ZOOM-DEPENDENT CALIBRATION FOR CONSUMER GRADE-CAMERAS

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Commission V, WG V/1

KEY WORDS: self calibration, camera calibration, lens distortion, zoom lens.

ABSTRACT:

A significant practical constraint currently applying to the adoption of consumer-grade digital cameras for photogrammetric measurement is the requirement to record images at fixed zoom and focus settings. This is a consequence of the variation of camera calibration parameters, especially principal distance and lens distortion, with changing zoom and focus. This paper describes a zoom-dependent calibration model, in which the image coordinate correction equations for departures from collinearity are expressed as a function of the nominal focal length written to the EXIF header of the images. Such a calibration approach frees the user from the constraint of recording images with both fixed focus and zoom. The newly developed zoom-dependent calibration approach is reviewed and the results of its application to the calibration of a number of off-the-shelf cameras are presented. The benefits of the approach for medium-accuracy close-range photogrammetry applications across fields as diverse as traffic accident reconstruction and heritage recording are then highlighted.

1. INTRODUCTION

The adoption of consumer-grade digital cameras for photogrammetric measurement to relative accuracies of, say, 1:1000 and higher is generally subject to the requirement of recording imagery with both fixed zoom and focus setting. This is due to the well-known variation of camera calibration parameters, especially principal distance and lens distortion coefficients, with changing focal length. For the case of changing focus, well-proven correction models for variation in radial lens distortion were formulated some three decades ago by Brown (1971). Even the variation within the photographic field has been described via both physical (Brown, 1971) and empirical (Fraser & Shortis, 1990) models. Moreover the linear variation of radial lens distortion with changing focus has been rigorously enforced by constraint functions in the self-calibration of lenses at multiple focal settings (Fraser, 1980).

When it comes to consumer-grade digital cameras with integrated zoom lenses (generally 3X to 5X optical zoom), the change in radial distortion with focus is generally of little concern. This is because the variation diminishes significantly beyond focused distances of around 15 times nominal focal length (Fryer & Brown, 1986; Fraser & Shortis, 1990) and most consumer-grade digital cameras have focal lengths of less than 40mm. The variation of camera calibration parameters with changing zoom, however, can be expected to be very significant and it must be taken into account in photogrammetric applications.

A zoom-dependent (Z-D) camera calibration procedure, in which the traditional image coordinate correction model is expressed as a function of the nominal zoom focal length written to the EXIF (Exchangeable Image Format) header of each image (usually jpeg), has recently been developed (Fraser & Al-Ajlouni, 2006). Z-D calibration is intended to be used in medium-accuracy digital close-range photogrammetry where a proportional accuracy level in object space positioning of 1: 5,000 or lower is required. Such applications areas comprise architectural photogrammetry and heritage recording, and forensic photogrammetry. This paper reviews the Z-D camera calibration approach and illustrates its accuracy potential and practical utility through reference to the results of experimental evaluations involving a number of digital cameras.

2. VARIATION OF CALIBATION WITH ZOOM

2.1 Principal Distance

The Z-D calibration process involves a modelling of the variation of camera calibration throughout the zoom range of the lens as a function of the recorded focal length. Thus, the first issue that must be addressed concerns the relationship between recorded focal length (*f*) in the EXIF header and the photogrammetric principal distance (*c*). The plots in Figure 1 show the difference between (*f*) and (*c*) at various zoom settings for eight selected consumer-grade cameras.

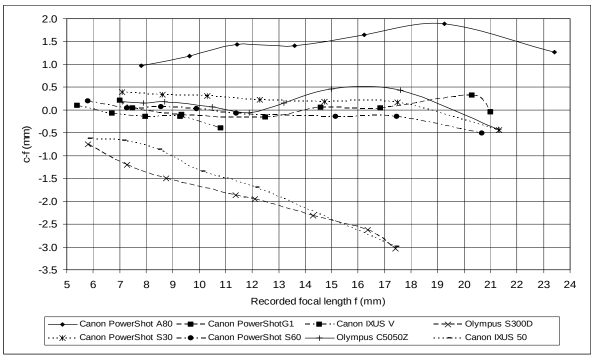


Figure 1 Variation in difference values between recorded focal length *f* and principal distance *c* throughout the zoom range for eight consumer-grade cameras.

In general terms the trend of the variations plotted in Figure 1 is linear. There are few practical alternatives to the adoption of a linear model to describe the difference *f-c*, and a linear variation function has been adopted for Z-D calibration.

2.2 Principal Point Coordinates

The principal point coordinates x_p and y_p can also vary with changing zoom setting. In plotting the change in these interior orientation parameters for the same sample of cameras it was noted that the variation for some cameras was near linear, suggesting constant alignment of the optical axis with the focal plane, whereas for others is was non-linear (see Fraser & Al-Ajlouni, 2006). These largely anticipated characteristics have previously been reported by Burner (1995), Wiley & Wong (1995) and Noma et al. (2002). Given that the variation in principal point offset is largely a function of the individual zoom lens, the only practical way to model this from relatively few sample points is again via a linear model, and this is the approach adopted in the Z-D calibration method.

2.3 Radial Lens Distortion

Radial lens distortion varies with both changing zoom and focus. In the case of changing focus, however, the variation is typically too small to be of metric concern in consumer-grade digital cameras. But, in the case of changing zoom the variation can be very significant. Shown in Figure 2 are plots of the Gaussian radial distortion for different zoom focal lengths, for three selected cameras. These profiles are obtained via the well-known odd-order polynomial expression for radial distortion:

$$dr = K_1 r^3 + K_2 r^5 + K_3 r^7 \qquad (1)$$

where dr is the radial distortion, K_i the coefficients of radial distortion, and r the radial distance.

From Figure 2 the following characteristics of radial distortion variation are noteworthy:

- The variation is non-linear.
- The radial distortion reaches a maximum at shortest focal length, even in cases where zero crossings occur.
- The profiles are invariably well described by the cubic term $K_1 r^3$ of radial distortion alone.
- Although not obvious from the figure, K_1 decreases monotonically with increasing zoom.

These observations are consistent with those made by others, e.g. Laebe & Foerstner (2004), Wiley & Wong (1995), Burner (1995) and Fryer (1986).

For medium-accuracy digital close-range photogrammetry applications the radial lens distortion can usually be modelled by the cubic coefficient K_1 alone. Figure 3 shows the variation of K_1 with changing zoom focal length. After an evaluation of various empirical models, a suitable function that accurately describes this variation was found to be of the form:

$$K_1^{(c_i)} = d_0 + d_1 c_i^{d_2} \qquad (2)$$

where c_i is the principal distance and d_i are empirical coefficients. For the eight cameras included in Figure 1, the power of the curve indicated by the coefficient d_2 varied from about -0.2 to -4.1.

2.4 Decentering Distortion

Decentering distortion varies with changing zoom and focus setting (Fryer & Brown, 1986), though the magnitude of both the distortion profile itself and its variation are very small. Also, decentering distortion can be projectively absorbed to a considerable degree by the principal point coordinates in a self-calibrating bundle adjustment. These characteristics, coupled with the focus of the Z-D approach on medium accuracy, have led to the decision to omit decentering distortion from the Z-D calibration model, though there is no reason not to include the terms as invariant with zoom in the resulting image coordinate correction process.

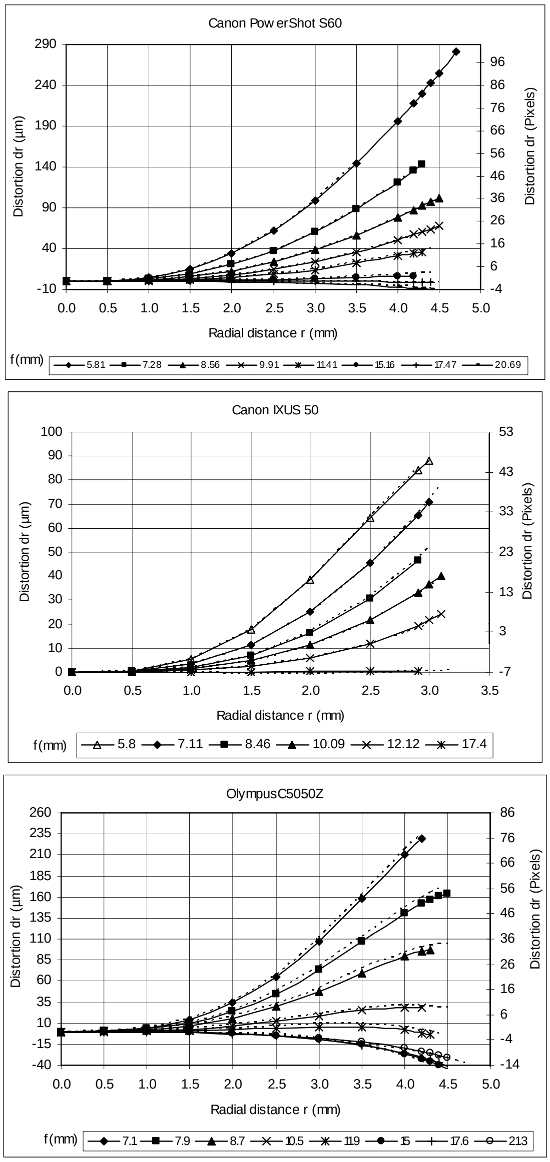


Figure 2. Radial distortion profiles at different zoom settings from two independent self-calibrations (solid & dashed curves).

3. ZOOM DEPENDENT CALIBRATION MODEL

Based on the characteristics of calibration parameters for consumer-grade cameras described above, the following model for Z-D calibration can be formulated:

$$\begin{aligned} x^{corr} &= x - x_p^{(c_i)} + \left(x - x_p^{(c_i)}\right) K_1^{(c_i)} r^2 \\ y^{corr} &= y - y_p^{(c_i)} + \left(y - y_p^{(c_i)}\right) K_1^{(c_i)} r^2 \end{aligned} \qquad (3)$$

where, x^{corr} and y^{corr} are the corrected image coordinates, x and y the measured coordinates. The Z-D calibration parameters are determined as follows:

- Principal distance $$c_i = a_0 + a_1 \ f_i \qquad (4)$$
- Principal point offset $$x_p^{(c_i)} = b_0 + b_1 c_i \qquad (5)$$ $$y_p^{(c_i)} = b_2 + b_3 c_i$$
- Cubic term K_1 of radial distortion: as in Eq.(2)

In order to determine the parameters a_i, b_i and d_i in Eqs. 2, 4 and 5, values of the interior orientation and radial lens distortion need to be determined via self-calibration from a minimum of two zoom settings in the case of interior orientation elements, and three for lens distortion coefficients.

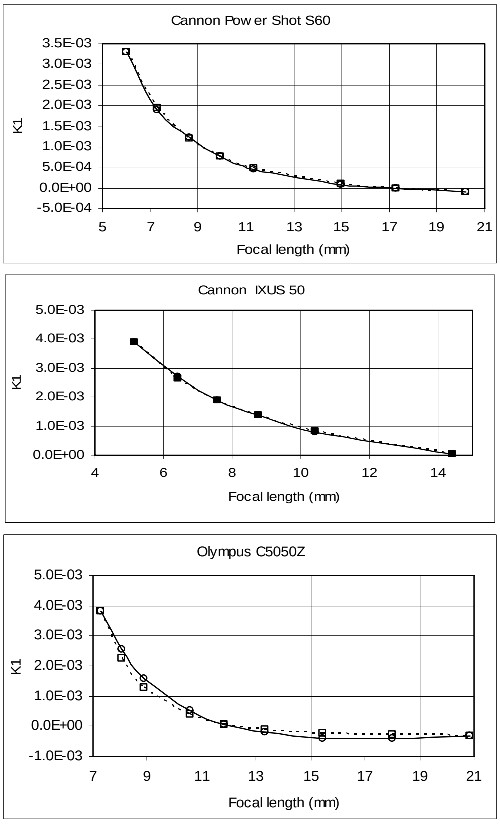


Figure 3 Variation of K_1 with changing zoom setting (solid line) along with a plot of $K_1^{(ci)}$ (dashed line) for three cameras.

A recommended procedure is to perform three self-calibrations, one with the lens fully zoomed out (shortest focal length), one fully zoomed in (longest focal length) and one in the mid-zoom region. There is of course no reason why additional self-calibrations cannot be performed in order to better model the empirical coefficients a_i, b_i and d_i. Whereas in the past the requirement for multiple self-calibrations might have been a practical impediment to implementing a Z-D calibration approach, digital camera self-calibration can now be a very straightforward, fully automatic procedure (e.g. Cronk et al., 2006) with each self-calibration survey needing 5 minutes or so.

4. EXPERIMENTAL EVALUATION

4.1 Test Field

In order to evaluate the proposed Z-D calibration approach, experimental application of the method was tested on a number of consumer-grade and better-quality SLR-type digital cameras. Firstly, a 5m x 3m x 1m(depth) test field comprising 160 retro-reflective targets was established, with object points being surveyed to better than 1:200,000 accuracy with a GSI INCA2 camera. A basic network configuration of six convergent camera stations was adopted for each self-calibration survey, and two images with orthogonal roll angles were recorded at each station. Two additional stations were included to evaluate the Z-D calibration approach for stereo imagery. The network geometry and target array are shown in Figure 4.

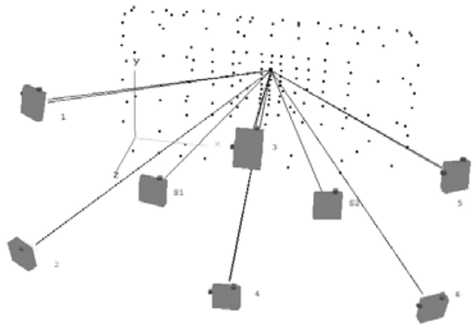


Figure 4 Camera station configurations and target array.

4.2 Self-Calibration Results

The fundamental procedure adopted for each of the cameras evaluated was to record the 14-image network indicated in Figure 4 using between 5 and 7 distinct zoom settings throughout the full focal length range for each camera. The self-calibration results from either 3 or 4 of these surveys were then used to compute the parameters of the Z-D calibration model (Eqs. 3-5). The empirically determined parameters were applied at the zoom settings that had not been employed in the empirical modelling, thus providing the means for an independent assessment of the accuracy achieved with the Z-D calibration. It was possible to check the object point coordinate determination in a relative sense (Z-D derived point coordinates versus self-calibration results) and also in an absolute sense (Z-D versus 'true' values from the INCA2 survey).

All image coordinates were measured automatically using the *Australis* system (Fraser & Edmundson, 2000; Photometrix, 2006), to an accuracy of around 0.03 pixel. Even though the Z-D calibration approach is intended to support low- to medium-accuracy measurement applications, every effort was made to ensure that the difference in accuracy between the traditional self-calibration and the Z-D calibration approach was attributable to the effects of the empirical Z-D modelling alone.

After the Z-D calibration parameters had been computed from three zoom settings (fully zoomed out, in and mid range), image coordinates at other zoom settings were corrected via Eq. 3 and a standard bundle adjustment (with no additional parameters, or APs) was performed for the network at each zoom setting. Although a number of cameras were used in the investigation, the self-calibration results from only one will be considered. Further results are provided in Fraser & Al-Ajlouni (2006), these being fully consistent with those presented here.

Shown in Table 1 is the outcome of self-calibrations with 4 APs (c, x_p, y_p, and K_1) at various zoom settings for the 5-megapixel Canon PowerShot S60 camera. Table 2 lists the results of applying the Z-D calibration at the zoom settings that were not included in the computation of the Z-D calibration parameters.
As seen in Table 1, the accuracy of the 3D point determination increases with increasing zoom, i.e. with increasing focal

length. The absolute accuracy achieved at each zoom setting, indicated by the RMS discrepancy against 'true' coordinate values, ranged from 0.7mm (1:7000) to 0.03mm (1:56,000). These are encouraging results for an off-the-shelf, consumer-grade camera. It is also noteworthy and very encouraging, when the results of Table 2 are considered, that the accuracy in object coordinate determination achieved in the Z-D calibration approach is quite consistent with that from the self-calibrations.

The relatively high accuracy of 3D point determination in the cases where Z-D calibration parameters are applied is largely a function of the precision of image measurement. The RMS value of image coordinate residuals ranged from 0.05 pixel to 0.2 pixel, and generally improved with increasing zoom. It should be noted that the manual measurement of imagery, which still predominates in applications in heritage recording and traffic accident reconstruction, for example, is likely to yield observation residuals in the range of 0.3 to 1.5 pixels and thus accuracies in object space can be expected to be significantly lower than those listed in Tables 1 and 2. The purpose in pursuing such high-precision image measurement was simply to provide a better assessment of the integrity of the Z-D calibration modelling.

4.3 Networks with Multiple Focal Settings

A prime motivation for adopting the Z-D calibration process is that it frees the user from the need to record either all or a subset of images at a fixed focal length. Any arbitrary zoom can be adopted. The only requirement is that the nominal focal length be written to the EXIF header. To experimentally assess the validity of the Z-D image correction model, networks were recorded at mixed zoom settings. Shown in Table 3 are summaries of the results obtained from applying the Z-D correction to images from 5 to 7 zoom settings for three different cameras, the PowerShot S60, a Canon IXUS 50 (5 megapixel) and an Olympus C5050Z (5 megapixel).

In each case, all image coordinates were corrected using the empirically derived Z-D calibration parameters and none of the zoom settings corresponded to those from which the calibration was determined. Standard bundle adjustments were then applied (all free network solutions) and the RMSE against true object point coordinate values was computed. As seen in Table 3, the accuracy ranged from 1:3000 for the IXUS 50 to 1:9000 for the PowerShot S60. While not being as impressive as the RMSE values listed in Tables 1 and 2, these accuracies nevertheless surpass the requirements of perhaps the majority of applications involving 3D measurement with consumer-grade cameras.

A further test was performed in which image coordinates were manually measured. The object was a historic building and natural features were used as targets. The camera involved was a 3-megapixel Canon PowerShot S30. An automatic camera self-calibration was first performed with the *iWitness* system (Cronk et al., 2006; Photometrix, 2006). The Z-D calibration parameters were then computed for the remaining zoom settings and applied in the bundle adjustment of the image network. Table 4 summarizes the results obtained. The accuracy achieved, around 1:2000, is typical for such a measurement project. What is noteworthy in the context of Z-D calibration is that both solutions effectively produced the same results.

5. TEMPORAL VARIATION OF CALIBRATION

In order to investigate the geometric stability and repeatability of camera calibration parameters, the series of experimental tests reported above was repeated after a period of a week for the Canon PowerShot S60, IXUS 50 and Olympus C5050Z cameras. For the Z-D calibration approach to be viable, a reasonable degree of repeatability is required for the camera parameters.

Focal length (mm)	Number of object points	RMS of xy image coordinate residuals (pixels)	Mean std. error of XYZ (mm)	Diameter of object (mm)	RMSE against 'true' XYZ coords. (mm) (proportional accuracy, 1:??,000)
5.81	167	0.18	0.22	5068	0.726 (7)
7.28	166	0.18	0.20	5068	0.742 (7)
8.56	133	0.14	0.15	4637	0.374 (12)
9.91	124	0.11	0.09	4434	0.273 (16)
11.41	118	0.08	0.07	3728	0.177 (21)
15.16	75	0.05	0.03	2441	0.043 (56)
17.47	72	0.05	0.02	2154	0.046 (47)
20.69	59	0.06	0.02	1666	0.030 (55)

Table 1. Results of self-calibrations with 4 APs (c, x_p, y_p & K_1); shaded zoom settings not used in determining Z-D calibration.

Focal length (mm)	RMS of xy image coordinate residuals (pixels)	Mean std. error of XYZ (mm)	RMSE of XYZ coords. against self-calib. with 4 Aps, (mm)	RMSE against 'true' XYZ coords. in mm (proportional accuracy, 1:??,000)
7.28	0.20	0.227	0.381	0.771 (7)
8.56	0.16	0.165	0.285	0.403 (12)
11.41	0.08	0.073	0.110	0.169 (22)
15.16	0.06	0.032	0.034	0.052 (47)
17.47	0.05	0.025	0.014	0.048 (45)

Table 2. Results of applying the Z-D calibration correction within the bundle adjustment.

Camera	Number of images @ zoom setting; total number	Number of object points	Effective diameter of object(mm)	RMS of xy residuals (Pixels)	Mean standard error of XYZ (mm)	RMSE against true XYZ coordinates (mm)	Proportional accuracy
Canon PowerShot S60	2@5.81+4@15.16+2@17.47 +2@8.56+1@9.91+1@11.41 + 1@13.16; 13	156	5070	0.17	0.242	0.556	1:9000
Canon IXUS 50	2@5.8+6@8.46+4@12.12+ 2@17.4+2@14.42; 16	97	5070	0.41	0.434	1.706	1:3000
Olympus C5050Z	2@10.5+1@14.5+2@21.3+1 @13.8+1@12.1+2@8.7+1@ 10.4+1@7.1; 11	120	4040	0.29	0.329	0.996	1:4000

Table 3. Z-D Calibration approach applied to various focal length settings for three cameras.

Results / Method	RMS of Image coord. xy residuals (pixels)	Number of images	Mean std. error of XYZ (mm)	Diameter of object (mm)	Proportional accuracy
Self Calibration	0.6	8	6.998	13500	1:1,900
Bundle adjustment with Z-D calibration	0.4	7	7.292	13500	1:1,850

Table 4. Camera self-calibration versus Z-D calibration approach with bundle adjustment for Canon PowerShot S30.

5.1 Temporal Variation of Principal Distance

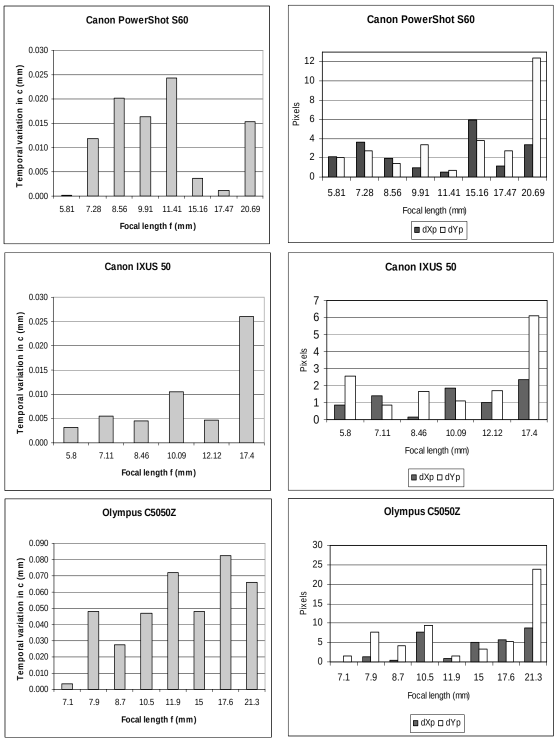
Shown in Figure 5a is the temporal variation of principal distance over a period of one week for the three cameras. No systematic variation was found, though it is apparent that for two of the cameras the variation increases with focal length, longer zoom settings exhibiting greater change.

5.2 Temporal Variation in Principal Point Coordinates

It is well known that the principal point coordinates for non-metric cameras are inherently unstable. These instabilities are typically more pronounced in zoom lenses. Shown in Figure 5b is the temporal variation in principal point coordinates for each of the three cameras considered. The maximum variation again occurs at the maximum zoom settings, but it is interesting to note that the longer the focal length, the more likely the prospect that errors in interior orientation will be projectively absorbed in the bundle adjustment by exterior orientation parameters. Generally speaking, the temporal variation of x_p and y_p is about ten pixels, except at maximum zoom.

5.3 Temporal Variation in Radial Lens Distortion

The Gaussian radial lens distortion profiles for the two independent networks are plotted in Figure 2, with the curves being drawn to the maximum radial distance encountered in the self-calibrations, i.e. there is no extrapolation. Encouragingly, and largely as anticipated from previous investigations, the temporal variation for radial distortion is of the order of a few pixels only for all zoom settings for all cameras. This variation is easily accounted for by uncertainties in the estimation process within the bundle adjustment. Consequently, the temporal variation in the empirically derived radial distortion for the Z-D calibration should also be reasonably stable over time. This was tested and found to be the case, with the variation in Z-D modelled radial distortion being within a few pixels.



(a) (b)

Figure 5. Temporal variation over one week for principal distance (a) and principal point coordinates (b).

5.4 Temporal Variation Effects on Triangulation Results

The impact of temporal variations in camera calibration on photogrammetric triangulation is of more interest than the extent of change in the actual calibration parameters. In order to quantify this effect, XYZ object point coordinates from the initial and follow-up calibrations were compared at the limits of the zoom setting for the same three cameras considered above. The object point array in this case was the test field of Figure 4 and all networks were again measured automatically via the *Australis* system.

Listed in Table 5 are the RMS coordinate discrepancies that resulted from a 3D similarity transformation between the corresponding object point arrays. The RMS values are shown in Table 5a for the case of 4 APs (c , x_p ,y_p , and K_1) and 8 APs (three of interior orientation and five of lens distortion). The results listed in Table 5b are obtained by simply assigning the estimated APs from the first survey to the second network, and vice versa, the idea being to examine the sensitivity of the object point coordinates to changes in calibration values and to indirectly assess the extent of projective compensation. To further examine whether projective compensation processes were at work in the networks, which would diminish to some extent the influence of errors/changes in calibration, arbitrary errors were introduced into the parameters that were most likely to undergo change, or apparent change. These are the principal point coordinates and the decentering distortion parameters P_1 and P_2. The results of this action are listed in Table 5c.

Of interest from a practical perspective is that no matter what case is considered, the relative accuracy attained is much higher than would be anticipated in routine photogrammetric measurement using these three cameras. This further supports the view that the Z-D calibration offers a practical approach for medium-accuracy measurement operations.

6. CONCLUSION

This paper has highlighted the benefits of the Z-D calibration approach for consumer-grade digital cameras. The method has been shown to produce quite acceptable accuracy, and it is relatively straightforward to implement, especially if one has the option to use fully automatic calibration software such as the *iWitness* system (Cronk et al., 2006, Photometrix, 2006). Moreover, the computation of the empirically determined Z-D calibration parameters is unlikely to be required too frequently. The investigations reported here indicate both that radial lens distortion is relatively stable and that any errors arising from small variations in interior orientation can be expected to be projectively absorbed to a degree in the bundle adjustment.

The real benefit of the Z-D calibration method is that it is very practical. Once the image coordinate correction parameters are established, and there are supporting data processing facilities, the user of close-range photogrammetry is freed from the traditional restriction of capturing images at fixed zoom and focus settings. This enhances the flexibility of moderate accuracy close-range photogrammetric measurement.

Camera	Zoom Setting	(a) RMS (8 APs) Proportional Accuracy mm	(1:??,000)	(a) RMS (4 APs) Proportional Accuracy mm	(1:??,000)	(b) RMS (8 APs) Proportional Accuracy mm	(1:??,000)	(c) RMS (8 APs) Proportional Accuracy mm	(1:??,000)
Canon PowerShot S60	Out	0.100	51	0.689	7	0.175	29		
	In	0.025	67	0.029	57	0.021	81	0.019	86
Canon Ixus 50	Out	0.231	22	0.648	8	0.083	61		
	In	0.096	22	0.098	22	0.046	47	0.058	37
Olympus C5050Z	Out	0.196	26	0.447	11	0.254	20		
	In	0.035	57	0.050	40	0.092	22	0.027	76

Table 5. Impact of temporal variation in calibration: (a) between the 2 self-calibrations, (b) between runs with swapped AP values, and (c) between runs with x_p , y_p shifted by +0.05 mm and P_1 and P_2 altered by -5.00e-05.

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