# Effects of JPEG Compression on the Accuracy of Photogrammetric Point Determination

**Zhilin Li, Xiuxiao Yuan, and Kent W.K. Lam**


## Abstract

*An empirical investigation into the effects of JPEG compression on the accuracy of photogrammetric point determination (PPD) is described. A pair of black-and-white aerial photographs of a city, taken at a scale of 1:8000, was selected and scanned at a resolution of 25 μm. Eighteen image points were measured with the ISDM module of an Intergraph digital photogrammetric workstation (DPW), and the bundle adjustment of a single model was performed using WuCAPS$_{SGPS}$ (Wuhan GPS-supported bundle block adjustment software). In processing various JPEG compressed images with Q-factors from 1 to 100, the accuracy of the 3D coordinates of the pass points was assessed and compared with that obtained from the original images (i.e., without compression). The empirical results show that, when the compression ratios are under 10, the compressed image is near-lossless. In other words, the visual quality of JPEG compressed images is still excellent and the accuracy of manual image mensuration is essentially not influenced. However, no indication can be found from the results that a compression of 10 is the critical value or the optimum compression level for PPD. Indeed, it is clear that the degradation of accuracy in PPD is almost linear.*


## Introduction

As we know, aerial photogrammetry has two central tasks, i.e., to accurately locate and to correctly recognize ground objects from airborne/spaceborne remotely sensed imagery, i.e., to extract the positioning and attribute information of the objects from images. The former is known as photogrammetric point determination (PPD).

Conventional PPD is performed in a least-squares adjustment with photo observations based on a certain number of ground control points. The photo observations are obtained by manual mensuration on hardcopy photographs by means of an accurate comparator. The advantage of the operation is the small volume of photo observations requiring storage. Its disadvantage is that it is manual, less efficient, and frequently erroneous. With the development of computer and image processing technology, photogrammetry has stepped into the softcopy photogrammetric era. In softcopy photogrammetry, expensive photogrammetric instruments are replaced by a digital photogrammetric workstation (DPW) and most operations are implemented automatically, such as interior orientation, image mensuration, DTM generation, etc. However, all operations in a DPW are based on digital images. Hardcopy photographs must be converted into digital images by a scanner. Doing so will create a huge volume of data. For example, a black-and-white digital aerial image scanned at a resolution of 20 μm contains approximately 10,000 by 10,000 pixels or 100 Mbytes of data. Sometimes more than six images are processed at the same time to measure image points automatically. As a result, reduction in image data volume is a matter of great significance in softcopy photogrammetry. Such a reduction in data volume can be achieved by image compression techniques.

A number of mature compression techniques have been developed. They can be broadly classified into two categories: lossless compression, e.g., the Lempel-Ziv and JBIG methods (Howard *et al.*, 1998), and lossy compression, e.g., JPEG, fractal, and wavelet compression (Jackson and Hannah, 1993). Lossless compression reduces the number of bits required to represent an image such that the reconstructed image is numerically identical to the original one on a pixel-by-pixel basis. This is of course ideal for photogrammetric applications. However, the compression ratio for such a method is generally 2 to 4 times for remotely sensed imagery (Wang *et al.*, 2000). The other type of method, lossy compression, on the other hand, allows the degradation of a reconstructed image in exchange for a higher degree of compression in data volume. These degradations may or may not be visually apparent. In this study, attention is paid to the loss of geometric quality due to compression.

In recent years, image compression has been an important topic in photogrammetry. Some researchers have concentrated their efforts on developing compression algorithms for airborne and spaceborne remotely sensed imagery (Lammi and Sarjakoski, 1992; Memon, 1994; Algarni, 1996; Xuan and Hu, 1999; Wang *et al.*, 2000; Zhang *et al.*, 2000). Others evaluate the effects of compression on the information extracted from the compressed digital aerial images (Mikhail *et al.*, 1984; Nunes *et al.*, 1992; Tada *et al.*, 1993; Jaakkola and Orava, 1994; Lammi and Sarjakoski, 1995; Robinson *et al.*, 1995; Novak and Shahin, 1996; Reeves *et al.*, 1997) and classification from the compressed satellite imageries (Paola and Schowengerdt, 1995; Correa *et al.*, 1998). In this study, particular attention has been paid to the effect of compression on the accuracy of image mensuration and PPD. A particular type of compression technique, JPEG, will be investigated. JPEG is selected because it has been


Dept. of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Kowloon, Hong Kong (lszlli@polyu.edu.hk).

X. Yuan is also with the School of Information Engineering, Wuhan University, Wuhan 430079, P.R. China (yxxqxhyw@public.wh.hb.cn).

K.W.K. Lam is also with Brilliant Technology Development Limited, Hong Kong



Photogrammetric Engineering & Remote Sensin[g]
Vol. 68, No. 8, August 2002, pp. 847–853

0099-1112/02/6808–847$3.00/[0]



© 2002 American Society for Photogrammetr[y] and Remote Sensin[g]

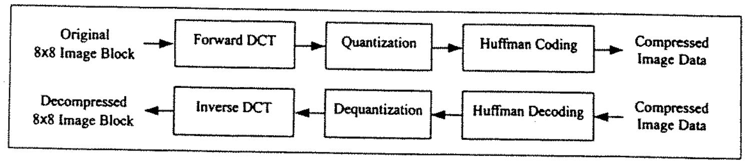



Figure 1. JPEG baseline compression scheme.

In lossless compression, the fidelity is 1.0 and the PSNR is infinite. When $\delta$ is equal to 1, the PSNR is 48.0 while, when $\delta$ equals 2, the PSNR is 42.0. One can regard image compression as near-lossless compression when the fidelity is more than 0.99 and the PSNR is above 42.0 (Xuan and Hu, 1999). Near-lossless compression means that the RMS of the gray values between pixels of the original and reconstructed images is less than the quantized noise in the radiometry, and positioning accuracy goes beyond the distortion of the sensor in the geometry.

## Design of this Experimental Study

### Platform and Test Area

JPEG has been implemented in all digital photogrammetric workstations (DPW). In this institution, an Intergraph DPW is available to the authors and was therefore used in this study.

A stereo pair of aerial photographs covering the Diamond Hill area of Hong Kong was used in this experiment (Figure 2). The photographs were taken from a flying height of about 1200 m (4,000 ft). The scale was 1:8,000. The area covers different land-cover types such as urban area with high rise buildings, a quarry site, a cemetery, and a hillside with medium vegetation coverage.

Approximately 160 Mbytes of raw image data were obtained by scanning these two photographs at a resolution of 25 $\mu$m using a Heleva scanner. Image mensuration was performed with the ISDM (ImageStation Digital Mensuration) tool of Intergraph DPW.

### Evaluation of the Effects of JPEG Compression on Image Quality

Equations 3 and 4, given in the previous section, address pictorial quality, i.e., how the pixel values are changed after compression, in comparison with the original image. This kind of measure is about visual satisfaction and is not of great interest to mapping scientists. Indeed, to this group of people, the geometric and thematic quality is the main concern.

Thematic quality means the accuracy of image classification. Classification accuracy is expected to decrease if compressed images are used. This is outside the scope of this study.

In this study, geometric quality is of great concern. Here geometric quality means the accuracy of photogrammetric measurement. Digital terrain models (DTM) and photogrammetric point determination (PPD) are typical results of photogrammetric measurement. An evaluation of the effect of JPEG compression on DTM accuracy has been conducted by Lam *et al.* (2001). In this paper, the effect of JPEG compression on the accuracy of PPD is investigated.

Because this investigation is about how JPEG compression affects PPD, only a relative evaluation was conducted. In other words, the 3D coordinates of the points determined using the original images were used as reference values. The 3D coordinates of the same points, determined using the images compressed at various levels, were then compared with the reference values to produce RMS values. The RMS values are used to indicate the quality of PPD. The distribution of the points to be evaluated is shown in Figure 3.

Figure 2. A photograph of the test area.

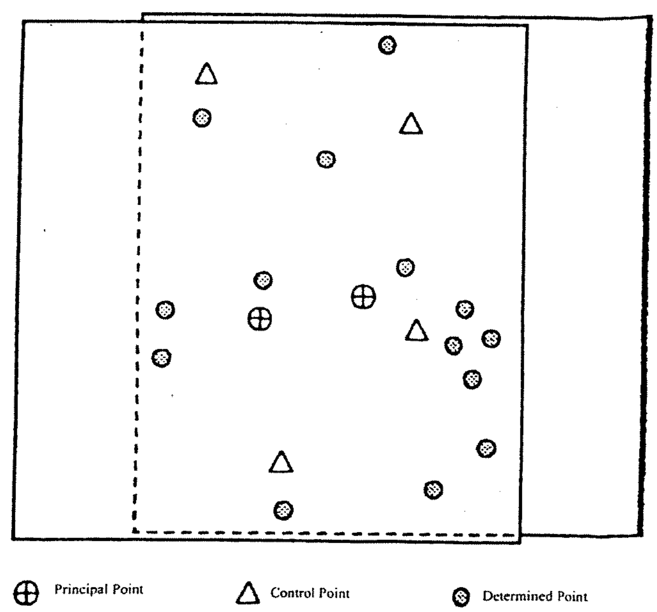



Figure 3. The distribution of photogrammetrically determined points.

TABLE 1. ACCURACY OF INTERIOR ORIENTATION IN LEFT IMAGE

| Q-Factor | 0 | 1 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ratio | | 1.93 | 5.10 | 7.94 | 10.86 | 13.35 | 15.60 | 17.77 | 19.97 | 21.98 | 24.03 |
| Fidelity | | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 0.998 | 0.998 | 0.998 | 0.998 | 0.998 |
| PSNR | | 54.55 | 43.16 | 41.25 | 40.23 | 39.41 | 38.76 | 38.20 | 37.69 | 37.23 | 36.81 |
| $\sigma_0/\mu m$ | 5.0 | 5.0 | 5.1 | 4.9 | 5.0 | 4.8 | 5.2 | 5.1 | 5.2 | 5.1 | 5.2 |

TABLE 2. ACCURACY OF INTERIOR ORIENTATION IN RIGHT IMAGE

| Q-Factor | 0 | 1 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ratio | | 1.92 | 5.08 | 7.84 | 10.77 | 13.25 | 15.46 | 17.56 | 19.68 | 21.62 | 23.60 |
| Fidelity | | 1.000 | 1.000 | 0.999 | 0.999 | 0.999 | 0.999 | 0.998 | 0.998 | 0.998 | 0.998 |
| PSNR | | 54.54 | 43.06 | 41.13 | 40.12 | 39.32 | 38.68 | 38.13 | 37.62 | 37.17 | 36.75 |
| $\sigma_0/\mu m$ | 4.9 | 4.9 | 5.1 | 5.0 | 5.1 | 5.3 | 5.0 | 5.5 | 5.5 | 5.6 | 5.2 |

### Selection of Compression Level: Q-Factor vs Compression Ratio

As discussed above, in JPEG compression the compression level of an image can be controlled by a constant, which is generally called the quality factor (Q-factor). A higher Q-factor gives higher compression. A lower Q-factor gives a better quality image, but a lower compression ratio. Therefore, variable compression can be achieved by simply scaling the Q-factor. An important property of the JPEG scheme is the adjustment of the Q-factor to balance the reducing image size and degraded image quality. In fact, different JPEG compression programs have different Q-factors. In JPEG compression as applied in the Intergraph DPW, the Q-factors can be valued from 1 to 250 and the default value is 30.

In this experimental study, a number of compression levels with Q-factors ranging from 0 to 100 were tested, at intervals of 10. As a particular case, a compression level with Q-factor equal to 1 was also tested. In this particular case, the compression ratio varies from 1 (i.e., when Q = 0) to 26 (i.e., when Q = 100).

## Experimental Testing and Results

### Procedures

In this study, the pair of digital images was first compressed at various levels, using Q = 0, 1, 10, 20, . . ., 100. The Ratio, Fidelity, and PSNR of the left and right images are listed in Tables 1 and 2, respectively. Figure 4 shows the effect of changing the Q-factors on compression ratio and PSNR.

PPD was implemented in each of these compression settings. Each of these compressed image pairs was used for PPD. PPD consists generally of three steps:

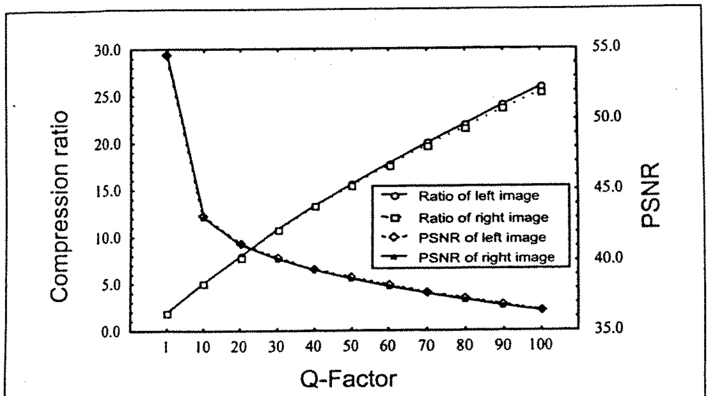



Figure 4. Compression ratio and PSNR vs. Q-factors.

- image mensuration,
- field survey of ground control points, and
- photogrammetric adjustment of image observation the minimum number of ground control points.

The flow chart of photogrammtric point determ as shown in Figure 5.

### Effect of JPEG Compression on the Accuracy of Orientations

The accuracy of the 3D coordinates of the photogra points is influenced by the errors occurring in each c steps described above.

The interior orientation of the image is the first s to establish the relationship between the pixel and t coordinate system. It is always implemented throug or automated mensuration of fiducial marks. The ac the interior orientation is determined by using the R residuals of the 2D coordinates of the fiducial marks this study, semi-automated interior orientation was using four fiducial marks in the image corners whic manually determined, and the accuracy of the interi tion was 5.0 $\mu$m. This result is similar to those repor ers, e.g., 0.13 pixels by Lue (1997). The effect of JPEG sion on the accuracy of interior orientations is also s Tables 1 and 2.

The next step of PPD is relative orientation to de relative position and attitude of two images with res another. After this step, a stereo model was formed b ing the $y$-parallax at all pass and tie points. The accu ative orientation is determined by the RMS of all $y$-p siduals. Although automated relative orientation i accurate, robust, and reliable (Heipke, 1997), the op had to manually measure all pass points in this stud only an Intergraph DPW without ISAT (ImageStation automated point measurement, and bundle adjustr gram) was available to the authors and used in our t

Eighteen passpoints well distributed over the m then measured stereoscopically (Figure 3). These p included four artificial points in the playgrounds, f points of some building tops, four control points pr on buildings, and six identifiable object points. Th were very clear in both of the original images. A sa these points is shown in Figure 6. In this figure, the compression on the position determination of these is also shown. The effect of JPEG compression on the relative orientation is shown in Figure 7.

In order to get the approximation of the exterio elements and 3D coordinates of the passpoints, the model was registered to the ground by absolute ori was implemented by using three or more ground co well distributed over the model. The RMS of the resi

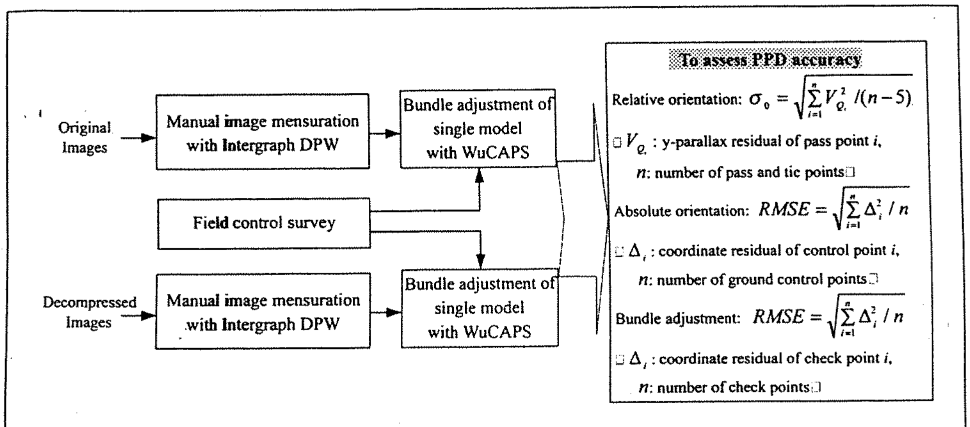
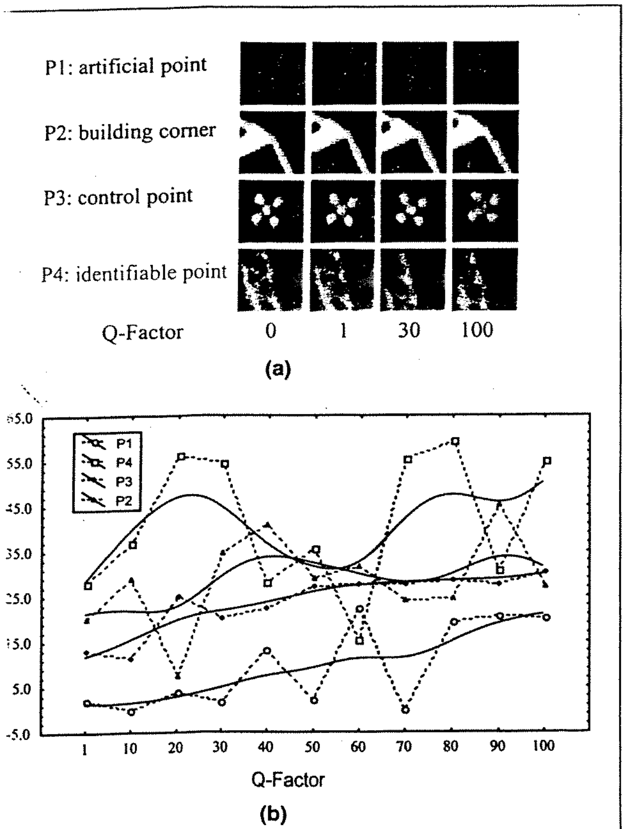



Figure 5. Flowchart of photogrammtric point determiniation.




…ıre 6. Position difference between original and JPEG com-…ssed images vs. Q-factors. (a) Feature points at various …actors. (b) Position changes of points with Q-factors.

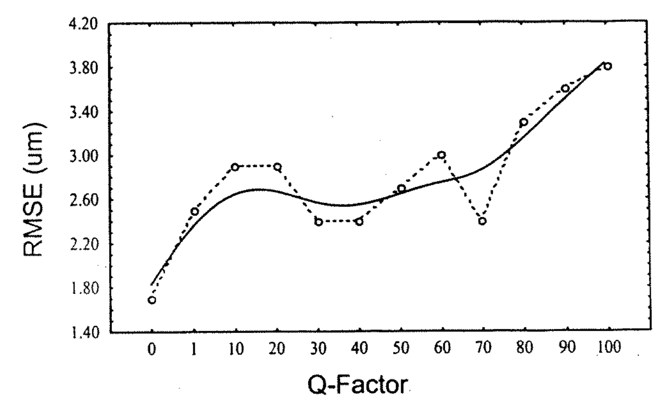



Figure 7. Accuracy of relative orientation vs. Q-factors.

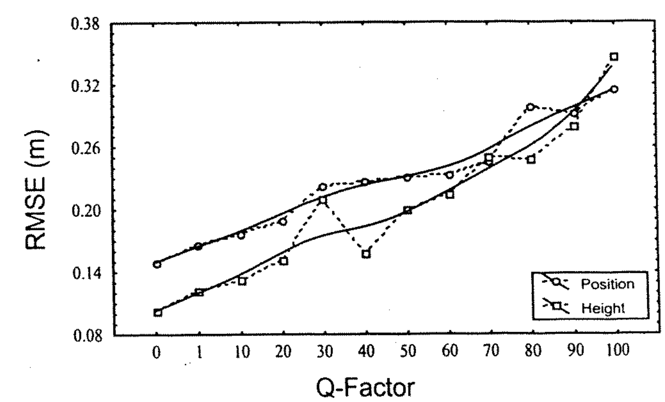



Figure 8. Accuracy of absolute orientation vs. Q-factors.

…rdinates on these control points is used as a measure of …curacy of absolute orientation. The effect of JPEG compres-…n the accuracy of absolute orientation is shown in Fig-…

### …f JPEG Compression on the Accuracy of PPD

…nal step of PPD is the adjustment of image observations. In …udy, bundle adjustment of a single model was carried out … WuCAPS$_{GPS}$, a GPS-supported bundle block adjustment …n developed by Yuan (2000). The PPD result shows that …nit weight standard deviation of image measurements was $\sigma_0 = 2.8\ \mu m$, and the theoretical accuracy of the 3D coordinates of the pass points were $m_X = 4.7\ cm$, $m_Y = 5.2\ cm$, $m_{XY} = 7.0\ cm$, and $m_Z = 20.1\ cm$ on the ground, respectively.

The final PPD accuracy is interesting in photogrammetric applications and is often assessed by using the RMS of the 3D coordinates of all checkpoints. In this study, 14 passpoints, excluding control points, were used as checkpoints. As stated

Table 3. Accuracy of PPD with JPEG Compressed Image Pairs

| Q-Factor | Relative orientation $\sigma_0$ ($\mu$m) | Absolute orientation (m) | | | | Bundle adjustment (m) | | | | | d |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $X$ | $Y$ | $XY$ | $Z$ | $\sigma_0$ ($\mu$m) | $X$ | $Y$ | $XY$ | $Z$ | › |
| 0 | 1.7 | 0.05 | 0.14 | 0.149 | 0.103 | 2.8 | 0.047 | 0.052 | 0.070 | 0.201 | |
| 1 | 2.5 | 0.08 | 0.15 | 0.167 | 0.122 | 5.4 | 0.13 | 0.22 | 0.254 | 0.270 | 2 |
| 10 | 2.9 | 0.08 | 0.16 | 0.176 | 0.133 | 7.3 | 0.07 | 0.26 | 0.272 | 0.334 | 2 |
| 20 | 2.9 | 0.11 | 0.15 | 0.190 | 0.151 | 5.7 | 0.17 | 0.20 | 0.268 | 0.341 | 2 |
| 30 | 2.4 | 0.10 | 0.20 | 0.222 | 0.210 | 6.5 | 0.15 | 0.24 | 0.288 | 0.346 | 3 |
| 40 | 2.4 | 0.12 | 0.19 | 0.226 | 0.157 | 5.6 | 0.13 | 0.29 | 0.312 | 0.395 | 3 |
| 50 | 2.7 | 0.12 | 0.20 | 0.232 | 0.200 | 5.9 | 0.17 | 0.28 | 0.329 | 0.417 | 3 |
| 60 | 3.0 | 0.12 | 0.20 | 0.234 | 0.215 | 8.2 | 0.18 | 0.28 | 0.332 | 0.406 | 3 |
| 70 | 2.4 | 0.11 | 0.22 | 0.245 | 0.251 | 4.6 | 0.16 | 0.33 | 0.367 | 0.409 | 4 |
| 80 | 3.3 | 0.14 | 0.24 | 0.298 | 0.247 | 8.2 | 0.16 | 0.30 | 0.341 | 0.452 | 3 |
| 90 | 3.6 | 0.15 | 0.25 | 0.291 | 0.280 | 7.0 | 0.21 | 0.33 | 0.391 | 0.491 | 4 |
| 100 | 3.8 | 0.15 | 0.28 | 0.316 | 0.347 | 7.0 | 0.20 | 0.36 | 0.412 | 0.555 | 4 |

Remarks:
(1) Q-Factor = 0 denotes original image. The accuracy of the bundle adjustment is theoretical accuracy $m_i = \sigma_0 \sqrt{(Q_{XX})_i}$, ($i = X, Y, X$
$\sigma_0$ is the unit weight standard deviation of image measurements; $Q_{XX}$ is the variance-covariance matrix.
(2) Q-Factor from 1 to 100 denotes JPEG compressed images with various levels. The accuracy of the bundle adjustment is the root-ı
errors of coordinate differences of passpoints, i.e., $\mu_i = \sqrt{\Sigma\Delta_i^2/14}$ ($i = X, Y, Z$); $\mu_{XY} = \sqrt{\mu_X^2 + \mu_Y^2}$.
(3) The accuracy degeneration of PPD is $(\mu_i - m_i)/m_i$. ($i = XY, Z$).

previously, the 3D coordinates of these points, determined using the original image pair, were used as reference values and, therefore, the accuracy assessment is used to compare other 3D coordinates of the checkpoints with these reference values. The comparison was done on a point-by-point basis (see Table 3). The results are shown in Table 3 and Figure 9. As stated previously, this accuracy is shown in a relative sense.

## Analysis of Results

Figure 4 shows that the compression ratios increase almost linearly and image quality falls with an increase in the Q-factor. It can also be seen that there is a sudden transition in image quality on compressing with Q-factors of 1 to 10. The degradation trends of the image quality were then slow with increasing compression ratios. According to the criteria in the section on Principles of the JPEG Compression Technique, the compressions are near-lossless when Q-factors are under 20. When Q-factors are over 20, the compressions are lossy. From this experiment, it can be noted that the JPEG compression with a Q-factor of 30 (or compression ratio equal to 10), which is recommended by Intergraph DPW, is near-lossless.

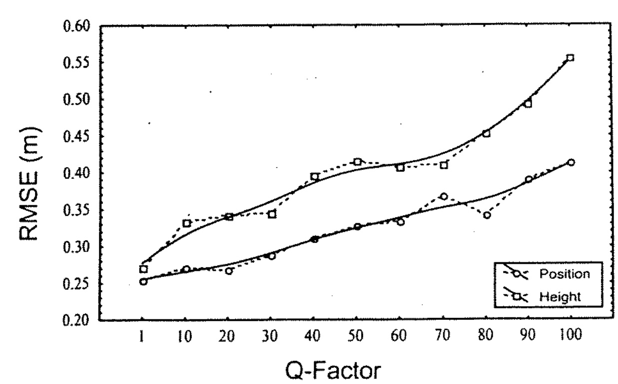



Figure 9. Overall (relative) accuracy of bundle adjustment vs. Q-factors.

From Tables 1 and 2, it can be concluded that thє of interior orientation remains almost unchanged wi crease in Q-factor (up to 100). This is because, althou ages of fiducial marks become more blurred with the in compression ratios, one can still recognize and acc cate their central points due to their very regular "c shapes. In addition, some systematic errors, for exan metric distortion, are compensated by the affine tran the adjustment of interior orientation. In this study, i that the geometric distortion of the compressed ima small, and the image coordinate system is not affecte compression ratio is under 25. This is very importan copy photogrammetry.

Figure 7 shows that the higher the compression poorer the accuracy of the relative orientation. The ir RMS is almost linear when the Q-factor is smaller tha larger than 70. From Q = 0 to Q = 100, the RMS value twofold. This is a consequence of the change in the p the feature points used for relative orientation. As sł Figure 6, such a change in position for artificial point corners, and control points is very clear.

Figure 8 shows the variation of the RMS of absolu tion with compression ratio. With an increase in con ratio, the increase in RMS is quite linear, and the RMS is larger than that in height.

Figure 9 depicts the RMS of PPD in both position a These RMS values are computed from the difference checkpoints both in planimetry and height. From thi can be seen that PPD accuracy falls off rapidly with aı in compression ratio. It seems that the increase is als ear. Table 3 lists the detailed quantification of the RN eration:

- 263 percent in planimetry and 34 percent in heig factor of 1,
- 311 percent in planimetry and 72 percent in heig factor of 30, and
- 488 percent in planimetry and 176 percent in heiį factor of 100.

On the other hand, if one only looks at the result 1, then the increase in RMS is not that great. From Fiį also appears that the RMS values in height for Q = 10,

ıost identical. This might be the reason that the In-
ɔh recommends a compression ratio of 10:1, which cor-
ıds to a Q-factor of 25 in this case.

## ʻusions

ʻ paper, an experimental investigation into the effect of ompression on the accuracy of PPD is reported. The ex-ent was conduced on an Intergraph DPW. A review of JPEG ʻession on the Intergraph DPW is first given; the design of ʻudy is then outlined, followed by a report of the results. ʻalysis of the results is also presented. Instead of dis-ʻg only the final results of PPD, the intermediate results for or, relative, and absolute orientations are also reported nalyzed. It is hoped that this will provide a more com-picture.

ʻhe empirical results show that, when the compression ra-ʻe smaller than 10, the JPEG compression is near-lossless. ıeans that the visual quality of the compressed images is ʻxcellent, i.e., without noticeable degeneration in picto-ʻuality. Theoretically speaking, in such a case, manual ʻuration is still of great accuracy, and the accuracy loss in ʻal PPD is acceptable for most photogrammetric applica- However, no indication can be found from the results compression of 10 is the critical value or the optimum ʻression level for PPD. Indeed, it is clear that the degrada-ʻf accuracy in PPD is almost linear.

## ʻowledgments

ʻork described in this paper was supported by a grant from ʻsearch Grants Council of the Hong Kong Special Admin-ʻve Region (Project No. PolyU 5091/97E). The authors ʻl also like to express their thanks to Professor Jiabin Xuan ʻIr. Qingwu Hu of the Wuhan Technical University of Sur-ʻg and Mapping for providing their compression software ʻting.

## ʻences


ʻi, D.A., 1996. Compression of remotely sensed data using JPEG, ʻternational Archives of Photogrammetry and Remote Sens-ʻg*, 31(B3):24–28.

ʻ. A.C., A.J. Blanchard, and J. Becker, 1998. The impact of lossy ʻmpression on the output of supervised and unsupervised classi-ʻcation products, *Proceedings of International Geoscience and ʻemote Sensing Symposium*, 06–10 July, Seattle, Washington, 1745–1747.

ʻe, C., 1997. Automation of interior, relative, and absolute orienta-ʻon, *ISPRS Journal of Photogrammetry & Remote Sensing*, ʻ2(1):1–19.

ʻrd, P.G., F. Kossentini, B. Martins, S. Forchhammer, and W.J. ʻucklidge, 1998. The emerging JBIG2 standard, *IEEE Transactions ʻn Circuits and Systems for Video Technology*, 8(7):838–848.

ʻola, J., and E. Orava, 1994. The effect of pixel size and compression ʻn metric quality of digital aerial images, *International Archives ʻf Photogrammetry and Remote Sensing*, 30(3/1):409–415.

ʻn, D.J., and S.J. Hannah, 1993. Comparative analysis of image ʻompression techniques, *Proceedings SSST '93, The 25th South-ʻstern Symposium on System Theory*, March, Tuscaloosa, Ala-ʻma, pp. 513–517.

Lam, K., Z.L. Li and X.X. Yuan, 2001. Effect of JPEG compression on the Accuracy of DTM, *Photogrammetric Record*, 17(98):331–342.

Lammi, J., and T. Sarjakoski, 1992. Compression of digital color images by the JPEG, *International Archives of Photogrammetry and Remote Sensing*, 29(B2):456–460.

———, 1995. Image compression by the JPEG algorithm, *Photogrammetric Engineering & Remote Sensing*, 61(10):1261–1266.

Lue, Y., 1997. One step to a higher level of automation for softcopy photogrammetry automated interior orientation, *ISPRS Journal of Photogrammetry & Remote Sensing*, 52(3):103–109.

Memon, N.D., K. Sayood, and S.S. Magliveras, 1994. Lossless compression of multispectral image data, *IEEE Transactions on Geoscience and Remote Sensing*, 32(2):282–289.

Mikhail, E.M., M.L. Akey, and O.R. Mitchell, 1984. Detection and subpixel location of photogrammetric targets in digital images, *Photogrammetria*, 39(3):63–83.

Nunes, P.R.R.L., A. Alciam, and M.R.L.F. da Silva, 1992. Compression of satellite images for remote sensing applications, *International Archives of Photogrammetry and Remote Sensing*, 29(B2): 479–483.

Novak, K., and F.S. Shahin, 1996. A comparison of two image compression techniques for softcopy photogrammetry, *Photogrammetric Engineering & Remote Sensing*, 62(6):695–701.

Paola, J.D., and R.A. Schowengerdt, 1995. The effect of lossy image compression on image classification, *Proceedings of International Geoscience and Remote Sensing Symposium—Quantitative Remote Sensing for Science and Applications*, 10–14 July, Florence, Italy, 1:118–120.

Pennebaker, W.B., and J.L. Mitchell, 1993. *JPEG Still Image Data Compression Standard*, Van Nostrand Reinhold, New York, N.Y., 638 p.

Reeves, R., K. Kubik, and Y.H. Lu, 1997. JPEG comparison and DTM accuracy, *Technical Papers of 1997 ACSM/ASPRS Annual Convention and Exposition*, 07–10 April, Seattle, Washington, 2:342–346.

Tada, T., K. Cho, H. Shimoda, and T. Sakata, 1993. An evaluation of JPEG compression for on-line satellite image transmission, *Proceedings IGARSS'93, Geoscience and Remote Sensing Symposium on Better Understanding of Earth Environment*, 18–21 August, Tokyo, Japan, 3:1515–1518.

Tichem, M., and M.S. Cohen, 1994. Sub$\mu$m registration of fiducial marks using machine vision, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 16(8):791–794.

Trinder, J.C., 1989. Precision of digital target location, *Photogrammetric Engineering & Remote Sensing*, 55(6):883–886.

Trinder, J.C., J. Jansa, and Y. Huang, 1995. An assessment of the precision and accuracy of methods of digital target location, *ISPRS Journal of Photogrammetry & Remote Sensing*, 50(2):12–20.

Wallace, G.K., 1991. The JPEG still picture compression standard, *Communication of ACM*, 34(4):27–142.

Wang, C.S., B.X. Yu, Y.S. Dai, and D.H. Wen, 2000. A transform coding compression of hyperspectral image with its edge features retained, *Journal of Remote Sensing*, 4(2):95–99 (in Chinese).

Xuan, J.B., and Q.W. Hu, 1999. The technique of quasi-lossless compression of remote sensing image, *Journal of Wuhan Technical University of Surveying and Mapping*, 24(4):290–294 (in Chinese).

Yuan, X.X., 2000. Principle, software and experiment of GPS-supported aerotriangulation, *Geo-Spatial Information Science*, 3(1):24–33.

Zhang, R., Z.K. Liu, and S. Zhan, 2000. Wavelet-based compression for multispectral imagery, *Journal of Remote Sensing*, 4(2):100–105 (in Chinese).


(Received 03 January 2001; accepted 16 January 2002; revised 07 February 2002)