 1997).

3. The HP (3) camera also shows a good stability in principal distance because of its fixed lens.

4. The Terratec web cam (2) shows significantly higher variations in principal distance than Logitech's web cam (1). Reason: May be the large compression ratio of 15.9, compared to the low ratio 2.9 of the Logitech web cam.

Observe, the variations in principal distance do not vary for different calibration models, except for the case where no compensation for non-linear distortion is provided.

3.2.2 Temporal changes in principal point.

The temporal changes of the principal point are shown in figure 4. Again we relate the changes to the image width, and give:

$$\max_{ij} \sqrt{(x_{H_i} - x_{H_j})^2 + (y_{H_i} - y_{H_j})^2}/w$$

We find the following:

1. The temporal changes in principal point show a dependency on the used camera model, this dependency is similar for all cameras.

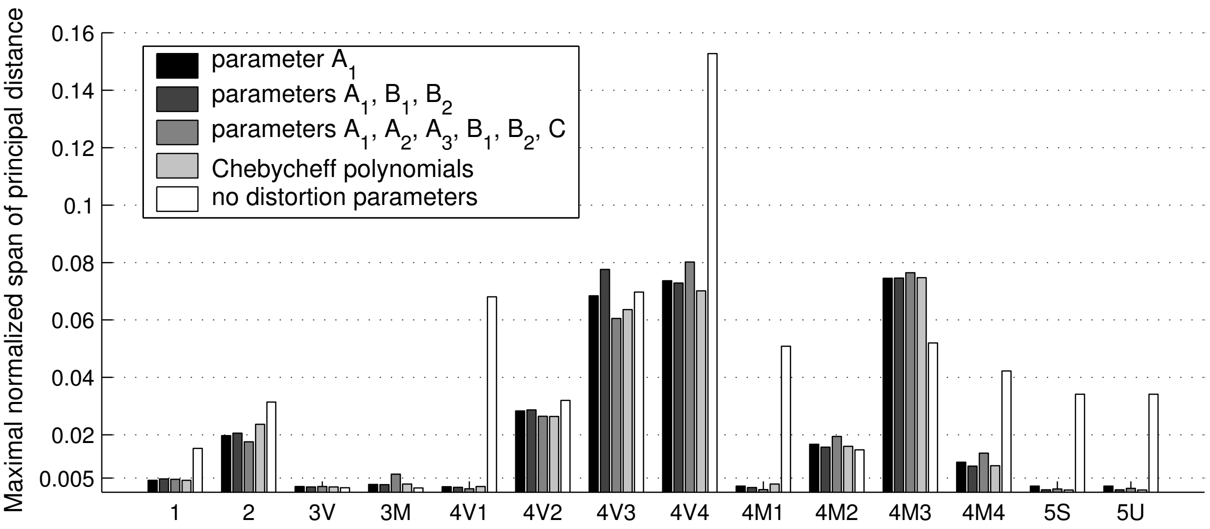

Figure 3: Maximum normalized range of changes in principal distance c. The spans are normalized with the image width. From left to right: Logitech camera(1), Terratec camera (2), HP camera with VGA and 3MB resolution (3), Sony camera with VGA and 5MB resolution with 4 different zoom values (4), Kodak DCS 460 without demounting of lens (5S), with demounting of lens (5U).

2. Again, the Kodak camera (5) is the best. But it shows a significantly less constant principal point when unmounting the lens between calibrations.

3. The HP camera (3) has the same stability as the Kodak camera.

4. When changing the zoom of the Sony camera (4), the principal point is more stable when using the full resolution.

5. Calibration without distortion parameters results in large differences of principal distance and principal point because of improper modeling. However, this effect does not occur when using the HP camera (3), because this camera has very low distortion.

3.2.3 Temporal changes in distortion.

Changes in distortion are given in figure 5, again referring to the image width.

We find the following:

1. The largest changes in distortion are observed for the Terratec web cam (2). Due to high compression ratio non of the calibration parameters could be estimated as accurate as for the other cameras.

2. Largest instabilities occur when using all distortion parameters. This modeling results in no clear minimum in the bundle adjustment, and can be explained by the inclusion of the radial distortion parameter A_3, which cannot be determined stable, cf. (Burner, 1995).

3. The stability of distortion estimation with the Kodak camera is *not* significantly better than HP, probably, because the Kodak camera has significantly larger distortion values.

4. Big differences in distortion *changes* regarding different zooms settings of the Sony camera could not be observed.

3.3 Changing Resolution

Nearly all cameras offer the possibility to change resolution. Therefore it might be possible to transfer the calibration of one resolution to another, as two different resolution only differ by resampling. So principal distance, principal point and distortion just needed to be scaled up or down. This is straight forward if aspect of width and height remains the same which is often the case.

We found this possibility depends on the camera. It works fine for the Sony camera, there the differences between one set of calibration parameters and the scaled parameters of another resolution are in the order of the temporal changes.

Recalculating calibration parameters does not work for the HP camera: We found differences between calibrated and rescaled coordinates of the principal point, probably as not the same pixels on the chip in the different resolutions is chosen. Therefore each resolution requires its own calibration of the principal point.

3.4 Effect of Zoom

We investigate the relation between nominal focal length and calibrated principal distance and the change of distortion as a function of zoom factor. We studied this with the Sony camera.

Today every camera stores the nominal focal length in the header of each image, using the so-called EXIF-format. We studied the relation between this nominal value and the calibrated principal distance, in order to find in how far the nominal value can replace the principal distance. Figure 6 shows a strong linearity between c and nominal focal length f. However, the RMS-error of 12.7 pixel is significantly larger than the accuracy of the calibrated principal distance which for 1 Mega-pixel resolution has a mean value of σ_c=0.7 pixel. So for precise measurements the camera needs to be calibrated at the used zoom factor.

Distortion varies extremely with zoom factor, cf. figure 7. At zoom factor 1x where the principal distance is stable (see figure 3) the distortion is maximal. The distortion parameter A_1 decreases nearly monotonically with a increasing zoom factor.

The distance of the principal point from the image center increases heavily with the zoom factor, even worse: there is no linear behavior, which at least in this case would not allow linear interpolation.

3.5 Influence of Focus

Changing focus changes the principal distance, though to a much smaller amount than zooming. We studied the effect of changing

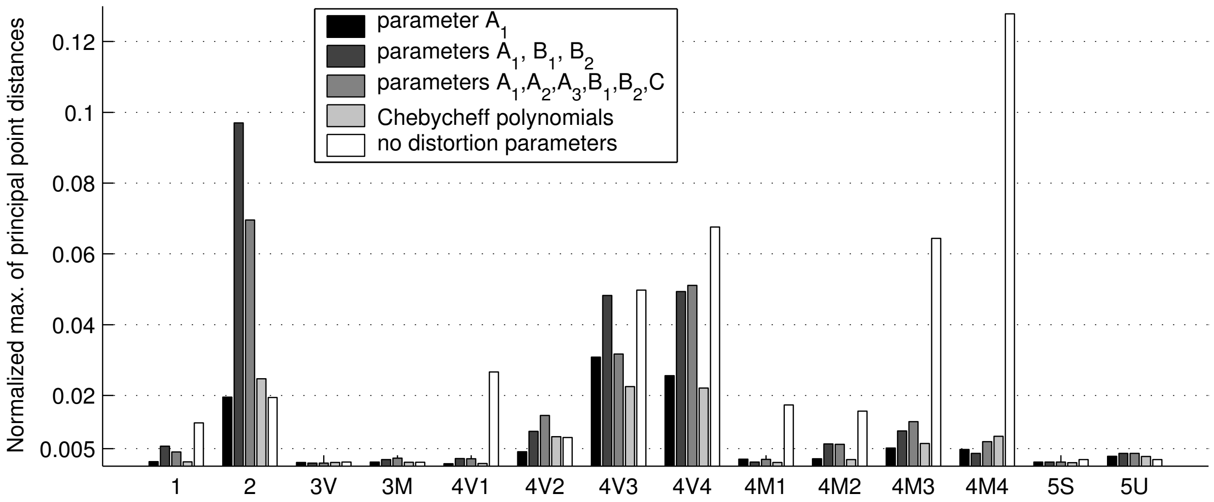

Figure 4: Maximum normalized distance in principal point. The distances are normalized with the image width. From left to right: Logitech camera (1), Terratec camera (2), HP camera with VGA and 3MB resolution (3), Sony camera with VGA and 5MB resolution with 4 different zoom values (4), Kodak DCS 460 without demounting of lens (5S), with demounting of lens (5U).

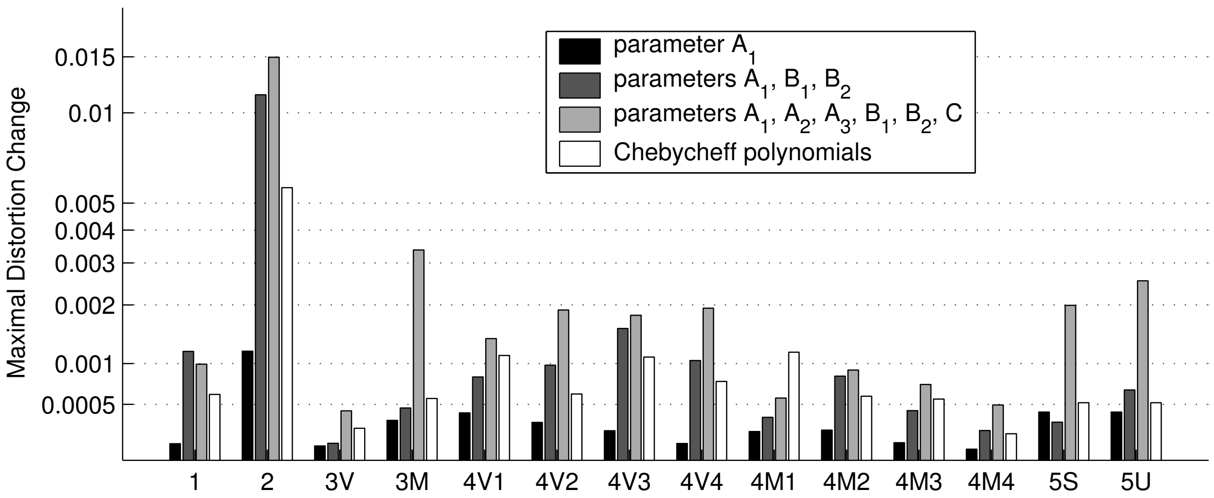

Figure 5: Distortion changes in pixels of a normalized image with width=1. From left to right: Logitech camera (1), Terratec camera (2), HP camera with VGA and 3MB resolution (3), Sony camera with VGA and 5MB resolution with 4 different zoom values (4), Kodak DCS 460 without demounting of lens (5S), with demounting of lens (5U). Note that the abscissa has logarithmic scale.

focus again with the Sony camera, as manually setting focus to a certain distance is possible with this camera. However, for this camera the focus setting is *not* stored in image headers.

The influence of focus is only visible for small distances, as to be expected. We found visible changes for distances shorter than 0.5 m, see figure 8.

For computing radial symmetric distortion parameters out of two sets of calibration parameters at two focus distances one can use the relation given by Brown (Brown, 1971). This relation has been empirically verified with the Sony camera, see figure 9. Here an optimal fit of Brown's function for the modeling of the distortion parameters is plotted. For this purpose two "reference" distortion parameters A_{s1} and A_{s2} were estimated at distances $s_1 = 0.1$m and $s_2 = 10$m.

3.6 Influence of Aperture Settings

The influence of the aperture was only investigated with Sony camera, because this is the only camera, besides the Kodak camera, with the possibility for changing aperture values. No influence of the aperture on the calibration parameters could be observed. The investigation was done with optical zoom 1x.

3.7 Comparison to results obtained with the Matlab Calibration Toolbox

We compared results obtained with the camera calibration toolbox for Matlab of J.-Y. Bouguet, cf. (Bouguet, n.d.) with ours. This toolbox provides the same camera model as ours with respect to the basic parameters (principle point and distance) and the additional parameters A_1, A_2, A_3, B_1 and B_2, and shear and scale difference, with the option to select a subset of these parameters. Results are similar. The achieved accuracies are about a factor of 1.9 worse than ours when using Matlab calibration toolbox with the same number of images, which may be explained by the specific point detector and the degree of robustness of the estimation procedure. Further investigations are necessary.

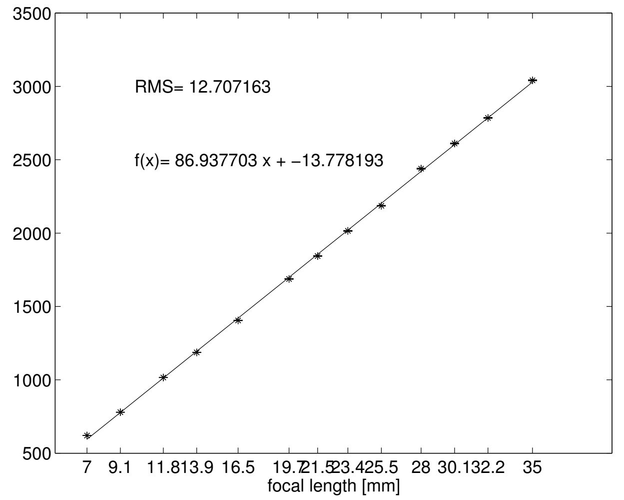

Figure 6: Principal distance of Sony DSC V1 at different optical and digital zoom levels (30.1-35 mm is digital zoom), used distortion: A_1, B_1, B_2. Resolution: VGA images.

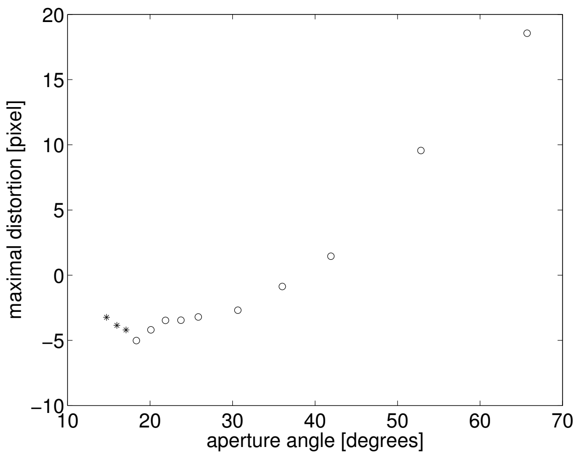

Figure 7: Distortion (maximal value) of Sony DSC V1 at different optical (o) and digital (*) zoom levels, resolution: VGA images.

4 SUMMARY AND OUTLOOK

We investigated the interior orientation of consumer cameras with respect to photogrammetric applicability. Time variations are in the order of 5-times the achievable precision, as long as no zoom is used. Interpolation of parameters appears not to be possible in general, especially concerning zoom and resolution. Therefore individual calibration is required, in case the camera parameters (zoom, focus, resolution) can be held fix, and high accuracy requirements are to be faced. Some cameras, e. g. the HP Photo Smart 435, shows very small and stable distortions, which also over longer times seem to guarantee accuracies below 0.5 pixels.

This investigation needs to be extended: (1) fixed focus cameras in mobile phones, (2) more flexible distortion models, such as finite elements, (Tecklenburg et al., 2001) and (3) the time stability of non-linear distortions. The Matlab public domain software for camera calibration also needs further attention, possibly extensions guaranteeing higher precision, and providing higher automation.

All together, consumer cameras under certain, limited accuracy

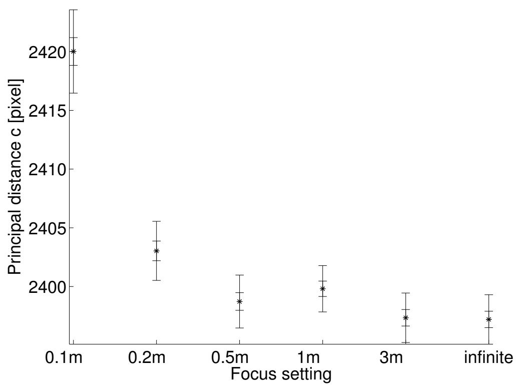

Figure 8: Principal distance at different focus settings with error bars 1σ and 3σ of Sony DSC V1 (zoom 2x).

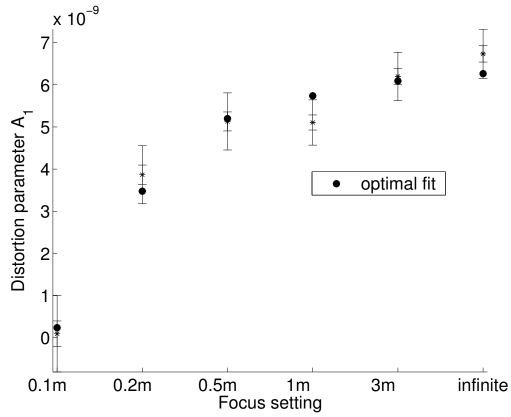

Figure 9: Radial symmetric distortion parameter A_1 with 1 σ- and 3 σ-error bars of Sony DSC V1 at different focus settings (zoom 2x).

requirements very well can be used for photogrammetric purposes.

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