EXPERIMENT ON PRECISION OF CAMERA CALIBRATION OF NON-METRIC DIGITAL CAMERAS

Ryuji Matsuoka*, Noboru Sudo, Hideyo Yokotsuka, Mitsuo Sone

Tokai University Research & Information Center
2-28-4 Tomigaya, Shibuya-ku, Tokyo 151-0063, JAPAN
ryuji@yoyogi.ycc.u-tokai.ac.jp, (sdo, yoko)@keyaki.cc.u-tokai.ac.jp, sone3@yoyogi.ycc.u-tokai.ac.jp

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ABSTRACT:

Although many camera calibration methods for a non-metric digital camera have been proposed, there are few reports on the precision of calibration results. Therefore, we conducted a field experiment in order to examine the precision of calibration results of a non-metric digital camera. We adopted a calibration method using a set of calibration points distributed on the 2-D plane with no ground survey. Four non-metric digital cameras were calibrated in the filed experiment. A round of camera calibration utilized a set of eight convergent images acquired from eight different directions with four different camera frame rotation angles of 0°, +90°, +180° and −90° around the optical axis of the camera. 32 rounds of camera calibration for each camera were conducted. The experimental results demonstrate that dispersions of image distortions between obtained image distortion models cannot be neglected. The most part of the difference between estimated image distortions was the difference of the estimated position of the principal point, while the differences of another components of the image distortion model were small enough to be negligible. Furthermore, the experiment results show that the error estimates of the obtained camera parameters cannot indicate the precision of the obtained image distortion model.

1. INTRODUCTION

1.1 Background of the study

The recent increase in number of pixels of images acquired by a non-metric digital camera encourages an amateur to utilize it for photogrammetric applications such as 3-D measurement and creation of orthoimages. A non-metric digital camera is required to be geometrically calibrated when it is used for photogrammetric applications.

Many camera calibration methods for a non-metric digital camera have been proposed. Most of amateurs would like to use a piece of software that has a calibration function using a 2-D flat sheet with the dedicated pattern (EOS Systems Inc., 2003), because a camera calibration method using 3-D distributed targets is inconvenient and expensive for an amateur to calibrate his digital camera.

A user of a piece of calibration software using a 2-D calibration sheet may find no small difference of image distortion between calibration results obtained from the different sets of images acquired by the same camera, even though all the error estimates of the obtained camera parameters will be small enough. At that time, he might wonder whether one or more trials of camera calibration might be inadequate. However, he would be unable to select an appropriate result, because there are few reports on the precision of an estimated image distortion distribution by the camera calibration.

By the way, there is no standard procedure to evaluate an estimated image distortion model directly. Calibration results are usually evaluated indirectly by such indexes as residuals on image, 3-D measurement errors of control points and/or check points, and error estimates of obtained camera parameters. On the contrary, the limits of capabilities of these indexes have already been shown by numerical simulation results (Matsuoka, *et al.*, 2003a). Moreover, it is difficult to evaluate the accuracy of the estimated image distortion model because of great expense. On the other hand, the precision of the estimated image distortion model can be easily evaluated, but there are few reports on the precision of calibration results.

1.2 Aim of the study

We conducted a field experiment in order to examine the precision of calibration results of a non-metric digital camera. The experiment results were expected to demonstrate the following to an amateur who would like to calibrate his non-metric digital camera by a piece of software using a set of calibration points distributed on the 2-D plane:

(A) How wide are dispersions of image distortion distributions between calibration results obtained from the different sets of acquired images when the error estimates of the obtained camera parameters are small enough?

(B) To what extent can the error estimates of the obtained camera parameters, which are often used to evaluate calibration results, indicate the precision of the obtained image distortion model?

In this paper, we define the aim of a camera calibration as estimating the distortion model of images acquired by the target camera. Consequently, the precision of a camera calibration is evaluated by the precision of an estimated image distortion model by the camera calibration.

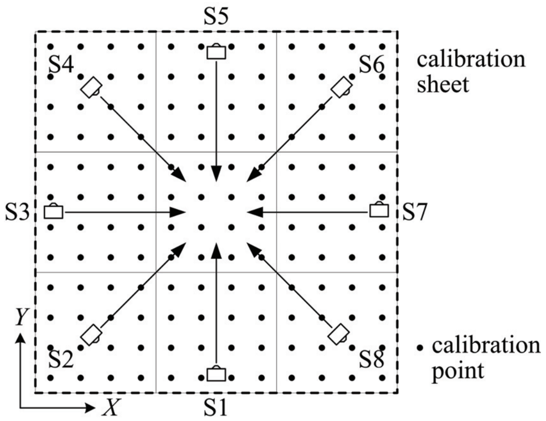
2. OUTLINE OF FIELD EXPERIMENT

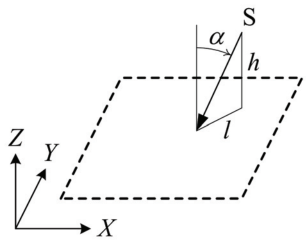
Since most of amateurs would like to use a piece of calibration software using a 2-D flat sheet with the dedicated pattern, a field experiment of camera calibration was conducted according to our developed calibration method using a set of calibration points distributed on the 2-D plane with no ground survey (Matsuoka, *et al.*, 2003b).

Our numerical simulation results confirmed that an image distortion model estimated by our method using a set of calibration points on the 2-D plane is expected to be as good as one estimated by a calibration method using a set of calibration points in the 3-D space (Matsuoka, *et al.*, 2005).

2.1 Image Acquisition for Calibration

We prepared a calibration field composed of three by three sheets of approximately 1 m length and 1 m width, nine sheets in all. Each sheet had ten by ten calibration points placed at intervals of approximately 0.1 m by 0.1 m. Therefore, the calibration field was approximately 3 m long and 3 m wide, and it had 30 by 30 calibration points, 900 calibration points in all. Each calibration point was a black filled circle with the radius

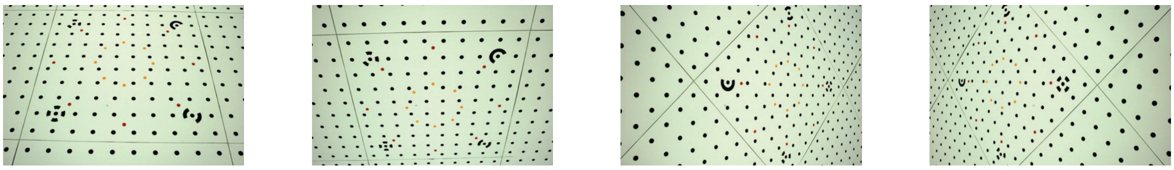




Camera frame rotation angle around the optical axis of the camera at each exposure station as follows:

[T] S1 and S4: 0° (no rotation)
[L] S3 and S6: +90° (left sideways)
[B] S5 and S8: +180° (upside down)
[R] S7 and S2: −90° (right sideways)

Figure 1. Convergent image acquisition from eight different directions



(a) Image at S1 [T] (b) Image at S5 [B] (c) Image at S6 [L] (d) Image at S2 [R]

Figure 2. Images acquired in the camera calibration

(a) D1 (b) D70 (c) E-10 (d) G2

Figure 3. Target cameras

	Nikon D1	Nikon D70	Olympus CAMEDIA E-10	Canon PowerShot G2
Image sensor	23.7 × 15.6 mm RGB CCD	23.7 × 15.6 mm RGB CCD	Type 2/3 RGB CCD	Type 1/1.8 RGB CCD
Unit cell size in μm	11.8 × 11.8	7.8 × 7.8	3.9 × 3.9	3.125 × 3.125
Number of recording pixels	2,000 × 1,312	3,008 × 2,000	2,240 × 1,680	2,272 × 1,704
Lens	24 mm F2.8	24 mm F2.8	9 – 36 mm F2 – F2.4	7 – 21 mm F2.0 – F2.5
35 mm film equivalent	36 mm	36 mm	35 – 140 mm	34 – 102 mm

Table 1. Specifications of the target cameras

approximately 11 mm.

A round of camera calibration utilized a set of eight convergent images acquired from eight different directions S1 – S8 with four different camera frame rotation angles of 0° [T], +90° [L], +180° [B] and −90° [R] around the optical axis of the camera as shown in Figure 1. The inclination angle α at image acquisition was approximately 35°. Figure 2 shows some images acquired in the field experiment.

Four cycles of image acquisition for each camera were executed. 32 images were acquired from eight different directions S1 – S8 with four different camera frame rotation angles [T], [L], [B] and [R] for each cycle of image acquisition. Hence, 128 images were utilized for the calibration of each camera.

2.2 Target Cameras

Four non-metric digital cameras shown in Figure 3 were investigated in the filed experiment. Table 1 shows the specifications of the target cameras. Nikon D1 and Nikon D70 were lens-interchangeable digital SLR (single lens reflex) cameras, Olympus CAMEDIA E-10 was a digital SLR camera equipped with a 4× optical zoom lens, and Canon PowertShot G2 was a digital compact camera equipped with a 3× optical zoom lens. These four cameras are called D1, D70, E-10 and G2 for short from now on. D1 and D70 were calibrated with a 24 mm F2.8 lens, while E-10 and G2 were calibrated at the widest view of their zoom lenses. Hence, they were calibrated with a lens equivalent to around 35 mm in 35 mm film format.

2.3 Image Distortion Model

Image distortion (Δx, Δy) of a point (x, y) on image is represented as

$$\begin{cases} \Delta x = \Delta x_P + \Delta x_R + \Delta x_D \\ \Delta y = \Delta y_P + \Delta y_R + \Delta y_D \end{cases} \quad (1)$$

$$\begin{cases} \Delta x_R = \bar{x}\left(\dfrac{\Delta c}{c_0} + k_1 r^2 + k_2 r^4 + k_3 r^6\right) \\ \Delta y_R = \bar{y}\left(\dfrac{\Delta c}{c_0} + k_1 r^2 + k_2 r^4 + k_3 r^6\right) \end{cases} \quad (2)$$

$$\begin{cases} \Delta x_D = p_1\left(r^2 + 2\bar{x}^2\right) + 2p_2\overline{xy} \\ \Delta y_D = 2p_1\overline{xy} + p_2\left(r^2 + 2\bar{y}^2\right) \end{cases} \quad (3)$$

$$\begin{cases} r^2 = \bar{x}^2 + \bar{y}^2 \\ \bar{x} = x - \Delta x_P \\ \bar{y} = y - \Delta y_P \end{cases} \quad (4)$$

where (Δx_P, Δy_P) are the offsets from the principal point to the center of the image frame, (Δx_R, Δy_R) are the radial distortion components, and (Δx_D, Δy_D) are the decentering distortion components. c_0 is the nominal focal length and Δc is the difference between the calibrated principal distance c and c_0.

2.4 Evaluation Indexes

Some indexes such as V_I, (σ_x, σ_y), σ_P, D_T, D_R, D_D and D_P were calculated to evaluate the calibration result.

V_I is root mean squares of residuals on image calculated at the camera calibration. V_I is sometimes used to evaluate calibration results (Chikatsu *et al.*, 1996, Noma *et al.*, 2002).

(σ_x, σ_y) are error estimates of the offsets (Δx_P, Δy_P) from the principal point to the center of the image frame. (σ_x, σ_y) are often used to evaluate calibration results indirectly (Chikatsu *et al.*, 1996, Habib *et al.*, 2002). σ_P is the absolute value of (σ_x, σ_y), which is calculated using the following equation:

$$\sigma_P = \sqrt{\sigma_x^2 + \sigma_y^2} \quad (5)$$

D_T, D_R and D_D are root mean squares of differences of total image distortions (Δx, Δy), radial distortion components (Δx_R, Δy_R) and decentering distortion components (Δx_D, Δy_D) calculated at all pixels on image between two obtained image distortion models respectively. These indexes are calculated using the following equations:

$$D_T = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left\{\left(\Delta x_k^{(T)} - \Delta x_k^{(R)}\right)^2 + \left(\Delta y_k^{(T)} - \Delta y_k^{(R)}\right)^2\right\}} \quad (6)$$

$$D_R = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left\{\left(\Delta x_{Rk}^{(T)} - \Delta x_{Rk}^{(R)}\right)^2 + \left(\Delta y_{Rk}^{(T)} - \Delta y_{Rk}^{(R)}\right)^2\right\}} \quad (7)$$

$$D_D = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left\{\left(\Delta x_{Dk}^{(T)} - \Delta x_{Dk}^{(R)}\right)^2 + \left(\Delta y_{Dk}^{(T)} - \Delta y_{Dk}^{(R)}\right)^2\right\}} \quad (8)$$

where N is the number of pixels of the image. Superscripts $^{(T)}$ and $^{(R)}$ indicate two obtained image distortion models, that is the target image distortion model and the reference image distortion model respectively.

D_P is the distance between the estimated principal points of two obtained image distortion models, which is calculated using the following equation:

$$D_P = \sqrt{\left\{\left(\Delta x_P^{(T)} - \Delta x_P^{(R)}\right)^2 + \left(\Delta y_P^{(T)} - \Delta y_P^{(R)}\right)^2\right\}} \quad (9)$$

3. RESULTS AND DISCUSSION

32 rounds of camera calibration for each camera were conducted by bundle adjustment with self-calibration. Table 2 shows combinations of eight images utilized in a calibration round from 32 images acquired from eight different directions S1 – S8 with four different camera frame rotation angles of 0° [T], +90° [L], +180° [B] and −90° [R] for a cycle of image acquisition.

3.1 Evaluation of Calibration Results

Table 3 shows the numbers of utilized calibration points and the root mean squares V_I of residuals on image calculated at the camera calibration. The values of V_I except for G2 were small enough. Although the mean value 0.259 pixels and the maximum value 0.328 pixels of V_I of G2 seemed slightly large, it would be almost impossible to judge from the value of V_I of G2 that a camera calibration of G2 was improper.

Table 4 shows the root mean squares D_T of differences of total image distortions. The values of D_T of 496 combinations of two obtained image distortion models for each camera were

	S1	S2	S3	S4	S5	S6	S7	S8
Round 1	[T]	[R]	[L]	[T]	[B]	[L]	[R]	[B]
Round 2	[R]	[B]	[T]	[R]	[L]	[T]	[B]	[L]
Round 3	[B]	[L]	[R]	[B]	[T]	[R]	[L]	[T]
Round 4	[L]	[T]	[B]	[L]	[R]	[B]	[T]	[R]
Round 5	[T]	[B]	[L]	[R]	[B]	[T]	[R]	[L]
Round 6	[R]	[L]	[T]	[B]	[L]	[R]	[B]	[T]
Round 7	[B]	[T]	[R]	[L]	[T]	[B]	[L]	[R]
Round 8	[L]	[R]	[B]	[T]	[R]	[L]	[T]	[B]

Table 2. Eight rounds of camera calibration

Camera	Number of calibration points			V_I (pixels)		
	Min.	Max.	Mean	Min.	Max.	Mean
D1	263	297	283	0.041	0.045	0.043
D70	273	293	281	0.043	0.048	0.045
E-10	292	325	307	0.060	0.074	0.065
G2	350	386	371	0.210	0.328	0.259

Table 3. Number of calibration points and root mean squares V_I of residuals on image

Camera	D_T (pixels)			D_T / mean V_I		
	Min.	Max.	Mean	Min.	Max.	Mean
D1	0.013	0.501	0.205	0.29	11.60	4.76
D70	0.019	0.503	0.159	0.42	11.08	3.50
E-10	0.026	0.955	0.404	0.40	14.69	6.22
G2	0.124	4.568	1.496	0.48	17.65	5.78

Table 4. Root mean squares D_T of differences of image distortions

calculated by using Equation (6). The maximum value 4.568 pixels of D_T of G2 was quite large, while the values D_T of D1 and D70 were small enough. The differences in the ratio of the value of D_T to the mean value of V_I between the cameras were somewhat small as shown in Table 4. The dispersion of the ratio of each camera was rather large as the maximum values of the ratios of all cameras exceeded 10. These results indicate that it would be difficult to estimate the precision of an obtained image distortion model from the value of V_I.

Figure 4 shows the root mean squares D_T, D_R and D_D of differences of total image distortions, radial distortion components, and decentering distortion components between two obtained image distortion models respectively. The values of D_T, D_R and D_D of 496 combinations were calculated by using Equations (6), (7) and (8) respectively. Moreover, Figure 4 shows the distances D_P between the estimated principal points of two obtained image distortion models calculated by using Equation (9). These results indicate that the most part of the difference between estimated image distortions was the difference of the estimated position of the principal point, while the differences of another components of the image distortion model were small enough to be negligible.

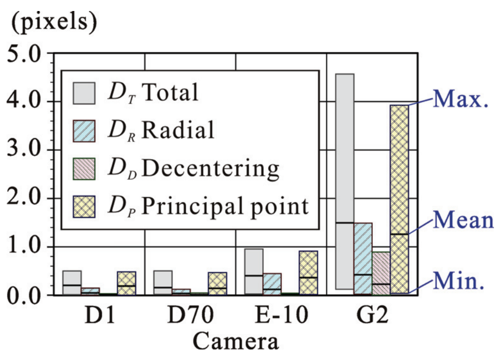


Figure 4. Root mean squares of differences of image distortions

From the results, calibration results of D1 and D70 were judged precise enough. On the other hand, calibration results of G2 would be imprecise.

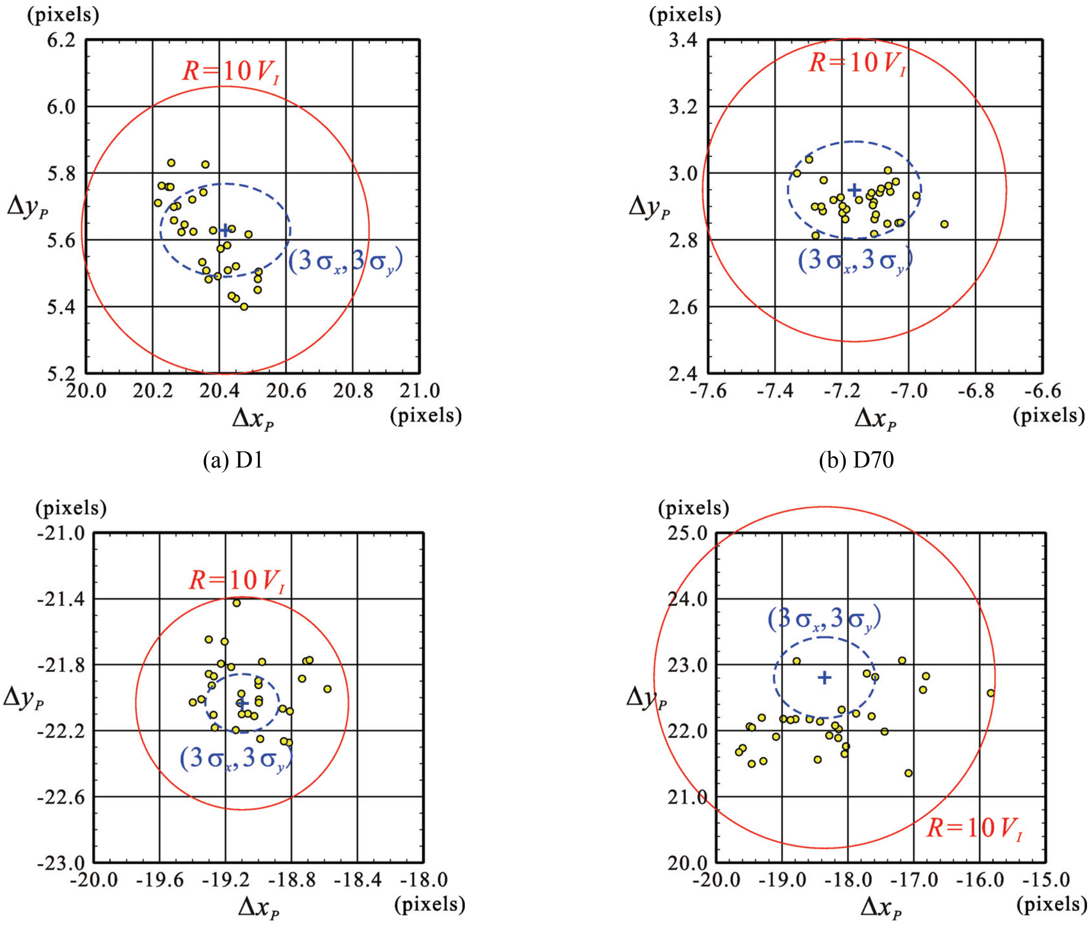
3.2 Discussion on Evaluation Indexes

Figure 5 illustrates the estimated offsets (Δx_P, Δy_P) of the principal point. In Figure 5 ellipses of broken line with the axes of three times as long as of the error estimates (σ_x, σ_y) of (Δx_P, Δy_P), and circles of solid line with the radius of ten times as long as the mean value of V_I are shown. The centers of both the ellipses and the circles are (Δx_P, Δy_P) estimated by the calibration using all 128 images of each camera.

Figure 5 indicates that the precision of the position of an obtained principal point can possibly be estimated from the values of (σ_x, σ_y), but it would be difficult to estimate the precision of the position of an obtained principal point from the value of V_I.

By contrast, error estimates of obtained camera parameters vary with a solution of the nonlinear least squares method. We obtained the image distortion models by the Gauss-Newton method, and the criterion for judgement of convergence was that the variation of V_I was less than 0.001 pixels. 32 image distortion models of each camera were derived at the fourth iteration in the Gauss-Newton method.

Figure 6 shows the variations of V_I, (Δx_P, Δy_P) and (σ_x, σ_y) of the calibration round with the farthest (Δx_P, Δy_P) from the center of the error ellipse for each camera in Figure 5. The upper and middle graphs of each camera in Figure 6 show the variations of (Δx_P, Δy_P) and (σ_x, σ_y). Dash-dotted horizontal



(a) D1 (b) D70

(c) E-10 (d) G2

Figure 5. Distribution of estimated offsets (Δx_P, Δy_P) of the principal point

lines in the graphs indicate (Δx_P, Δy_P) estimated by using all 128 images of each camera. On the other hand, the lower graph of each camera in Figure 6 shows the variation of V_I.

From the third iteration to the fourth iteration, the variations of both (Δx_P, Δy_P) and V_I were nearly zero, while those of (σ_x, σ_y) were more than one pixel as shown in Figure 6.

At the fourth iteration, since the values of (σ_x, σ_y) were small enough except for G2, the obtained calibration results would be judged highly precise from the values of (σ_x, σ_y). However, distributions of the estimated (Δx_P, Δy_P) were rather wide in comparison with the error ellipses ($3\sigma_x$, $3\sigma_y$) as shown in Figure 5.

If the criterion for judgement of convergence is that the value of V_I is less than 0.1 pixels, all image distortion models of D1, D70 and E-10 will be derived at the third iteration. At the third iteration, since the values of (σ_x, σ_y) are rather large, the obtained calibration results would be judged imprecise from the values of (σ_x, σ_y). However, the values (Δx_P, Δy_P) derived at the third iteration were as almost same as those derived at the fourth iteration. Consequently, the accuracy of the estimated (Δx_P, Δy_P) at the third iteration was nearly equal to that at the fourth iteration.

These results show that the error estimates of the obtained camera parameters, which are often used to evaluate calibration results, could be unable to indicate the precision of the obtained image distortion model. The authors propose that the precision of calibration results should be evaluated by as many calibration trials as possible.

4. CONCLUSION

The experiment results demonstrate that dispersions of image distortions between obtained image distortion models cannot be neglected. The most part of the difference between estimated image distortions was the difference of the estimated position of the principal point, while the differences of another components of the image distortion model were small enough to be negligible.

Furthermore, the experiment results show that the error estimates of the obtained camera parameters cannot indicate the precision of the obtained image distortion model. The authors propose that the precision of calibration results should be evaluated by as many calibration trials as possible.

In conclusion, we consider that our future work will be to develop a calibration method that can estimate the position of the principal point accurately and precisely enough.

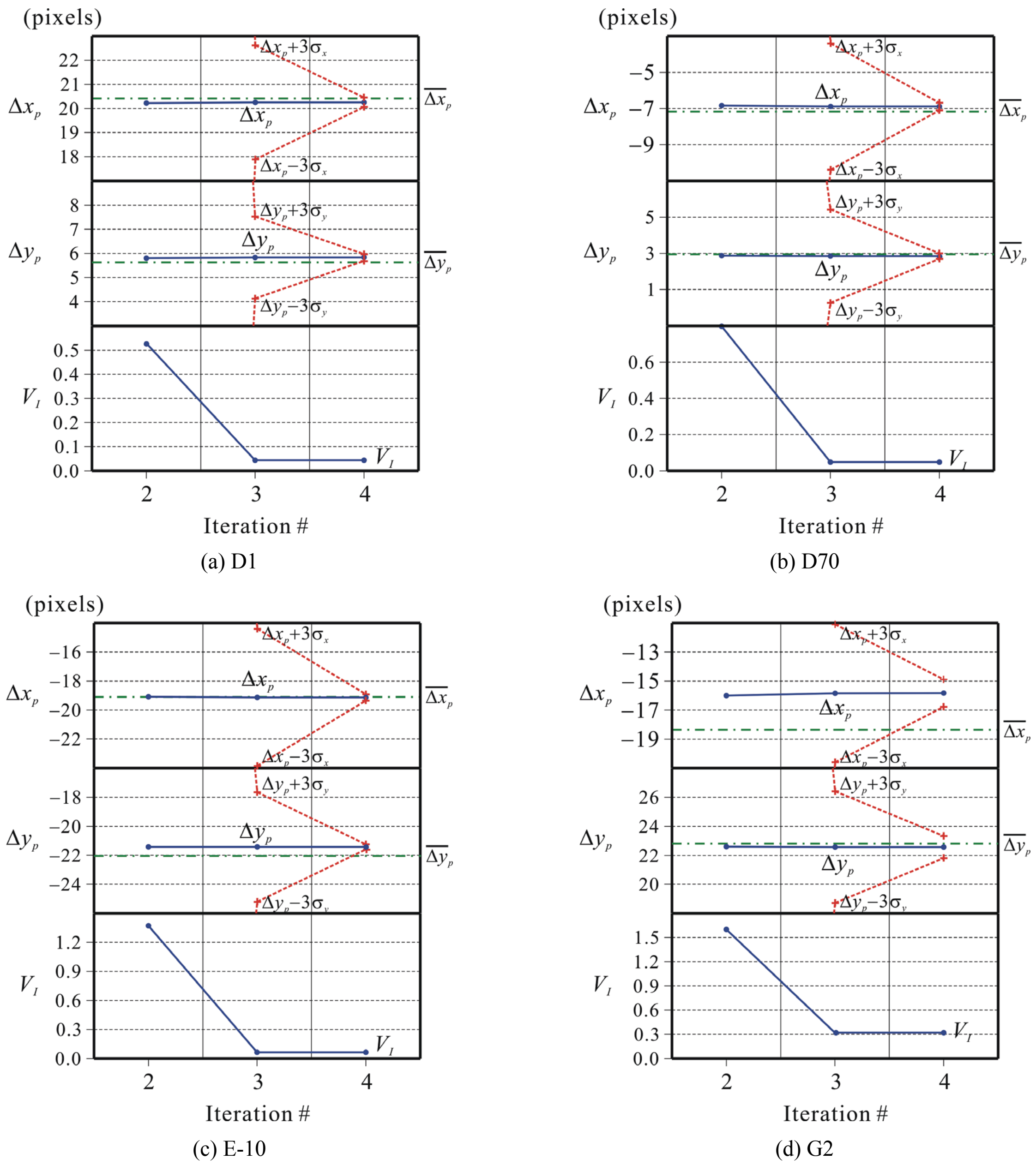


Figure 6. Variation of estimated offsets (Δx_P, Δy_P) of the principal point

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