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EFFECTS OF JPEG COMPRESSION ON THE ACCURACY OF DIGITAL TERRAIN MODELS AUTOMATICALLY DERIVED FROM DIGITAL AERIAL IMAGES

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Abstract

It is well recognised that data volume represents a huge overhead for softcopy photogrammetry. For example, a file size of 100 Mbytes will be generated from a black and white aerial photograph if digitised with a resolution of 20 μm. Large data volumes not only create storage problems but also affect the speed of image processing. As a consequence, data compression of image data is a matter of great significance. This paper describes an investigation into the effects of image compression on the accuracy of digital terrain models (DTMs) extracted from the compressed images. The JPEG system implemented in the Z/I Imaging ImageStation digital photogrammetric workstation (DPW) was used in the study. A systematic test has been carried out on the effect of different levels of JPEG compression (with Q-factors from 1 to 100) on the resulting DTM, which is automatically generated by the DPW using Match-T software. An analysis of the results from the two sites tested shows that image compression tends to cause more significant degradation when the image texture is richer, but that recommendations on Q-factors for use with the ImageStation appear to err on the side of caution. This analysis leads to some tentative conclusions and recommendations both for future investigation and for photogrammetric practice.

Keywords: digital photogrammetric workstation, DTM accuracy, JPEG compression, softcopy photogrammetry

Introduction

With the development of computer and information technology, photogrammetry has stepped into a softcopy photogrammetric era. In softcopy photogrammetry, the

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inputs are digital images either captured directly from digital sensors or hardcopy photographs converted using a scanner. Final products can also be in a digital format, such as Digital Terrain Models (DTMs), Digital Orthophoto Quadrants (DOQs) and Digital Line Graph (DLG) databases. However, the volume of data can be a problem with digital imagery, both in terms of storage and transmission. For example, a black and white digital aerial image scanned at a resolution of 20 μm contains approximately 10 000 × 10 000 pixels or 100 Mbytes of data. Using such huge volumes of data is one of the critical issues in softcopy photogrammetry.

A number of compression techniques have been developed and can now be described as mature. They can be broadly classified into two categories: *lossless* compression, such as the Lempel-Ziv and Joint Bi-level Experts Group (JBIG) methods (Howard et al., 1998) and *lossy* compression, including the Joint Photographic Experts Group (JPEG) method, and 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 on a pixel-by-pixel basis. This is of course the ideal case. However, the maximum compression ratio for such a method may only reach about four if the image context is rather complex (Wang et al., 2000). Lossy compression, on the other hand, allows for degradation of the reconstructed image in exchange for a higher degree of compression in data volume. This degradation may or may not be visually apparent. Greater compression ratio can be achieved by allowing a higher degree of degradation. As a consequence, the resultant images will have poorer geometric or radiometric quality. However, for many applications, there is no need for high accuracy and thus a higher degree of degradation might be well acceptable. The most important requirement is to know how the image quality is affected with different levels of compression. This study therefore examines lossy techniques.

In recent years, image compression has been an important topic in photogrammetry. Some researchers have devoted effort to the development of compression algorithms for airborne or spaceborne remotely sensed imagery (Lammi and Sarjakoski, 1992; Memon et al., 1994; Algarni, 1996; Xuan and Hu, 1999; and Wang et al., 2000). Others have evaluated the effects of lossy compression on the geometric quality of digital aerial images (Mikhail et al., 1984; Nunes et al., 1992; Tada et al., 1993; Jaakkola and Orava, 1994; Lammi and Sarjakoski, 1995; and Novak and Shahin, 1996) and on classification from compressed satellite imagery (Paola and Schowengerdt, 1995 and Correa et al., 1998). In this study, special attention has been paid to the effect of compression on one specific type of product, DTMs automatically derived from compressed images. Just one compression technique (JPEG) was selected for investigation because this has come to be considered as an industrial standard and it has been implemented in almost all DPWs.

This introduction is followed by a description of the basic principles of image compression. The implementation of the JPEG algorithm in the Z/I Imaging ImageStation DPW is then described, this being the equipment used in this study. This is followed by a description of the experimental test procedures and the results are then reported and analysed.

BASIC FEATURES OF IMAGE COMPRESSION

In order to make the test results more understandable and more meaningful, a brief description of the key concepts in image compression is given here. More detailed information can be found in Pennebaker and Mitchell (1993) and Wallace (1991).

General Principle of Lossy Compression

It can be observed that, in most areas of an image, the grey values of adjacent pixels are highly correlated. This means that a great deal of information about the grey value of a pixel can be obtained by inspecting its neighbours. Therefore, image pixels can be represented by a smaller number of grey values (represented by a smaller number of bits), rather than the full range of 256 levels (8 bits), through the removal or reduction of this correlation between these pixels. To achieve the best representation of an image with a minimum number of bits, image compression is normally performed in three steps.

(1) *Transform.* This procedure uses a mathematical transformation, such as a discrete cosine transform (DCT) or wavelet transform, to transform the original image to a different coordinate basis so as to reduce the dynamic range of the grey values and to eliminate the correlation among the original grey values. After transformation, the original image is transformed to a new domain, such as the frequency domain, and the number of grey values is much smaller than in the original.

(2) *Quantisation.* In this step the transformed grey values are mapped onto a smaller and finite number of output levels, in order to reduce the number of possible output symbols. The reduction of the number of output symbols leads to degradation in the reconstructed image quality. Thus the quantisation stage is a lossy process.

(3) *Coding.* To reduce the volume of the image data further, the stream of small integers is replaced by a more efficient alphabet of variable-length characters. Huffman coding is a commonly used method.

Image Compression Ratio

The image compression ratio is generally defined as the ratio of the number of bytes of the original image before compression and the number of bytes of the compressed image. It can be expressed as follows:

$$\text{compression ratio} = \frac{\text{original image data volume}}{\text{compressed image data volume}}. \tag{1}$$

For an n-bit image, according to Shannon's first theorem, a maximum compression ratio can be achieved when the image coding results in bits-per-pixel rates equal to the image entropy (Carreto-Castro et al., 1993), which may be written as:

$$\text{compression ratio}_{\max} = \frac{\log_2 M}{H} \tag{2}$$

where $M = 2^n$ is the number of grey levels in the image and H is the image entropy, expressing the minimum number of bits necessary for the representation of an image without any loss of information.

Measures for Quality Evaluation of Compressed Images

In image compression, the quality of a reconstructed image can be evaluated by two measures: *fidelity* and *peak signal-to-noise ratio* (PSNR). Fidelity is the similarity between the original and the reconstructed image, that is, a measure of geometric distortion of the reconstructed image. PSNR represents, however, radiometric degradation of the reconstructed image. For an 8-bit image with $m \times n$ pixels, these measures of quality can be expressed as follows:

$$\text{fidelity} = \sum_{i=1}^{m} \sum_{j=1}^{n} (g_{ij} * g'_{ij}) \Big/ \sum_{i=1}^{m} \sum_{j=1}^{n} g_{ij}^2 \tag{3}$$

$$\text{PSNR} = 20 \log\left(\frac{255}{\delta}\right) = 48 - 20 \log \delta \tag{4}$$

where g_{ij} and g'_{ij} are the grey values of the original and reconstructed images respectively, and

$$\delta = \sqrt{\frac{1}{mn} \sum_{i=1}^{m} \sum_{j=1}^{n} (g_{ij} - g'_{ij})^2} \tag{5}$$

is the root mean square error that represents the grey differences between the original and the reconstructed image. This is one numerical measure for determining the accuracy of a compressed image.

In lossless compression, the fidelity is 1·0 and PSNR is infinite. When δ is equal to 1, the PSNR is 48·0. When δ equals 2, the PSNR is 42·0. One can regard image compression as near-lossless when the fidelity is more than 0·99 and the PSNR is above 42·0 (Xuan and Hu, 1999). The near-lossless compression means that in the radiometry the rms error of the grey values between pixels of the original and reconstructed image is less than the quantised noise, and that in the geometry the positioning accuracy goes beyond the distortion of the sensor.

JPEG IMAGE COMPRESSION IN THE Z/I IMAGING IMAGESTATION

JPEG compression, which is the international standard for compressing continuous tone still photographic images, was established by the committee known as the Joint Photographic Experts Group, within Working Group 1 of ISO SC29. The JPEG standard contains four modes of operation: sequential encoding, progressive encoding, lossless encoding and hierarchical encoding. Sequential encoding is DCT-based and progressive encoding is a lossy technique. The lossless mode is based on a predictive method. The hierarchical mode encodes the image at multiple spatial resolutions using either DCT-based compression or the lossless mode. Although JPEG provides a number of possibilities for encoding, it also gives a basic compression scheme, baseline sequential encoding, for straightforward use. JPEG compression in the ImageStation is based on this scheme, to reduce the volume of original images. Fig. 1 indicates the sequential steps of the JPEG baseline compression scheme.

The JPEG baseline system starts by dividing the original image into blocks of 8×8 pixels. Each block is independently transformed into the frequency domain using the DCT. Next, the resulting DCT coefficients are normalised by applying a

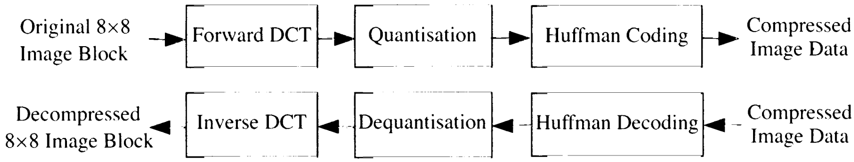


FIG. 1. JPEG baseline compression scheme.

user-defined normalisation array that is fixed for all blocks. The normalised coefficients are then uniformly quantised by rounding to the nearest integer. These quantised coefficients are formatted into a one dimensional (vector) array using the zigzag ordering scheme. This zigzag ordering rearranges the coefficients in approximately decreasing order. Many coefficients towards the end of the array are zero. From the above description one can easily imagine that different normalisation arrays will yield different compression ratios and image quality. The level of compression of an image can be modified by changing this array, for example by scaling it by a constant multiplier. This constant is generally called the quality factor (Q-factor). Finally, one lossless encoding module, Huffman coding, can be used to encode the quantised coefficients. The resultant image is efficiently compressed and can be reproduced with virtually no visually detectable loss.

It is noted here that at the quantisation stage one may adjust the Q-factor to change the degree of loss. A higher Q-factor gives a higher compression ratio, and a lower Q-factor gives a better quality image but a lower compression ratio. Therefore, variable compression is achieved simply by scaling the Q-factor. This adjustment of Q-factor to balance the reducing image size and degraded image quality is an important property of the JPEG compression scheme. In fact, different JPEG compression programs can have substantially different Q-factors. In the JPEG compression scheme used in the ImageStation, the Q-factors can range from 1 to 250 and the default value is 30.

EXPERIMENTAL TESTING

To study the quality of JPEG compressed images and the potential of applying JPEG compression in softcopy photogrammetry, experiments have been carried out using the ImageStation in accordance with the procedure illustrated in Fig. 2.

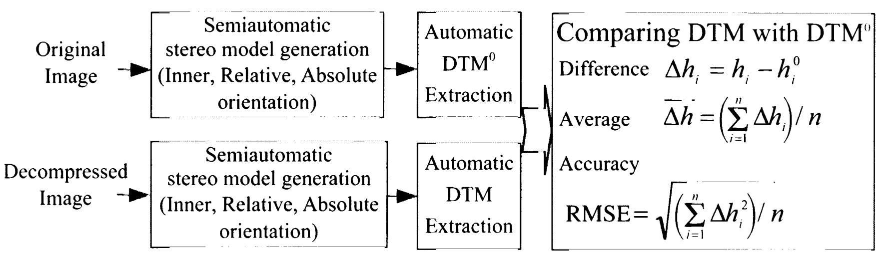


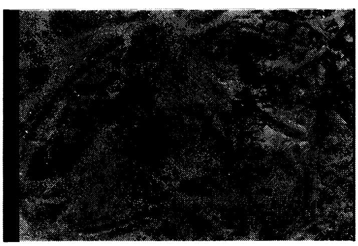
FIG. 2. Flow diagram of DTM extraction by ImageStation.

A stereopair of 1:8000 scale aerial black and white photographs covering the Diamond Hill area of Hong Kong was used. Approximately 160 Mbytes of raw image data was obtained by scanning the two photographs at a resolution of 25 μm. Both Helava and Z/I Imaging Photoscan scanners were used and yielded essentially the same results. Fig. 3 shows original digital sub-images for the two sites selected for testing. Their sizes are 1392 × 1124 pixels and 2641 × 1481 pixels. Both sites have good image texture. Site I covers an abandoned quarry and Site II covers a hillside with medium vegetation coverage. Urban areas with high-rise buildings were not used in this study because of the high rate of mismatching in those areas.

A stereoscopic model was generated for each site using semi-automatic interior and relative orientations performed in the ImageStation. The accuracies of interior and relative orientations were 5·0 μm and 2·5 μm respectively. Absolute orientation was performed using four well-distributed control points by manual measurement. The rms errors of residuals of 3D coordinates on these four control points were 0·162 m, 0·087 m and 0·150 m at ground scale. After forming the model, a DTM was generated automatically using Match-T software in the ImageStation.

The DTMs of the two sites were generated with a 5 m grid interval. Fig. 4 shows the DTMs and their related contours for each site. In the experimental tests, the original images were compressed to various levels by means of JPEG compression. A set of DTMs was then extracted automatically from the compressed image pairs, using the same procedure and the same set of orientation parameters. In the evaluation, the DTM extracted from the original stereoscopic images (without compression) was used as a reference and denoted as DTM^0. The DTMs created using the JPEG-compressed images were then compared with DTM^0 to obtain a set of height differences Δh_i (Fig. 2). The standard deviation of such differences for n points provides a measure of the accuracy degradation caused by JPEG compression (Robinson et al., 1995; Reeves et al., 1997b). The rms errors of these DTMs are listed in Tables I and II. This treatment is appropriate because only relative accuracy is of concern in this study.

Site I has homogenous ground coverage. The image entropy is 5·707 bits per pixel. The maximum ground height difference is 27·05 m. Site II has larger terrain variation with a height range of 95·33 m. The image content is richer and its entropy is 6·142 bits per pixel. The two images were compressed to various levels using Q-factors ranging from 1 to 100. Fig. 5 shows the effect of changing the Q-factors, on the compression ratio and PSNR. DTMs were automatically extracted for each



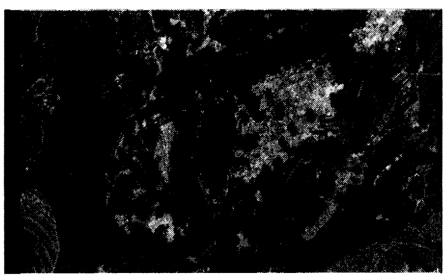


FIG. 3. Original digital aerial sub-images for two sites, scanned with a resolution of 25 μm (Site I (left) and Site II (right)).

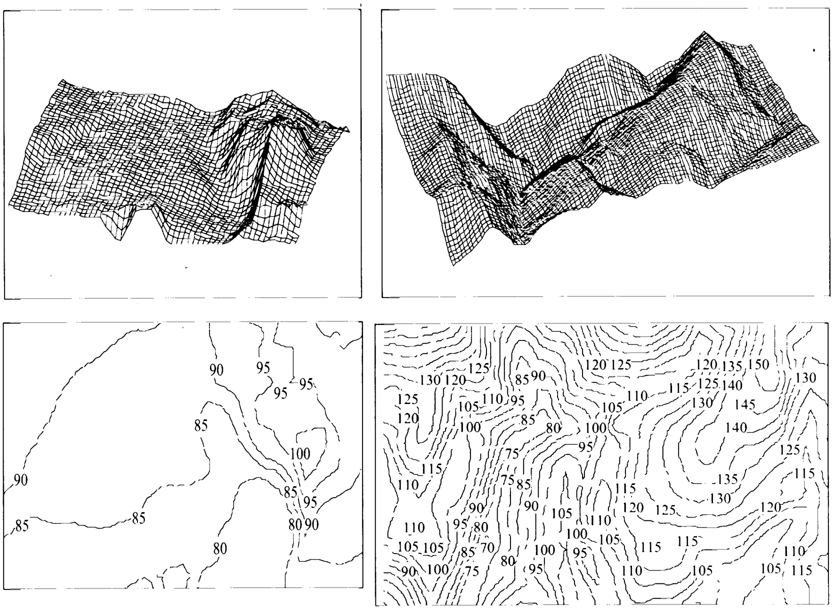


FIG. 4. Perspective view of DTM and contours extracted from original digital aerial images (Site I (left) and Site II (right)).

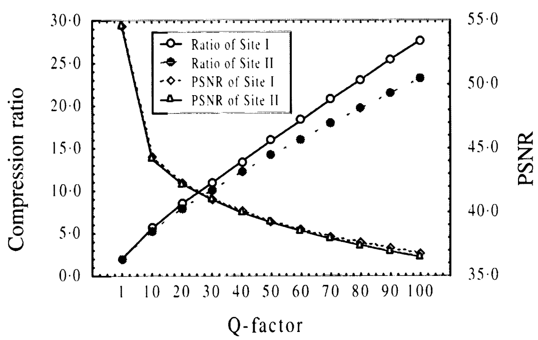


FIG. 5. Compression ratio and PSNR versus Q-factor.

of these compression settings. The heights of these DTMs were compared with the benchmark DTM^0 at regular grid intervals (Tables I and II). Fig. 6 shows the overall trend of accuracy effects on DTMs automatically generated from these JPEG-compressed images.

ANALYSIS OF RESULTS

For these two test images, the maximum achievable compression ratios for lossless compression schemes (in accordance with equation (2)) were $8/5{\cdot}707 = 1{\cdot}4$

TABLE I. Accuracy of DTMs extracted with JPEG-compressed image pairs for Site I.

Q-factor	1	10	20	30	40	50	60	70	80	90	100
Compression ratio	2·06	5·59	8·51	10·94	13·44	15·91	18·29	20·74	23·03	25·44	27·63
Fidelity	1·000	1·000	1·000	1·000	1·000	0·999	0·999	0·999	0·999	0·999	0·999
PSNR	54·51	44·28	42·27	41·05	40·05	39·30	38·67	38·11	37·63	37·19	36·82
Points	1652	1621	1516	1644	1512	1632	1637	1639	1631	1639	1640
$\overline{\Delta h}$ *(m)*	−0·001	−0·007	0·005	0·001	−0·006	−0·023	−0·019	−0·031	−0·035	−0·020	−0·027
Rms error (m)	0·092	0·117	0·142	0·145	0·146	0·164	0·184	0·185	0·213	0·241	0·253

TABLE II. Accuracy of DTMs extracted with JPEG-compressed image pairs for Site II.

Q-factor	1	10	20	30	40	50	60	70	80	90	100
Compression ratio	1·99	5·28	7·96	10·09	12·25	14·21	16·06	17·94	19·68	21·49	23·18
Fidelity	1·000	1·000	0·999	0·999	0·999	0·999	0·998	0·998	0·998	0·998	0·998
PSNR	54·51	44·16	42·22	40·99	39·97	39·18	38·52	37·91	37·39	36·91	36·49
Points	4261	4191	4197	4131	4200	4050	4071	4073	4175	4191	4211
$\overline{\Delta h}$ *(m)*	−0·009	0·019	−0·042	−0·039	−0·014	−0·025	−0·011	−0·014	−0·034	−0·040	−0·036
Rms error (m)	0·171	0·245	0·269	0·295	0·304	0·308	0·329	0·348	0·382	0·400	0·432

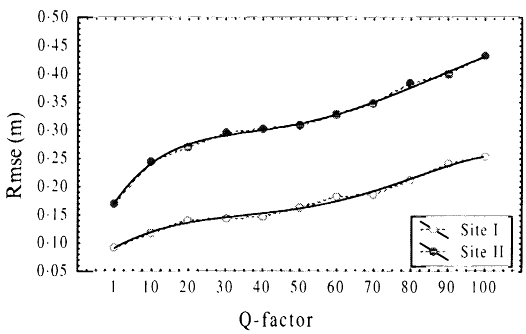


FIG. 6. DTM accuracy versus Q-factor.

for Site I and 8/6·142 = 1·3 for Site II. The lossy JPEG compression ratios with Q-factor 100 are 27·63 for Site I and 23·18 for Site II. This difference between compression ratios of images at the same Q-factor is due to the amount of redundancy available in image I and the large information content in image II.

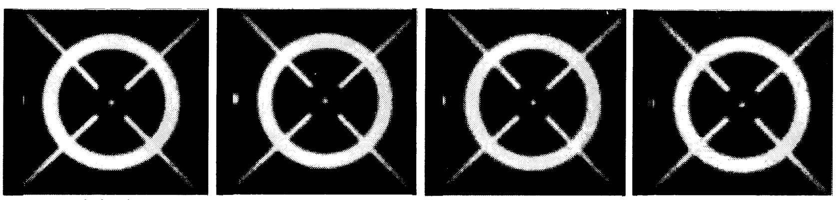
Fig. 5 shows that the rise in compression ratio is close to linear and that image quality falls with increasing Q-factors, while the change amplitude is closely related to the image entropy. The greater the entropy of the original image, that is, the larger the information content, the smaller is the resulting compression ratio. From Fig. 5, however, it can also be seen that there is a linear relationship between Q-factor and PSNR for Q-factors from 1 to 10. Above Q-factors of 10, the degradation of image quality decreases at a slower rate with increasing compression ratios. According to the quality evaluation criteria outlined earlier, the compression is near-lossless when the Q-factor is under 25. For Q-factors over 25, compression is lossy. From this experiment one can conclude that the JPEG compression with a Q-factor of 30 recommended for the ImageStation is close to lossless. In this case, however, the compression ratio reaches approximately 10.

Fig. 7 shows the visual change in reconstructed images. Comparing the images of a fiducial mark, it is clear that the visual quality of the reconstructed image for near-lossless JPEG compression is acceptable. When the compression ratio is more than 10, the reconstructed images blur and some block patterns appear. With higher compression ratios, the block patterns become increasingly obvious. However, Fig. 6 shows that the effect on the accuracy of DTMs extracted automatically from the compressed images is apparent even at the most minimal compression with a Q-factor of 1. Moreover, the more complex the terrain, the greater is the effect on accuracy. In the case of near-lossless JPEG compression recommended by Z/I Imaging for the ImageStation, the loss of DTM accuracy reaches 0·295 m. The rms error value is equivalent to around 0·25 ‰ of the flying height. This is close to the experimental results obtained by others (Reeves et al., 1997a).

In order to examine the significance of relative height errors (that is, differences at DTM grid intersections) caused by lossy JPEG compression, a statistical test was carried out. Here a DTM derived from the images of Site II compressed with Q-factor 30 is taken as an example. A total of 4131 height differences were used, and the expectation and variance of these differences were calculated. These height differences and the corresponding histogram are shown in Fig. 8. From the figure, one can not detect systematic errors in the height differences. The height differences for 63% of the DTM points are less than 0·2 m, and differences for a further 22·7% of DTM points range from 0·2 m to 0·4 m. The probability distribution of the height differences of the whole grid of points compared conforms to the normal distribution. The average height differences of near zero can be seen in Tables I and II. In other words, the average elevation planes of DTMs are unchanged after image compression.

CONCLUSIONS

In this study, the effect of image compression on the accuracy of DTMs automatically extracted from digital aerial images has been investigated. The empirical results show that when the compression ratio is under 10, JPEG compression is



Original Q-factor 30 Q-factor 60 Q-factor 100

FIG. 7. Images of a fiducial mark compressed with various Q-factors.

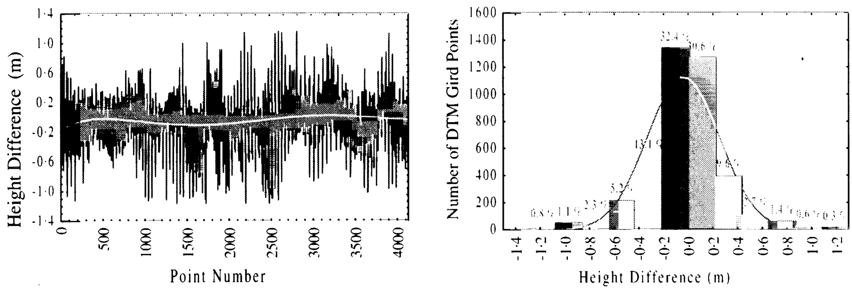


FIG. 8. Height differences between DTMs:
JPEG-compressed (Q-factor 30) versus original images for Site II.

near-lossless and the visual quality of the reconstructed images is excellent, without noticeable degeneration. If manual measurement is used in the ImageStation, the accuracy of the final photogrammetric results will remain essentially unaffected. In this case, the file size of one JPEG-compressed image is only one tenth of the original image volume. On the other hand, if a fully automatic image correlation scheme is used for measurement in the DPW, the photogrammetric results will suffer from some loss of geometric quality. The loss of accuracy would escalate with an increase in compression ratios.

The results also reveal the following:

(1) more significant degradation of image quality will be caused when the image texture is richer;
(2) the trend of quality degradation is curvilinear when the compression ratio is less than 15 and nearly linear when the compression ratio is over 15; and
(3) the level of degradation in image quality with the Q-factor of 30, as recommended by Z/I Imaging for their DPW, is not very different from that with a Q-factor of 50 which corresponds to a compression ratio of around 15.

It follows that a compression ratio of 15 may be recommendable for most photogrammetric applications.

It should be emphasised that the above conclusions are based only on the results obtained from this experiment, using 25 μm images. These results provide users with some hints on the loss of the DTM accuracy due to image compression. However, it could be dangerous to generalise the results. Indeed, more investigation is required before a generalised conclusion can be reached.

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Résumé

Il est bien établi que le volume des données constitue une grosse surcharge, handicapant la photogrammétrie traitant d'images numériques. C'est ainsi par exemple, qu'une numérisation effectuée au pas de 20 μm sur une photographie aérienne noir et blanc, générera un fichier atteignant 100 Méga-octets. Les gros volumes de données ne créent pas seulement des problèmes d'archivage, mais affectent aussi la vitesse de traitement des images. Il en résulte que la compression des données issues d'une image présente une grande importance. On présente dans cet article une recherche sur l'influence de la compression d'image sur la précision des MNT issus d'images préalablement comprimées. On a utilisé dans cette étude le système JPEG installé dans la station de travail de photogrammétrie numérique DPW de Z/I Imaging. On a mené des essais systématiques pour mettre en évidence l'influence des différents niveaux de compression permis par JPEG (avec des facteurs Q allant de 1 à 100) sur les MNT résultants, établis automatiquement par le logiciel Match-T du DPW. L'analyse des résultats provenant de deux polygones d'essai a montré que la compression d'image avait tendance à provoquer des dégradations d'autant plus importantes que la texture de l'image était plus riche. En revanche, les recommandations sur la valeur des facteurs Q à utiliser dans l'ImageStation, énoncées au nom du principe de précaution, se sont avérées en retrait des possibilités du système. Cette analyse a permis d'esquisser quelques conclusions et recommandations utiles à la fois à la poursuite des recherches et à la pratique photogrammétrique.

Zusammenfassung

In der Digitalen Photogrammetrie stellen die Datenmengen eine großes Problem dar. So produziert ein schwarz/weißes Luftbild, das mit einer Auflösung von 20μm digitalisiert wird, ein digitales Bild mit 100 MByte Größe. Grosse Datenmengen können nicht nur Speicherprobleme verursachen, sondern beeinflussen auch die Geschwindigkeit der Bildverarbeitung. Deshalb ist die Datenkompression digitaler Bilder von großer Bedeutung. Dieser Beitrag berichtet über eine Untersuchung über die Einflüsse der Datenkompression auf die Genauigkeit von Digitalen Geländemodellen (DGM), die aus komprimierten Bildern abgeleitet werden. Das JPEG System, das in ImageStation, der Digitalen Photogrammetrischen Arbeitstation (DPW) der Firma Z/I Imaging, zur Verfügung steht, wurde für diese Studie verwendet. In einem systematischen Test wurden die Einflüsse der verschiedener Grade der JPEG Komprimierung (mit Q-Faktoren von 1 bis 100) auf das resultierende DGM untersucht, das in der Arbeitstation mit Hilfe des Match-T Programmes erzeugt wurde. Eine Analyse der Ergebnisse aus zwei Testgebieten zeigt, dass negative Auswirkungen der Bildkomprimierung eher in Gebieten mit reicher Textur auftreten, dass man aber hinsichtlich einer Empfehlung für die Wahl des Q-Faktors in der ImageStation im Zweifelsfall eher zu vorsichtig sein sollte. Diese Analyse führt zu mehreren Schlussfolgerungen und Empfehlungen sowohl für weitere Untersuchungen als auch für die photogrammetrische Praxis.