IMAGE COMPRESSION VERSUS MATCHING ACCURACY

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ABSTRACT

The improvements of aerial image scanners regarding the scan resolution and in particular the development of new digital cameras (e.g. the DMC of Z/I Imaging) comes along with the production of Gigabytes of image data. To handle these big data sets image compression algorithms are applied. The number of developed image compression procedures is growing and investigations of the consequences for photogrammetric image processing are becoming very important for users of compressed image data.

This paper investigates theoretically and experimentally the impact of different compression algorithms on image matching quality. The focus is laid on automated point transfer using the area based least squares matching principle. Other automated processes like aerial triangulation, DTM acquisition and relative orientation often directly rely on the results of the employed point transfer process thus consequences on these processes are inferable. In the experimental investigations simulated stereo imagery and real stereo image pairs are taken into account. Representative algorithms of three different compression methods, the JPEG, Wavelet and Fractal compression, are used to verify and quantify the theoretically found relation between matching accuracy and compression ratio. Regarding the peak-signal-to-noise-ratio (PSNR) of the images induced by compression, Wavelet compression proves to be superior to JPEG and Fractal compression. With respect to the success rate and matching accuracy of point transfer a continuous decrease is to be expected with increasing compression rate. But unlike the PSNR results a changed ranking of the compression methods has to be observed. The highest matching success quotas combined with the most precise point transfer were achieved with the JPEG algorithm. Wavelet compression followed quite closely but Fractal compression dropped down significantly, therefore is not recommended for photogrammetric applications. For high precision point transfer, which is required in most photogrammetric applications, the investigations show that compression ratios not lower than 1:5 can be tolerated. Using images with lower compression ratios will produce point transfer errors above 0.1 to 0.2 pixels.

1 INTRODUCTION

To deal with the enormous disk space requirements of photogrammetric image data sets various compression algorithms are in use. Up to now algorithms based on JPEG compression are the most commonly used compression software but Wavelet based algorithms are not far behind any more. A third group of compression procedures are based on Fractal compression techniques. Often high compression rates are anticipated from developments in this area. In the following we do not want to review the compression techniques. Instead we refer to Pennebaker and Mitchel, 1993, Barnsley and Hurd, 1993, Louis et al., 1994 and Saupe et al., 1997. An overview can be found in Hahn and Kiefner (1998) in which we started reporting about this research.

Empirical studies on the dependency of photogrammetric accuracy and image compression started some years ago. Most investigators used JPEG compression and proposed, for example, compression ratios of 1:10 (Jaakola and Orava, 1994) or 1:12,5 (Novak and Shahin, 1995). Others investigated the accuracy of DTMs made with compressed images and related the loss of DTM accuracy to JPEG quality factors (Reeves et al., 1997, Robinson et al., 1995). The aim of this research is to extend those studies by taking the other mentioned compression techniques into account. Because compression rates of 10 or more can not be achieved by lossless compression, at least not with photogrammetric images, our investigations deal only with lossy compression techniques.

In a broad variety of applications of general image processing often JPEG compression ratios in the order of 1:10 are recommended. Even though JPEG compression ratios of 1:40 or even smaller can be achieved, subjective differences are readily discernible at compression rates in the order of 15. However careful scrutiny will reveal differences in the compressed images at much lower compression rates. Wavelet compression generally produces less visible image distortions than JPEG compression thus a higher compression rate may be used without producing a significant derogation of the visual impression of the compressed image. Furthermore, the achievable Wavelet compression rates are a multiple of that of JPEG compression as outlined in Thierschmann et al.(1997). The fact that compression induced distortions might not be visible should not be misinterpreted by assuming that therefore the consequences for photogrammetric applications are negligible. First results using all three compression techniques indicated errors of transferred point locations of 0.5 pixels at compression ratios of 1:10 (Hahn and Kiefner, 1998).

Before developing a model for relating compression and accuracy in Section 3, we will examine the impact of compression on the gray value image and show that the effect of JPEG, Wavelet and Fractal compression can be properly approximated by a Gaussian distribution. Section 4 reports about aspects of image quality under the influence of compression. The images and point transfer methods used in the experimental investigation are presented in Section 5. The results of a series of experiments using scanned aerial images, images taken by the digital airborne camera system DPA and images recorded with the spaceborne MOMS system are reported in Section 6. We conclude with a summary of our findings, including recommendations for the use of compression algorithms in digital photogrammetry.

2 DISTRIBUTION OF COMPRESSION NOISE

The theoretical framework used in this paper is related to least squares point transfer with two shift parameters: the parallaxes in x and y direction of the image coordinate system. This framework requires that image noise can be modeled as Gaussian noise. Transferring the Gaussian noise assumption to compressed images requires that JPEG, Wavelet and Fractal compression can be modeled as degrading the image by the addition of Gaussian noise. This has to be true for all three compression techniques over a large region of different compression ratios. To prove this assumption the gray level differences between the original image and the compressed images are calculated which represent compression noise.

Three image data sets are used in the experiments. The first is a spaceborne MOMS image with a ground pixel size of 17 m. The second image is recorded by the DPA camera which is an airborne line imaging scanner. The third image is a digitized photographic aerial image. The latter both have a ground pixel size of 80 cm.

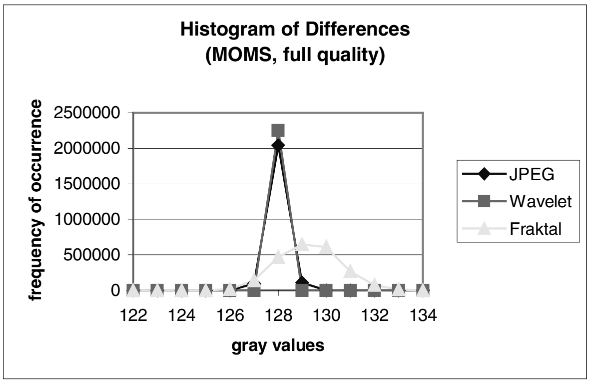

Figure 1: Histogram of the gray value differences between the original and the compressed MOMS image using full quality

Figure 1 shows the impact of the compression algorithms at full quality. Most compression algorithms use a quality parameter to specify the impact of compression and with that indirectly the compression ratio. Full quality means that ideally no information should be lost and the gray values of an image compressed at full quality should not differ significantly from the original image. The results obtained for the MOMS image are shown in Figure 1. The chart reveals two important issues. Firstly, compression at full quality which may result in compression ratios in the order of 1:1.3 to 1:2 or 1:3 produces a very small percentage of gray value differences of 1 or 2 gray levels for Wavelet and JPEG compression which fits to the expectation. The value 128 on the horizontal axis of the chart represents a gray value difference of 0. More surprising is the result of the Fractal compression algorithm. Obviously the differences are much bigger than for the other two methods and the compression algorithms produces a systematic gray value shift of nearly 2 gray levels. Because the matching procedure (Section 5) is

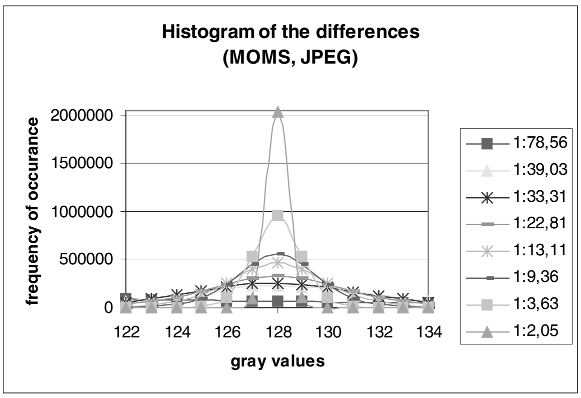

Figure 2: Differences between original and compressed images for a series of different compression ratios using the JPEG algorithm

invariant to a gray scale shift this systematic error caused by the Fractal compression algorithm is without significance for this investigation.

A histogram of the differences between original and JPEG compressed images generated for various compression ratios shows Gaussian curves of different width (Figure 2). The series of compression ratios ranges from 1:2 to 1:78 whereby the achieved rate of nearly 80 is a remarkably high JPEG rate. The figure indicates that the distribution with the differences is close to the Gaussian distribution. The corresponding histograms for the other two compression methods are very similar to those plotted on Figure 2 with the peculiarity that the Fractal results show up with an additional offset. It should be noted that the used images have to be big enough (1000 by 1000 pixels or more) to have a large statistical sample. Histograms of differences determined from smaller fragments of images (e.g. 200 by 200) often are show up with a distribution which is more peaked than the Gaussian distribution. For JPEG compression this effect is caused by a loss of high frequencies and the appearance of artifacts such as block boundaries (Reeves and Hahn, 1997).

3 A MODEL FOR RELATING COMPRESSION AND ACCURACY

The theoretical framework used in this paper to relate compression and accuracy is based on the least squares approach of area based image matching. The idea is to formulate a model which allows to predict the accuracy of point transfer to a given measure for image compression. A proper measure for image compression is compression noise. As outlined in the previous section compression noise can be approximated by additive Gaussian noise. The theoretical accuracy of point transfer using least squares matching with two parallax unknowns *px* and *py* is given by the well-known formula

$$D\begin{pmatrix} px \\ py \end{pmatrix} = \frac{\hat{\sigma}_n^2}{m} \begin{pmatrix} \sigma_{f_X}^2 & \sigma_{f_X f_Y} \\ \sigma_{f_X f_Y} & \sigma_{f_Y}^2 \end{pmatrix}^{-1} \tag{3.1}$$

with
- m = number of pixels in the matching window
- $\hat{\sigma}_n^2$ = variance of image noise
- $\sigma_{f_X}^2, \sigma_{f_Y}^2$ = mean sum of squared gradients of the image
- $D(.)$ = covariance matrix of the parallaxes

Assuming that image noise is substituted by the superimposition of compression noise and image noise or just by dominating compression noise, equation (3.1) can be interpreted in the light of image compression. If the mean sum of squared gradients are determined from the uncompressed image there is no impact of compression on equation (3.1) other than compression noise. Assuming further that the off-diagonal elements of the 2 x 2 matrix in (3.1) are small compared to the mean sum of the squared gradients the following formula is obtained

$$\hat{\sigma}_{pxy} = \sqrt{\frac{\left(\hat{\sigma}_{px}^2 + \hat{\sigma}_{py}^2\right)}{2}} = \frac{\hat{\sigma}_{cn}}{\sqrt{2m}} \sqrt{\left(\frac{1}{\sigma_{f_X}^2} + \frac{1}{\sigma_{f_Y}^2}\right)} \tag{3.2}$$

Compression noise $\hat{\sigma}_{cn}$ and the remaining expression in (3.2) which relates to the mean sum of squared gradients and the window size are the two parameters which influence the estimate of the achievable accuracy of point transfer using compressed images. To verify this model rms errors can be computed by matching a simulated stereo image pair for which the true parallaxes are known. In a second step the investigations then will be extended to real image pairs of the above mentioned image data sets. But before we continue in this direction we will have a closer look at the quality of compressed images, in particular, to the entropy and the PSNR.

4 QUALITY OF COMPRESSED IMAGES

A frequently used measure for the quality of images is the entropy. It is defined by the following formula:

$$H = -\sum_{g=0}^{255} p(g) \log_2 (p(g)) \tag{4.1}$$

For computing the entropy H the probabilities or relative frequencies of the different grey values have to be determined first to be entered into to equation (4.1). The entropy calculated for the three image data sets and for all three compression methods is given in Table 1. The column entitled 'Min' lists the minimum entropy obtained with the highest compression rate achieved by the three compression schemes.

For images with 8 bit information and the entropy should be close to 8. From Table 1 can be seen that the aerial images (RMK Top camera) possess the highest entropy H(RMK) = 7.7 followed by significantly lower entropy values of H(DPA) = 6.2 and H(MOMS) = 5.8. This means the image data which enter into the point transfer investigations differ considerably regarding the information content measured by the entropy. Remarkable is that there is a minor loss of entropy between the original images and the highly compressed images. Significant differences between the three compression methods can not be observed in the entropy values obtained for the compressed images.

Camera	Method	Original Image	Min
RMKTOP	JPEG Fraktal Wavelet	7,70	7,62 7,58 7,68
DPA	JPEG Fraktal Wavelet	6,21	5,70 6,19 6,20
MOMS	JPEG Fraktal Wavelet	5,78	5,43 5,70 5,73

Table 1: Entropy for the different images and the three compression methods. For comparison the entropy for the original images is listed also.

A second measure for image quality is the peak-signal-to-noise-ratio. In Netravali and Haskell (1994] the PSNR is defined as follows:

$$PSNR = 10 * \log_{10}\left(\frac{255^2}{MSE}\right) \tag{4.2}$$

with

$$MSE = \frac{1}{N*M} * \sum_{i=1}^{N}\sum_{j=1}^{M}(g_{ij}^{o} - g_{ij}^{c})^2 \tag{4.3}$$

g_{ij}^{o} are the gray values of the original and g_{ij}^{c} the gray values of compressed images. A dependency of the PSNR on the compression method and compression ratio is to be expected. The PSNR values obtained for all three compression algorithms over a multitude of compression ratios are plotted in Figure 3. The PSNR decreases largely for compression rates up to 5. For higher rates the curves are rather flat. Looking at each specific image type individually shows the following ranking between the algorithms:

1. Wavelet
2. JPEG
3. Fractal

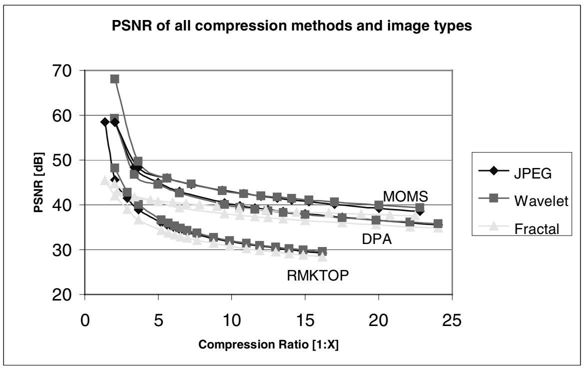

Figure 3: PSNR values for JPEG, Wavelet and Fractal compression

The PSNR curves of Wavelet compression are always a little bit above those of JPEG. The lowest curves are those obtained by Fractal compression. A closer look at the results shows that the differences between JPEG and Wavelet are quite small and only Fractal compression results are significantly behind. This coincides with our observations about the compression noise distribution (cf. Section 2). Another finding of Figure 3 is that the PSNR depends stronger on the image signal than on the used compression algorithm. While the PSNR curves follow nearly the same trend for each compression method the curves are highest for the low entropy MOMS images and lowest for the high entropy RMK images.

5 STRATEGIC ASPECTS OF POINT TRANSFER

The computation of entropy and PSNR has given an impression of the impact of the different compression methods on the image quality. With the model proposed in Section 3 the loss of image quality can be related to geometric accuracy of point transfer. Point transfer procedures employ a certain matching routine and moreover may include control strategies which are used to eliminate matches which do not fit to the expectation. Before we discuss the experiments on matching accuracy under compression we first outline the transfer methods and give some more details about the used images.

5.1 Point Transfer

Basis of the point transfer procedure is area based least squares matching with the standard six geometric parameters of an affine transformation. For point transfer a point in the matching window is selected and transferred to the other image. For convenience mostly the center point in the matching window is used as reference or transfer point. Two strategic options are implemented in the transfer process. The first option called "Standard LSM" transfers the reference point from the master image to the slave image. If matching converges as expected and the plausibility check by cross correlation indicates a successful match then the point is transferred. The second option is "LSM with self control" which takes an additional check into account. A point transferred by Standard LSM is transferred back to the master image in a second match with an exchanged role of master and slave image. If the second match is successful too and the back transferred point location does not differ significantly (commonly 0.1 pixels deviation is tolerated) from the reference location of the point in the master image then this check is passed and the point is considered to be successfully transferred. From experience we know that points transferred with the self control mechanism are more reliable, i.e. matching errors appear not as often as in results obtained by Standard LSM.

For investigating the influence of the compression algorithms a sufficiently large sample size of points is used. Reference points for point transfer are simply defined by a regular grid. Precisely a sample of 3481 points is used in each series of the experiments.

5.2 More Details about the Used Image Data

With a real stereo image pair it is difficult to separate the influence of image compression on matching accuracy from the effects induced by a imperfect approximation of the geometric relation between the two images. Therefore we carry out the investigations with simulated stereo pairs and with real stereo image pairs.

The simulated stereo pair is created from one real image. A 1500 by 1500 pixel image is extracted from the original image. By cutting out a second image with an offset of one pixel in *x*- and *y*-direction a simulated stereo partner of the same size is obtained. Afterwards both images were put through the compression algorithms. For each of the three compression methods a series of compressed images with different compression ratios are generated. For point transfer the compressed images are decompressed to be available as a standard image matrix.

For the investigations with real stereo images, pairs of images of the already mentioned MOMS, DPA and RMK cameras are used (cf. Section 2). To have a reference for point transfer with compressed images the points transferred in the uncompressed image pairs are computed. The differences between point transfer in compressed and uncompressed images show the influence of the compression algorithms.

6 MATCHING ACCURACY IN COMPRESSED IMAGES

The results using simulated stereo images are discussed briefly in this section since that part of the investigation has already been presented in a previous paper (Hahn and Kiefner, 1998). The emphasis will be laid on investigations with real image pairs.

6.1 Investigations with Simulated Stereo Images

Point transfer in compressed images has been carried out for a series of compression ratios and all three image data sets. Figure 4 shows the results for the RMK Top image. The deviations between the match results and the known true parallaxes (rms values) are plotted with respect to its corresponding compression ratios. What may be noticed first by looking at the chart is that JPEG compression delivered more accurate results than Wavelet and Fractal compression. The JPEG curve is below the other both for almost the full range of compression ratios. An error level of 1/10 of a pixel is passed with JPEG images at a ratio of 1:7 whereas the same error is already obtained with Wavelet compression at a ratio of 1:4. For Fractal compression this mark

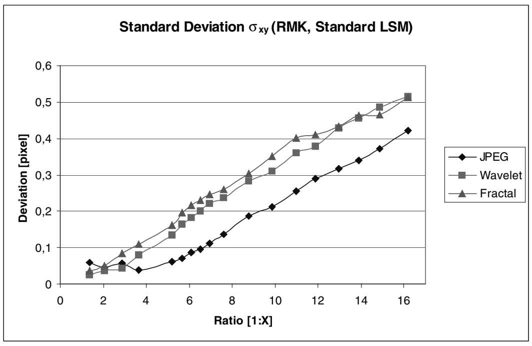

Figure 4: Point transfer errors for different compression ratios (RMK Top, Standard LSM))

is passed somewhere between the rations 1:3 and 1:4. The exact compression rates for the 1/10 of a pixel point transfer error level are listed in Table 2 for all three image types and for both point transfer strategies. Figure 4 shows the typical behavior of the error curves for accuracy for all three image data sets. In all images and for both point transfer strategies the ranking of the compression algorithms is observed:

1. JPEG
2. Wavelet
3. Fractal

Camera	Algorithm	Compression Ratio 1:X	
		Standard LSM	With Self Control
RMK Top	JPEG	5,6	6,7
	Wavelet	3,9	5
	Fractal	3	4,2
DPA	JPEG	3,8	4,5
	Wavelet	2	2,9
	Fractal	<1,8	2,2
MOMS-02	JPEG	9,6	10
	Wavelet	6,6	6,8
	Fractal	2	2,6

Table 2: Compression ratios 1:X which lead to a point transfer error of 1/10 of a pixel. (Standard LSM and LSM with Self Control)

The higher compression rates for point transfer mode LSM with self control satisfies the expectation. The reason is the elimination of a certain percentage of points transferred by Standard LSM which do not satisfy the requirements of self control. For compression ratio of 1:5 the loss of transferred points is between 5% and 10% for all three image types. The higher the compression rates the bigger is the difference between the two transfer methods.

6.2 Investigations with Real Image Pairs

For the experiments with the real image pairs Fractal compression is not taken into account because of its bad performance in all experiments carried out so far. The points transferred in the uncompressed image pairs are used as a reference for point transfer with compressed images. The deviations between point transfer in compressed and uncompressed images are calculated and used to measure the error induced by compression.

Figure 5 shows the error curves obtained for all three image data sets. Displayed are the results for compression ratios between 1:1 and 1:16. The point transfer strategy applied was Standard LSM. The superiority of the JPEG results over the Wavelet results can be directly seen from the graphs. The difference between the two lines for certain compression ratios is up to 0.1 pixel.

If a larger range of compression ratios is considered an interesting effect takes place. For rates above 20 the Wavelet compression leads to smaller point transfer errors and the JPEG algorithm takes only the second rank. But in this compression range the transfer errors are likely to be above the 0.3 (MOMS) or the 0.6(RMK) pixel error level which is not of interest in photogrammetric point transfer.

For comparison the exact compression rates for the 0.1 pixel error level are listed in Table 3 for the simulated and the real image pairs. For the RMK and MOMS data sets the compression

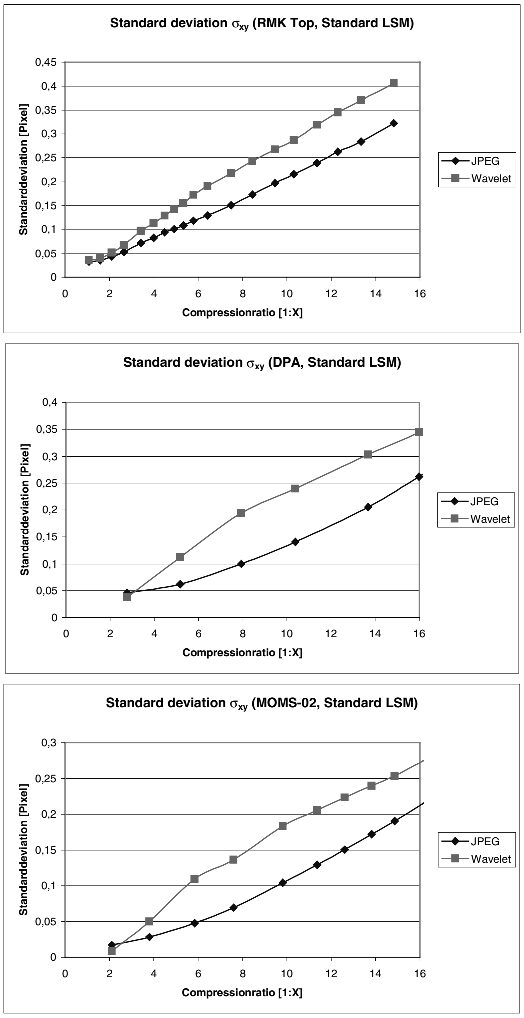

Figure 5: Accuracy of the point transfer of all images, Standard LSM

Camera	Algorithm	Compression Ratio 1:X (Standard LSM)	
		Simulated	Real Stereo
RMK Top	JPEG	5,6	4,8
	Wavelet	3,9	3,5
DPA	JPEG	3,8	7,9
	Wavelet	2	4,8
MOMS-02	JPEG	9,6	9,3
	Wavelet	6,6	5,4

Table 3: Comparison between real stereo images and the simulated stereo pair, Standard LSM

ratios for simulated and real stereo image pairs are fairly close. Looking at the DPA results a considerable difference of compression ratios can be noticed. Quite astonishing is that the higher rate has to be observed for the real image pair.

Vice versa this means, that for a given compression ratio less error influence propagates into the point transfer results than for the simulated DPA image pair. Just opposite is the situation for the RMK and the MOMS images. A sufficient explanation for this behavioral difference is not at hand.

The point transfer results of LSM with self control basically follow the results of Standard LSM. The graphical visualization is omitted since effectively the only difference is a certain shift and a minor variation in the inclination of the lines. The expectable higher compression rates for point transfer mode LSM with self control can be seen from Table 4. Roughly can be stated that an additional error of 0.1 pixels must be taken into account for point transfer in real image pairs at compression ratios of 1:5 to 1:7 for Wavelet compressed images and 1:6 to 1:10 for JPEG compressed images if the self control mechanism is applied.

Camera	Algorithm	Compr. Ratio 1:X (Standard LSM)
RMK Top	JPEG	6
	Wavelet	4,5
DPA	JPEG	8,5
	Wavelet	5,2
MOMS-02	JPEG	10,6
	Wavelet	7,1

Table 4: Compression ratios 1:X which lead a point transfer error of 0.1 pixel. (LSM with Self Control)

Thus the ranking remains unchanged: JPEG allows higher compression ratios than Wavelet if only small point transfer errors are tolerated. From the superior performance of Wavelet compression at stronger compression ratios (higher compression rates) precise point transfer can not really take advantage.

6.3 On the Validity of the Theoretical Model for Relating Compression to Accuracy

The validity of the model for relating compression noise to the accuracy of point transfer shall be examined with all three types of simulated and real image pairs. Experimental evidence for the validity of the theoretical model using simulated image pairs was already given in Hahn and Kiefner (1998). Therefore it is interesting to examine the model with the real image pairs of all three data sets.

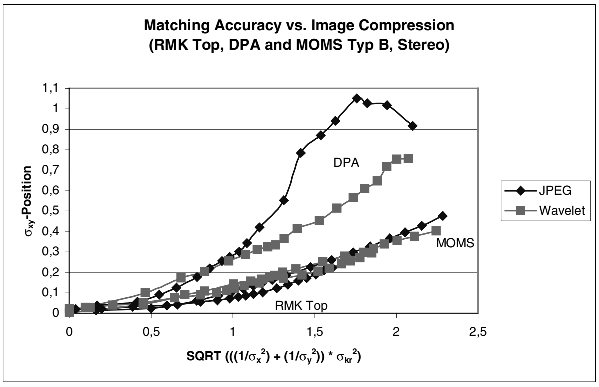

Figure 6: Relationship between matching errors and compression (real image pairs, LSM with self control)

In Figure 6 the point transfer error is plotted against the signal and compression noise dependent parameters defined in equation (3.2). Merely the scaling with the square root of the number of pixels in the matching window was not taken into account. A full confirmation of the model would be given if the graph would show one straight line for all three image types. Obviously the lines obtained for the real images differ from such a ideal model, in particular, for higher compression rates. Further a distinction must be made between the MOMS and RMK Top images in the one side and the DPA images on the other side. The results for the DPA images show big differences between JPEG and Wavelet compressed images and distinguish significantly from the other results. The lines for the JPEG and Wavelet results for MOMS and RMK Top images are fairly close to each other. And focussed on the that part of Figure 6 where the errors are below 0.1 pixel a straight line is certainly a reasonable approximation which supports the model for relating compression to accuracy. Nevertheless this results demand for a refinement of that model, e.g. by extending the model from white to correlated compression noise.

7 CONCLUSIONS

The goal of the presented work is to investigate the relation between image compression and the accuracy of point transfer. In this context image quality of compressed images plays an important role. Experiments with image quality measures, in particular the PSNR, show that Wavelet compression influences the compressed images less that JPEG and Fractal compression. Because the PSNR mainly depends on compression noise it is to be expected that the ranking between the different compression algorithms will propagate into the accuracy of point transfer.

Our primary interest is the establishment of a relationship between an image compression measure and the point transfer errors resulting from lossy image compression. It is well known that for least squares image matching in practice often a matching accuracy of 0.1 pixel is accepted as a very good result. If compressed images are taken into account the high accuracy is called in question. With simulated and real image pairs experiments are carried out to investigate the dependency between compression noise and matching error empirically for a large range of different compression rates.

Considering a compression induced error of 0.1 pixel as an acceptable error level for matching of compressed images, point transfer in real image pairs is limited to compression ratios of 1:5 (max 1:10) for JPEG compressed images, 1:3.5 (max 1:6) for Wavelet compressed images if a standard least squares matching procedure is applied. If point transfer is carried out with a self control mechanism limits for the compression ratios of 1:6 (max 1:10) for JPEG compressed images and 1:5 (max 1:7) for Wavelet compressed images are found from three different types of image data sets. Further Fractal compression was included in the experiments. Because its performance regarding image quality and point transfer errors was always at the lower end it can not be recommended for use in digital photogrammetry.

The ranking that JPEG compression yields better results than Wavelet compression was generally rather tight but true for all point transfer experiments. In summary, using lossy JPEG compression with a ratio of 1:5 should not negatively influence photogrammetric work with digital images. Even in high precision point transfer the produced error at compression rates less or equal to 5 is in the order of 0.1 pixels.

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