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EFFECTS OF JPEG 2000 COMPRESSION ON AUTOMATED DSM EXTRACTION: EVIDENCE FROM AERIAL PHOTOGRAPHS

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Abstract

This paper evaluates the effects of JPEG 2000 compression on automated digital surface model (DSM) extraction, using the area-based matching technique. Two stereopairs of aerial photographs, which have different photo scale, pixel size, and topographic type, are used as the images for the experiments. In the experiments, the DSM generated from the uncompressed image is set as the reference, and the elevation accuracy is computed for a range of compression ratios (2:1 to 100:1). The results show that the employed indices of image quality based on the JPEG 2000 compression are clearly superior to the commonly used JPEG compression technique—especially for high compression ratios. However, the elevation accuracy varies with the compression ratios. Also, JPEG 2000 compression does not have a significant influence on the percentage of the successful matching rate. In addition, a near linear fall-off is observed in extracted DSM accuracy with increasing compression ratios.

Keywords: area-based matching, digital surface model, image compression, JPEG 2000

Introduction

Image compression has become a common technique to reduce storage space and access time because it is inconvenient to manage large volumes of data for storage, retrieval, and transmission. A typical aerial image (23 cm by 23 cm, 20 μm pixel size, and 8 bits per pixel) can easily reach 140 megabytes. As the existing standard, JPEG is the most commonly applied algorithm in photogrammetry for data compression, among many image compression techniques (Mittal et al., 1999; Li et al., 2002). However, JPEG 2000, which is a new image compression technique intended to replace the original JPEG standard, has been approved recently. The objective of this paper is to compare the two compression techniques and evaluate their effects on automated digital surface model (DSM) extraction.

Image compression has been one of the important issues in photogrammetry and remote sensing in recent years. JPEG, the existing standard in image compression, has been shown to result in high visual quality for aerial images (spatial remote pictures) and high accuracy of manual image measurement. When the compression ratio is lower than 10:1, the compressed image has nearly no loss in geometry accuracy (Li et al., 2002). When the compression ratio approaches 10:1 or higher, the compressed image has high classification accuracy (Paola and

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Schowengerdt, 1995). However, researchers have also uncovered the limitations of JPEG. Although the classification retains overall appearance, the smoothing effect of JPEG tends to eliminate much of the pixel-to-pixel detail (Paola and Schowengerdt, 1995). Particularly for DSM extraction, JPEG tends to cause significant degradation (Lam et al., 2001). Based on their study of two test sites using Match-T software, Lam et al. found that JPEG is not an efficient algorithm for images that have rich texture.

JPEG 2000

The JPEG Committee decided in 1997 that a new standard was needed due to concerns over the requirements of the increasingly intensive image applications. JPEG 2000, which was proposed as the new standard, is an ideal technology for remote sensing and geographical information system (GIS) applications (JPEG, 2004). The original requirements for JPEG 2000 included requirements from the remote sensing and GIS community. Greater bit depths, tiles, resolution progression, quality progression, and fast access to spatial locations all contribute to the capability and functionality of JPEG 2000.

Among the many components of the JPEG 2000 standard, this paper focuses on the core coding system. The other components are extension, motion JPEG 2000, conformance testing, and reference software (Adams, 2001c). In general, JPEG 2000 has several features, including the discrete wavelet transformation (DWT), scalar quantisation, context modelling, arithmetic coding, and post-compression rate allocation. JPEG 2000 handles both lossy and lossless compression, using the same transform-based framework as JPEG, and imitating the embedded block coding with an optimised truncation (EBCOT) scheme. To obtain the desired level of image quality, quantisation allows greater compression to be achieved, by representing transform coefficients with only the minimal precision required. Transform coefficients are quantised using scalar quantisation with a deadzone. A different quantiser is employed for the coefficient of each sub-band, and each quantiser has only one parameter, the step size (Adams, 2001c). Each sub-band is divided into rectangular blocks (called codeblocks, typically 64 coefficients wide and 64 coefficients high). Context modelling is applied to entropy coding and bit-plane arithmetic coding (Santa-Cruz et al., 2002). The coded data are organised in layers, which act as quality levels. The post-compression rate allocation is applied to generate output code stream in packets. The file extension convention for JPEG 2000 is .jp2.

JPEG 2000 offers numerous advantages over the old JPEG standard (Aboufadel, 2001; Adams, 2001c). JPEG 2000 supports both lossy and lossless compression of single-component (for example, grey scale) and multi-component (for example, colour) imagery. It also offers higher compression ratios for lossy compression than JPEG based on the same peak signal-to-noise ratio (PSNR) values (Aboufadel, 2001). Additionally, JPEG 2000 is able to display images at different resolutions and sizes from the same image file, while its predecessor JPEG was only able to display images at a set resolution. Another advantage of JPEG 2000 is its “region of interest” (ROI) capability. JPEG 2000 is also superior to JPEG in terms of error resilience (Adams, 2001c).

IMAGE COMPRESSION AND JPEG 2000

The purpose of this study is to evaluate the variation of elevation in the resulting DSMs when different compression algorithms are applied. To better facilitate the discussion on the JPEG vs. JPEG 2000 comparison, this section will briefly summarise two basic features of image compression. The definition of image compression ratio will be presented first, followed by the index of image quality.

Image Compression Ratio

There are two commonly applied indices for describing the image compression ratio. The first index is the ratio between the original image size and the compressed image size (Lam et al., 2001; Tai, 2001). The second index is the number of bits per pixel (bpp) after the compression. This study uses the first index as the image compression ratio because JasPer, which is the software used to perform the compression, specifies the first index as the input parameter (Adams, 2001b). The formula of the first index is

$$Compression\_Ratio = \frac{\text{Number of bits of the original image}}{\text{Number of bits of the compressed image}}. \tag{1}$$

Indices of Image Quality

There are two indices for objective evaluation of the quality of a reconstructed image: *PSNR* and *entropy.*

Consider a discrete image $f(x, y)$ for $x = 1, 2, \ldots, N$ and $y = 1, 2, \ldots, M$, to be used as a reference image. Also, consider another image $\hat{f}(x, y)$ to be compared to the reference image. Both $f(x,y)$ and $\hat{f}(x, y)$ have the same spatial dimensions.

$$\text{PSNR} = 10 \,.\, \log_{10} \frac{(\text{peak-to-peak value})^2}{\sigma_e^2} \tag{2}$$

where

$$\text{Noise} = \sigma_e^2 = \frac{1}{MN} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} [\hat{f}(x, y) - f(x, y)]^2.$$

The PSNR represents radiometric degradation of the reconstructed image. A larger PSNR value indicates higher reconstruction fidelity and less noise. In comparison,

$$\text{Entropy} = -\sum_{x=0}^{M-1} \sum_{y=0}^{N-1} P(x, y) \log P(x, y) \tag{3}$$

where $P(x, y)$ denotes the probability of the occurrence of the pixel (x, y).

The entropy (or the uncertainty) of the source is the average amount of information obtained by observing a single-source output. A larger entropy value indicates more uncertainty and, thus, more information is associated with the source.

Automatic DSM Extraction

The process of image matching is fundamental to the automatic extraction of a DSM. Image matching is the process of finding conjugate points in two or more overlapping images (Schenk, 1999; Gooch and Chandler, 2001).

There are three types of method to achieve image matching. They are "area-based matching", "feature-based matching", and "hybrid methods", where hybrid methods combine the first two (Reeves et al., 1996; Schenk, 1999). Area-based matching is also called signal-based matching and is associated with image grey levels. That is, the grey level distribution of small areas of two images is compared and measured for similarity. Similarity measure is a quantitative measure of how well matching entities correspond to each other. Generally, the degree of similarity is measured by the cross-correlation coefficient or the standard deviation in least squares matching (Schenk, 1999). The two software packages used for DSM extraction in this study are based on the area-based matching technique (the *PCI Geomatics OrthoEngine V9.1* will be abbreviated as OrthoEngine and *Leica IMAGINE OrthoBASE V8.6* will be abbreviated as OrthoBASE in the remainder of this paper).

OrthoEngine uses a mean normalised cross-correlation matching method with a multi-scale strategy to match the images. Specifically, OrthoEngine collects the statistics from defined windows, which are called image patches. Matching is performed by initially considering the neighbourhood surrounding a given pixel in the left quasi-epipolar image (thus forming a template). Then the template is moved within a search area to the right epipolar image, until a position is reached providing the best match (Maeder, 1998; Schenk, 1999; Hijazi, 2002).

The actual matching procedure employed by OrthoEngine generates correlation coefficients between 0 and 1 for each matching pixel, where 0 represents a complete mismatch and 1 a perfect match. A second-order surface is then fitted around the maximum correlation coefficients to find the matching position of sub-pixel accuracy. The difference in location between the centre of the template and the position of the best match gives the disparity or parallax arising from terrain relief. From terrain relief the absolute elevation value is then computed (Hijazi, 2002).

OrthoBASE uses a similar matching strategy to OrthoEngine. An image pyramid is adopted by OrthoBASE during image matching to reduce the computation time and to increase the matching reliability (Leica, 2002). An image pyramid is a data structure consisting of the same image represented several times, at a decreasing spatial resolution each time. The matching process is performed at each level of resolution. There are four pyramid layers for OrthoBASE with the resolution of 1/8, 1/4, 1/2, and 1. The search is first performed at the lowest resolution level (that is, the layer with resolution 1/8) and subsequently at each higher level of resolution. The OrthoBASE also uses epipolar geometry to constrain the image matching process in order to produce highly accurate and reliable matching image point pairs (Leica, 2002).

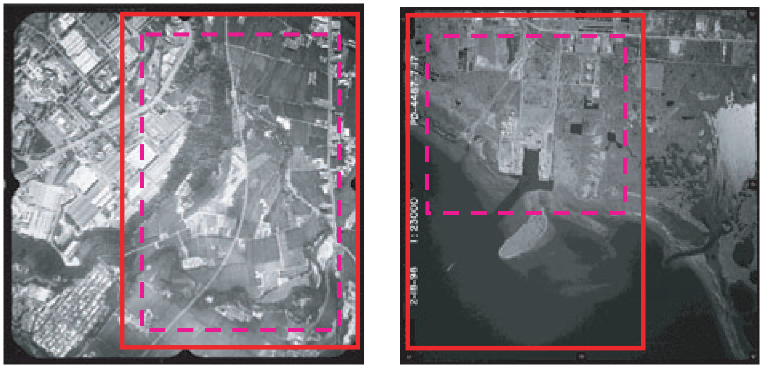
In contrast, feature-based matching is based upon the use of image processing methods to extract the features of interest from the images. These features are usually points, lines, or regions that have characteristics making them uniquely identifiable (Reeves et al., 1996; Gooch and Chandler, 2001; Hijazi, 2002).

METHODOLOGY

Two stereopairs of aerial photographs are selected to extract the DSMs. The description and comparison of these two sites are in Table I. These two sites will be abbreviated as *MI* and

TABLE I. Descriptions of two stereopairs used for the experiments.

Items	*Focal length (mm)*	*Flying height (m)*	*Photo scale*	*Pixel size (μm)*	*Base to height ratio*	*Maximum ground height difference (m)*	*Location*
MI	305·11	1525	1:5000	20	0·23	121	Hsinchu, Taiwan
MII	152·93	3520	1:23 000	21	0·51	47	Tampa Bay, USA



(a) (b)

FIG. 1. Original aerial images for two test sites: (a) site I; (b) site II. The overlap areas are indicated by solid rectangles; dashed lines show trimmed borders for the extracted DSM.
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MII in the remainder of this paper. Both sites are derived from completed photogrammetric missions. The exterior orientation parameters are available.

As shown in Fig. 1(a), stereopair *MI* covers a portion of the Hsinchu area, Taiwan. The other stereopair *MII* (Fig. 1(b)) covers a coastal zone of Tampa Bay, USA. *MI* includes a suburban area and agricultural land, and has a maximum ground height difference of 121 m. The image entropy is 7·72 bpp. *MII* has smaller terrain variation with a ground height range of 47 m. The image entropy is 7·04 bpp. Therefore, the image content of *MI* is richer than *MII*.

Although the original photo is a colour image, only the grey scale image is scanned at a resolution of 20 μm and stored as a TIFF file for *MI*. The dimensions of these two photographs are 11 995 × 11 905 pixels with a depth of 8 bpp. In contrast, for *MII*, the pixel size is 21 μm and this is also stored as a TIFF file. The image size of *MII* is 11 240 × 11 239 pixels with a depth of 8 bpp.

In Fig. 1(a) and (b), the overlapping area of each stereopair is shown by a rectangle with a solid line, while the trimmed DSMs used in the study are marked by dashed lines. Typically, the outer edges of an extracted DSM contain large errors (Leica, 2002), so these regions are excluded from the final output DSM.

To investigate the effects of JPEG 2000 compression on automated DSM extraction, manual measurement operations to derive the parameters of exterior orientation have to be avoided. For *MI*, the parameters of exterior orientation are obtained from an aerial triangulation adjustment with PAT-B (Inpho, 2002), and for *MII*, they are derived from the aerial triangulation report of OrthoBASE (Leica, 2002). Identical exterior orientation parameters are applied to the uncompressed images as well as compressed images for each compression ratio. Therefore, the general methodology for the experiments is given in the following.

(1) A DSM is extracted from the original imagery. This DSM is held as the reference against which the terrain heights obtained from compressed imagery are compared.
(2) The imagery is then compressed with 11 different ratios ranging from 2 to 100.
(3) The DSMs are then derived for each of the compressed pairs, with the same exterior orientation parameters.

Fig. 2 illustrates the flow diagram of the automatic DSM extraction.

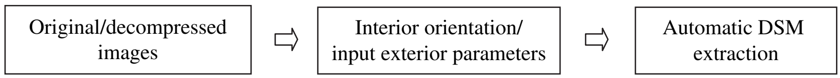

FIG. 2. Flow diagram of automatic DSM extraction in this study.

The DSMs of the two sites were extracted with a 1 m × 1 m and 2·5 m × 2·5 m grid distance for sites *MI* and *MII*, respectively, based on different ground pixel size. The generated DSMs for the two sites are shown in Fig. 5. The DSM extracted from uncompressed images is used as the reference DSM even though it might not be the best of all the DSMs generated from uncompressed and compressed images. The measure used to compare the effects of different compression algorithms is the relative elevation error. This is the measure commonly adopted by many researchers (Robinson et al., 1995; Reeves et al., 1996; Lam et al., 2001).

The next step is to quantify the relationship between the accuracy of the DSM and the compression ratio. Eleven different compression ratios ranging from 1 to 100 are used both with JPEG and JPEG 2000. The comparison is based on two DSM data-sets with *X*, *Y*, *Z* format that are generated from uncompressed images and compressed images, respectively. The DSM data-sets may have different success percentages, so this study treats two points from different DSM data-sets that are less than 0·1 m apart to be identical points. The relative error in elevation is then measured at the identical points by comparing the uncompressed and compressed images. Equations (4), (5), and (6) show the formulae to calculate the accuracy measure using root mean square error (rmse):

$$\text{The difference} \quad \Delta Z_i = Z_i - Z_i^0 \tag{4}$$

where Z_i^0 is the elevation from the DSM extracted from uncompressed images and Z_i the elevation from the DSM extracted from compressed images;

$$\text{Average} \quad \overline{\Delta Z} = \left(\sum_{i=1}^{n} \Delta Z_i \right) / n; \tag{5}$$

$$\text{Accuracy} \quad \text{Rmse} = \sqrt{\left(\sum_{i=1}^{n} \Delta Z_i^2 \right) / n}. \tag{6}$$

JPEG 2000 compression is performed with JasPer 1.5 image compression software. JasPer is freely available for academic use and supports various image formats, including .bmp (Windows Bitmap), .jp2 (JPEG 2000), .jpg (JPEG), .pnm (PNM/PGM/PPM), and .ras (Sun Rasterfile) (Adams, 2001a, b). The current version 1.701.0 of JasPer software is available for downloading from the JasPer project home page (http://www.ece.uvic.ca/~mdadams/jasper/).

The compressed JPEG 2000 files are then converted to the TIFF format so they can be recognised by OrthoEngine and OrthoBASE. In contrast, JPEG compression is performed with IrfanView (IrfanView, 2003). The level of compression of JPEG is also controlled by the Q-factor for IrfanView. The different JPEG compression programs can have substantially different Q-factors. For example, the Q-factor ranges from 1 to 100 for IrfanView while performing JPEG compression. However, the Q-factors can range from 1 to 250 in the ImageStation (Lam et al., 2001). Consequently, the compression ratio vs. JPEG compression is the ratio between the original image size and the compressed image size after the original image was compressed using various Q-factors in IrfanView.

Results and Analyses

The two indices for objective evaluation of the quality of a reconstructed image for *MI* and *MII* are presented in Table II. The indices, PSNR and entropy, are presented graphically for comparison in Fig. 3. In general, the indices show that image quality decreases with increasing compression ratio. As shown in Fig. 3(a), the PSNR value decreases as the compression ratio increases. This pattern holds across different compression algorithms (either JPEG 2000 or JPEG compression), and different sites (either *MI* or *MII*). The results suggest that the degradation of image quality decreases at a slower rate, as the compression ratio increases. Fig. 3(a) also shows that JPEG 2000 consistently outperforms JPEG. At the same compression ratio, the PSNR values associated with JPEG 2000 are higher than those associated with JPEG. Also, the difference in PSNR values between JPEG 2000 and JPEG becomes more significant as the compression ratio increases in *MI*. The findings imply that JPEG 2000 is superior to JPEG because it maintains better image reconstruction fidelity across a range of different compression ratios.

The comparison between JPEG 2000 and JPEG based on entropy values at different compression ratios is shown in Fig. 3(b). For JPEG 2000, the entropy value stays relatively constant as the compression ratio increases. In contrast, for JPEG, the entropy value decreases as the compression ratio increases. This finding suggests that JPEG 2000 is better than JPEG at preserving the information content, particularly at high compression ratios. JPEG 2000 and JPEG also perform differently when the images vary in texture richness. The texture of *MI* is richer than that of *MII*. As shown in Fig. 3(b), for JPEG, the entropy values decrease at a faster rate when compression is applied to *MI* than when it is applied to *MII*. This pattern indicates that JPEG compression tends to cause more significant degradation when the image texture is richer.

Next, Table III and Fig. 4 report the DSM correlation success percentage for both OrthoEngine and OrthoBASE. The *correlation success percentage* in OrthoEngine or the *general mass point quality* in OrthoBASE represent a ratio, which is the number of matched points with correlation larger than a given threshold divided by the total number of points. It is known that JPEG causes severe destruction when the compression ratios are greater than 32, that is, less than 0·25 bpp (Tai, 2001). As shown in Fig. 5, for example, the edges of buildings are severely affected with a JPEG compression ratio of 50. Here, the JPEG compressed images with compression ratio higher than 32 are retained for the sake of comparison.

Table II. PSNR and entropy (denoted $H_0(S)$) vs. compression ratio (only applies to the left image of the stereopair for each site).

Compression ratio	*1*	*2*	*5*	*8*	*11*	*13*	*16*	*20*	*25*	*33*	*50*	*100*
PSNR_MI_JPEG 2000	n/a	66·29	44·38	41·57	39·75	38·6	37·92	37·11	36·1	34·93	33·41	30·9
PSNR_MI_JPEG	n/a	44·7	42·8	40·93	39·12	38·27	37·42	36·22	35·2	33·71	31·64	28·31
PSNR_MII_JPEG 2000	n/a	58·55	35·01	32·39	31·18	30·72	30·31	29·75	29·31	28·82	28·17	27·15
PSNR_MII_JPEG	n/a	46·96	31·97	30·93	30·07	29·80	29·35	29·05	28·67	28·16	27·48	26·15
$H_0(S)$*_MI_JPEG 2000*	7·72	7·64	7·72	7·71	7·71	7·71	7·71	7·70	7·70	7·69	7·69	7·66
$H_0(S)$*_MI_JPEG*	7·72	7·69	7·67	7·67	7·62	7·59	7·55	7·49	7·42	7·21	6·78	5·17
$H_0(S)$*_MII_JPEG 2000*	7·04	7·05	7·05	7·04	7·02	7·02	6·99	6·97	6·96	6·95	6·94	6·93
$H_0(S)$*_MII_JPEG*	7·04	7·04	7·00	7·03	7·00	6·99	6·99	6·98	6·97	6·91	6·62	5·69

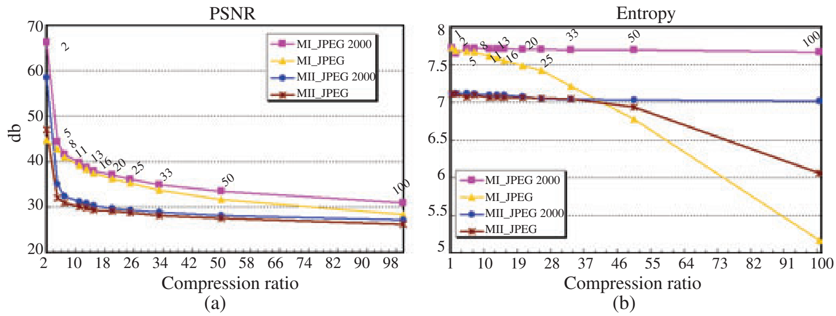

FIG. 3. (a) PSNR and (b) entropy vs. compression ratio for two sites (only the left image of stereopairs is applied to the calculation).
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TABLE III. DSM correlation success percentage vs. compression ratio.

Compression ratio	*1*	*2*	*5*	*8*	*11*	*13*	*16*	*20*	*25*	*33*	*50*	*100*
MI_JPEG 2000	81·91	81·88	82·38	82·43	82·86	83·10	82·85	82·51	82·84	82·67	82·28	82·11
MI_JPEG	81·91	81·38	82·03	82·49	83·29	82·80	83·05	81·79	82·16	80·42	76·85	68·85
MII_JPEG 2000	80·18	79·98	79·96	79·42	79·14	79·32	79·41	79·74	80·37	80·73	81·09	80·36
MII_JPEG	80·18	80·13	81·52	79·48	80·91	80·95	81·01	80·68	80·28	79·92	78·83	70·93

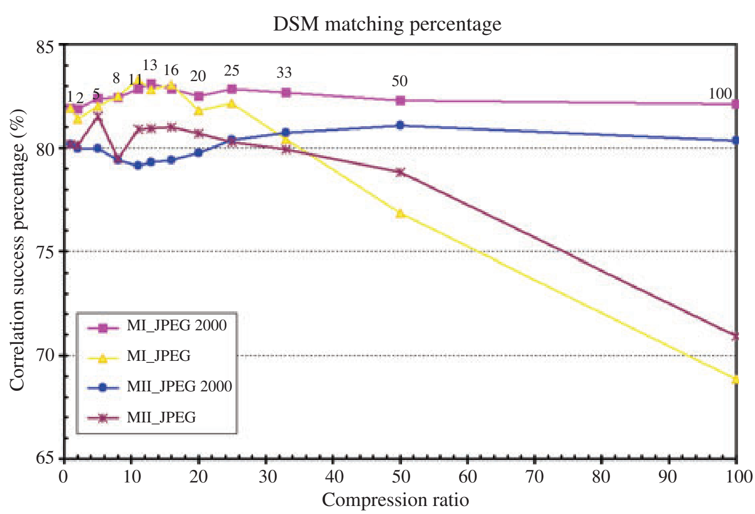

FIG. 4. The DSM correlation success percentage vs. compression ratio.
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Because image quality decreases as compression ratio increases, the DSM correlation success percentage is expected to decrease correspondingly. Prior research shows that, for JPEG compression, the average error in the matching accuracy grows rapidly as the image quality decreases (Maeder, 1998). However, the experimental results are not exactly what were

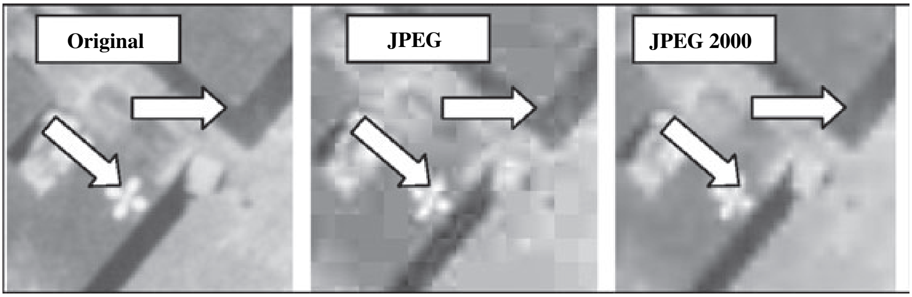

FIG. 5. Comparison between original and compressed imagery (with compression ratio 50).

expected. Table III and Fig. 4 show that there is no significant variation in the correlation success percentage vs. compression ratio for JPEG 2000. More specifically, for small compression ratios, JPEG 2000 and JPEG result in similar correlation success percentages. However, as the compression ratio increases, JPEG results in a significant reduction in the correlation success percentage, while JPEG 2000 results in little change. This finding suggests that there is an elimination effect, which removes high-frequency structures when compression is based on a discrete cosine transform (DCT) process (Schiewe, 1998). The removal of high-frequency structures makes the image less sharp, and causes block boundaries, an artefact of the process, to appear. Fig. 5 illustrates the elimination effect associated with JPEG and compares the compressed images (at the same compression ratio) with the original image. In contrast to the image based on JPEG compression, the image based on JPEG 2000 compression is smooth and allows a sufficient interpretation of targets.

Based on the DSM matching principles of OrthoEngine and OrthoBASE, one possible reason for the steady matching percentage of JPEG 2000 compression may be the smoothing effect as shown in Fig. 5. The smoothing effect more or less compensates for the quality loss due to the compression. To prove this assumption, the 5×5 mean filters are applied to the uncompressed images for *MI* and *MII*, resulting in a 6% and 4·7% rise, respectively, in the DSM correlation success rate.

Furthermore, Figs 3(b) and 4 show similar patterns. The richer image texture results in higher DSM correlation success percentage. It can be seen that the DSM correlation success percentage is closely related to the richness of texture. The DSM correlation success percentage dropped abruptly with the higher compression ratio while the texture richness decreased at a faster rate.

The area-based image matching approach works well for areas with significant surface texture (Fox and Gooch, 2001; Leica, 2002). Blunders can be expected to occur on surfaces with poor texture, such as open areas with homogenous texture and the roofs of large buildings. The visualisation of extracted DSMs on surfaces with poor texture is shown in Fig. 6. Visual evaluation suggests that the quality of DSM decreases as the compression ratio increases, although the corresponding DSM correlation success percentage has no significant variation, as reported in Table III. For JPEG 2000, the noise combinations (denoted by the black speckles in Fig. 6) increase as the compression ratio increases. These speckles result from incorrect matching of pixels. Therefore, the DSMs extracted from the uncompressed and compressed images have to be manually edited to remove the black speckles caused by incorrectly matched pixels. For example, there are 141 987 points in total from the DSM which were extracted from uncompressed images of *MI*. Among them, 336 points were removed from the DSM editing. This procedure is taken to avoid comparing blunders with blunders.

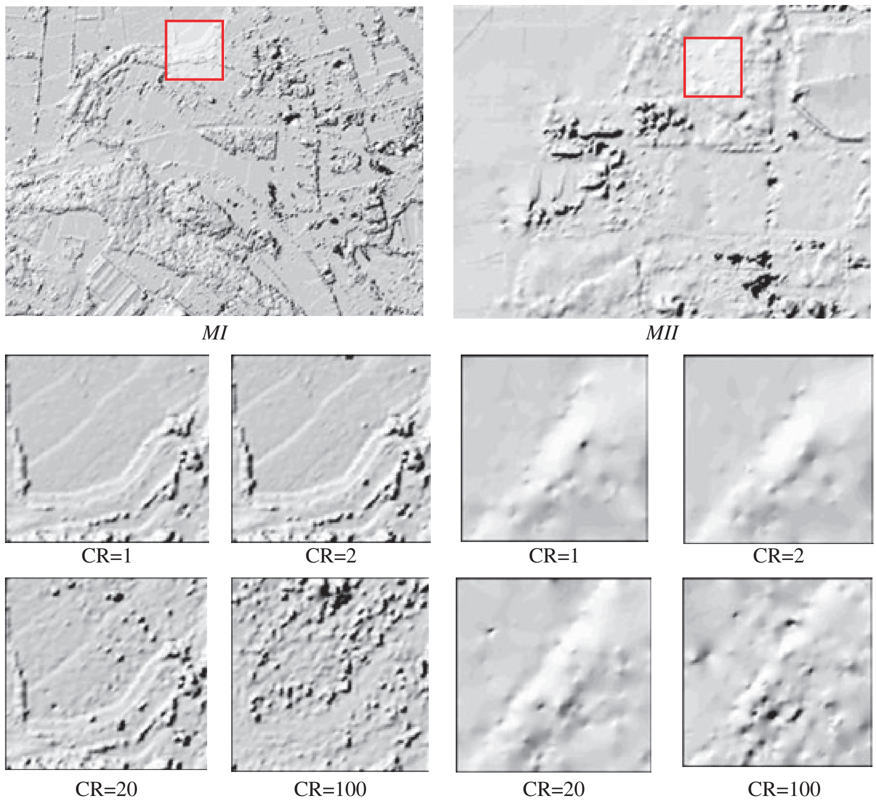

FIG. 6. Changes in the appearance of the DSMs for the two sites, resulting from different JPEG 2000 compression ratios.
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TABLE IV. Average errors by compression ratio.

Compression ratio	*2*	*5*	*8*	*11*	*13*	*16*	*20*	*25*	*33*	*50*	*100*
MI_$\overline{\Delta Z}$_JPEG 2000 (m)	−0·000	0·004	0·009	0·014	0·022	0·029	0·037	0·046	0·099	0·150	0·391
MI_$\overline{\Delta Z}$_JPEG (m)	−0·004	−0·001	0·005	0·012	0·016	0·021	0·035	0·057	0·098	0·206	0·383
MII_$\overline{\Delta Z}$_JPEG 2000 (m)	−0·003	0·001	−0·002	0·010	−0·001	0·005	0·028	0·018	0·018	0·032	0·031
MII_$\overline{\Delta Z}$_JPEG (m)	−0·001	0·030	−0·010	0·026	0·027	0·030	0·026	0·026	0·050	0·023	0·029

The next step is to quantify the relationship between the accuracy of DSM and the compression ratio. The average error and rmse of DSM between uncompressed images and compressed images are shown in Tables IV and V, respectively. As shown in Fig. 7, the accuracy of DSM decreases as the compression ratio increases for both JPEG 2000 and JPEG. The predicted linearity is supported for the range of compression ratios investigated (from 2 to 100). Table V shows that the rmse ranged from 0·10 to 2·00 m for *MI* and from 0·21 to 0·93 m for *MII*, as the compression ratio increases for JPEG 2000. Furthermore, the DSM accuracy decreases with increasing compression ratios for JPEG 2000, although the DSM matching

TABLE V. Rmse vs. compression ratio for two sites.

Compression ratio	*2*	*5*	*8*	*11*	*13*	*16*	*20*	*25*	*33*	*50*	*100*
MI_rmse_JPEG 2000 (m)	0·105	0·290	0·366	0·407	0·477	0·526	0·595	0·682	0·943	1·182	2·002
MI_rmse_JPEG (m)	0·252	0·308	0·393	0·467	0·519	0·558	0·658	0·796	1·07	1·574	2·475
MII_rmse_JPEG 2000 (m)	0·211	0·239	0·286	0·317	0·344	0·356	0·397	0·440	0·501	0·607	0·930
MII_rmse_JPEG (m)	0·251	0·277	0·301	0·338	0·360	0·385	0·414	0·474	0·535	0·701	1·103

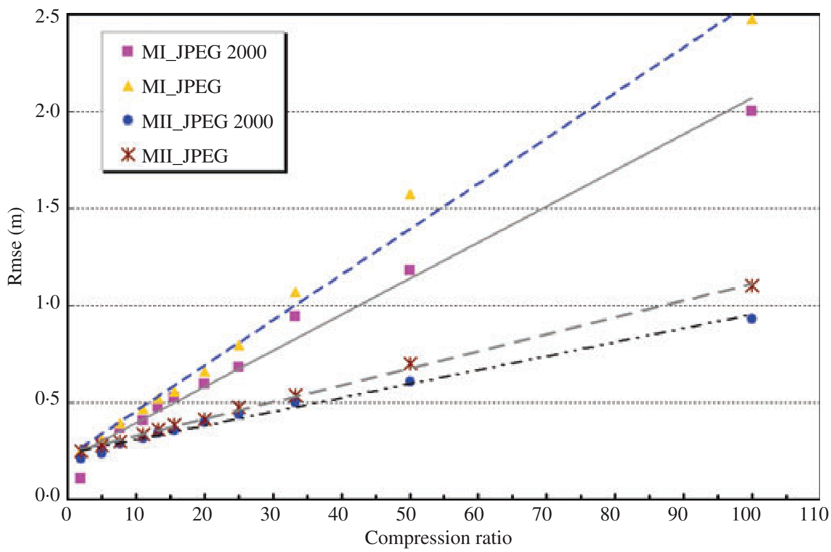

FIG. 7. Rmse vs. compression ratio for two sites.
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success percentage stays relatively constant across different compression ratios. It reveals that the smoothing effect not only brings more successful matching pairs but also results in more inaccurate matching points in the matched DSM. Therefore, one could conclude that the DSM correlation success percentage is not a good measure to evaluate the DSM matching quality when it works alone without applying other measures.

As suggested by preliminary visual examination of the DSMs (Fig. 6), the automatically extracted DSMs have some significant errors. JPEG 2000 compression could potentially cause significant errors in relative height. The distribution of the errors of a DSM extracted from the images of *MII* with compression ratio 20 is illustrated in Fig. 8. The peaks in Fig. 8(a) show that most of the matched points correspond well with the check points from the reference DSM. The probability distribution of the height differences agrees approximately to the normal distribution.

For JPEG 2000, comparable transect elevations were plotted from the DSMs that are generated from different compression ratios for *MI* (Fig. 9). The elevation profiles developed for the study area are in good accordance with the DSMs generated from uncompressed images and compressed images (at compression ratio of 2:1) in the entire elevation range. Elevation profiles also showed that DSMs generated from a higher compression ratio have less agreement with the transects, for compression ratios ranging between 20:1 and 100:1.

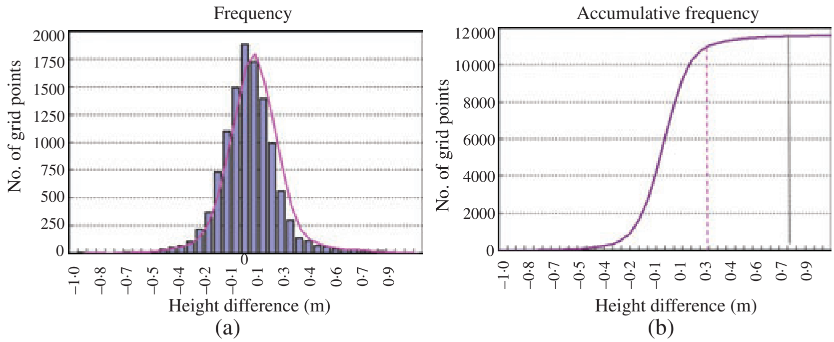

FIG. 8. Height differences between two DSMs for *MII*: (a) height difference vs. frequency; (b) height difference vs. accumulative frequency. JPEG 2000 compression (compression ratio is 20) vs. uncompressed images. This figure appears in colour in the electronic version of the article and in the plate section at the front of the printed journal

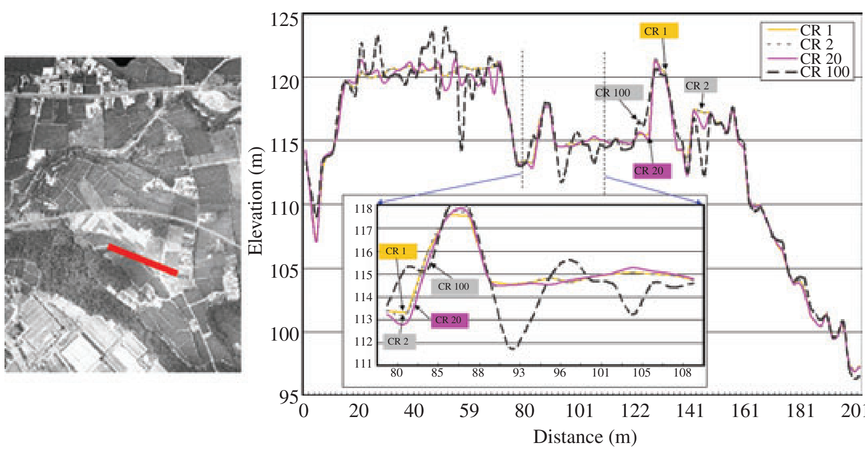

FIG. 9. Profile comparison between different compression ratios of JPEG 2000 for *MI*. This figure appears in colour in the electronic version of the article and in the plate section at the front of the printed journal

CONCLUDING REMARKS

In this study, the effects of JPEG 2000 compression on automated area-based DSM extraction from aerial photos have been evaluated. The influences on DSM heights obtained via OrthoEngine and OrthoBASE are investigated using two stereopairs of aerial photography. The following conclusions were drawn based on the experimental results:

(1) There are two image quality indices applied in this study, that is, the PSNR and entropy. The compression algorithm based on wavelet transforms (DWT) (JPEG 2000) is clearly superior to the DCT (JPEG) method, especially for higher compression ratios. Besides, compared to JPEG 2000, the JPEG compression tends to cause more significant degradation when the image texture is richer.

(2) The JPEG 2000 compression has no significant influence on the matching success percentage of automated DSM extraction using area-based matching. Furthermore,

richer image texture results in higher DSM correlation success percentage. It can be concluded that the DSM correlation success percentage is closely related to the richness of texture.

(3) The rmse ranged from 0·10 to 2·00 m for *MI* and from 0·21 to 0·93 m for *MII* as the compression ratio increases from 2 to 100 for JPEG 2000. The rmse curves suggest a near linear fall-off in accuracy with increasing compression ratios.

(4) Elevation profiles showed that DSMs generated from higher compression ratios have less agreement with the transects.

These observations should provide users with some information on the behaviour of JPEG 2000 with respect to the loss of accuracy in surface modelling. In deciding the optimal compression ratio when using JPEG 2000 for photogrammetric applications, the degradation of height accuracy should be considered.

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Résumé

On étudie dans cet article les effets de la compression JPEG 2000 sur l'extraction automatisée des modèles numériques des surfaces (MNS), basée sur l'emploi de la technique d'appariement surfacique. On a utilisé dans cet essai deux couples stéréoscopiques de photographies aériennes, ayant des caractéristiques différentes quant à leur échelle, la taille du pixel et la topographie du terrain imagé. On a pris comme MNS de référence celui obtenu à partir des images non compressées, sur lequel on a pu calculer la précision altimétrique de la compression d'image pour une gamme allant de 2:1 à 100:1. Les résultats montrent que les indices de qualité d'image utilisés, résultant de la compression JPEG 2000 sont nettement supérieurs à ceux des techniques de compression JPEG généralement utilisées—surtout s'il s'agit de forts taux de compression. On constate que la précision altimétrique varie évidemment avec les taux de compression. Mais la compression JPEG 2000 n'a pas une influence significative sur le pourcentage d'appariements réussis. Enfin on a pu remarquer que la diminution de la précision du MNS ainsi extrait était une fonction quasi-linéaire des taux de compression.

Zusammenfassung

Es wird der Einfluss von JPEG 2000 Kompression auf die Ergebnisse der automatisierten Generierung Digitaler Oberflächenmodelle (DSM) mittels intensitätsbasierter Bildzuordnung untersucht. Als Testdaten werden zwei Stereomodelle mit unterschiedlichem Bildmaßstab, Pixelgröße über unterschiedlicher Topographie verwendet. Als Referenz dient jeweils ein Oberflächenmodell, das aus unkomprimierten Bilddaten gewonnen wurde. Die Höhengenauigkeit wird für Kompressionsverhältnisse von 2:1 bis 100:1 untersucht. Es hat sich gezeigt, dass speziell für hohe Kompressionsraten die Bildqualität bei einer Kompression mit JPEG 2000 deutlich besser ist, als bei der üblichen JPEG Kompression. Jedoch zeigte sich bei der Höhengenauigkeit eine klare Abhängigkeit vom Kompressionsverhältnis. Eine Kompression mit JPEG 2000 hat keinen signifikanten Einfluss auf bessere Bildzuordnung. Es wurde eine nahezu lineare Abnahme der DSM Höhengenauigkeit mit steigender Kompressionsrate beobachtet.

Resumen

Este artículo evalúa los efectos de la compresión JPEG 2000 en la extracción automática de Modelos Digitales de la Superficie (MDS) usando correlación por áreas. Para los experimentos se usaron dos estereopares de fotografías aéreas con diferentes escalas, tamaño de píxel y tipo de relieve. El MDS generado a partir de la *imagen sin comprimir se utiliza como referencia y se calcula la exactitud de la elevación para diferentes tasas de compresión (de 2:1 a 100:1). Los resultados muestran que los índices de calidad de imagen en la compresión JPEG 2000 son claramente superiores a los de la compresión JPEG utilizada corrientemente—especialmente para tasas de compresión altas. Sin embargo, la exactitud de la elevación varía en función de la tasa de compresión. Además, la compresión JPEG 2000 no tiene una influencia significativa en la tasa de éxito de la correlación. Por último, se observa un descenso casi lineal de la exactitud del MDS calculado a medida que se incrementa la tasa de compresión.*

