SOFTCOPY PHOTOGRAMMETRY WITH JPEG COMPRESSED IMAGES

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ABSTRACT

The aim of our research is to find out how softcopy photogrammetry responds to image compression. Specifically, we wish to know if using JPEG image compression leads to loss of accuracy in DTMs derived by softcopy methods. We first review JPEG compression, and since we use the Virtuozo softcopy photogrammetry software, we briefly review it's principle of operation. We analyse existing research on the effect of JPEG compression on the geometric accuracy of point location. We outline a method by which DTM accuracy can be meaningfully compared to the geometrical pointing precision, and then we apply the method to existing research on the accuracy of DTMs made with JPEG compressed images. We conclude that the accuracy of the DTMs made with JPEG compressed images is lower than we might expect from the studies of geometric pointing accuracy. Since this analysis was conducted assuming that the error covariance between the compressed and uncompressed image DTMs was approximately equal to the error variance of the uncompressed image DTM, we test this assumption by explicitly calculating the variances and co-variance, using a DTM produced by the analytical stereo-plotter as the ground truth. We also examine the bias that exists between the DTMs made with the softcopy workstation, and with the analytical plotter. The bias is not affected by compression, and it seems that it can be accounted for by systematic errors, introduced at the relative and absolute orientation stages, and possibly by scanning.

1 INTRODUCTION

Image compression is a standard option with many softcopy photogrammetry systems, and its use can significantly reduce storage space required for digital images. Unfortunately, compression introduces changes into the imagery which may affect the accuracy of photogrammetric operations such as DTM construction. Our research aims to discover the effect of JPEG compression on DTM accuracy. We first review JPEG compression in Section 2, and since we use the Virtuozo softcopy photogrammetry software, we briefly review it's principle of operation in Section 3. In Section 4 we briefly contrast softcopy photogrammetry with the operation of the analytical stereo plotter. In Section 5, we analyse existing research on the effect of JPEG compression on the geometric accuracy of point location. Then we examine existing research on the accuracy of DTMs made with JPEG compressed images in Section 6. We conclude that the accuracy of the DTMs is lower than we might expect from the studies of geometric pointing accuracy. Since this analysis was conducted assuming that the error covariance between the compressed and uncompressed DTMs was approximately equal to the error variance of the uncompressed DTM, we test this assumption in Section 7. We also address the bias that exists between the DTMs made with the softcopy workstation, and with the analytical plotter in Section 8. Some conclusions are drawn in Section 9.

2 JPEG COMPRESSION

In this paper we will confine our attention to the JPEG compression standard, which is comprised of four modes: lossless, sequential, progressive, and hierarchical. Sequential JPEG is a lossy compression scheme that divides the image into blocks of 8×8 pixels. Each block is transformed to a set of coefficients using the well known Discrete Cosine Transform (DCT), and then quantized using a frequency dependent quantization table. The table can be optimized for each image, and each different compression ratio, but commonly a default table suggested in the standard is used. This is scaled to give different compression ratios. Progressive JPEG uses a similar representation scheme to sequential JPEG, but the coefficients are transmitted in a sequence that allows a low resolution image to be quickly reconstructed, and then successively refined. Hierarchical JPEG sends a low resolution image encoded by one of the other JPEG modes. A succession of encoded difference images then convert the upsampled low resolution image to higher resolution images, until the original resolution is reached.

More details on the JPEG algorithm can be found in [9, 5, 2].

3 VIRTUOZO SOFTCOPY PHOTOGRAMMETRY SOFTWARE

Automatic techniques for the production of DTMs using digital stereo images are widely used in photogrammetry and computer vision. The basic principle involved in the recovery of 3D information is matching the corresponding pixels in the stereo images. The 3D coordinates of that point may then be obtained by triangulation using the disparity of the corresponding pixels and knowledge of the image capturing geometry. Stereo image matching is the first and most difficult step in recovering 3D information from a pair of aerial or satellite images. The Virtuozo matching method is correlation based, within a probability relaxation framework. A Hopfield model neural network is also used. Probability relaxation is a useful technique for ensuring consistency among neighboring matching points. Compared with the traditional methods, the matching results reduce local ambiguity and enhance global consistency [13, 10]. A problem of many correlation based approaches is that the presence of a slope in the terrain effectively shrinks or expands the length of a feature by different amounts in each stereo image, which leads to unreliable matching. Virtuozo uses bridge mode processing to overcome this difficulty. This essentially re-samples corresponding regions in each image so that they can be meaningfully correlated. The neural network takes spatial relationships into account and greatly improves global consistency. The commonality between the probability relaxation method and the neural network technique make Virtuozo image matching quite efficient. A more detailed description of the Virtuozo system can be found in [12].

4 SOFTCOPY PHOTOGRAMMETRY COMPARED TO ANALYTICAL STEREO PLOTTER

The standard method of producing DTMs over the past two decades has been by the analytical stereo plotter which makes use of the innate stereo vision of the human visual system. In this process, the human operator uses their stereo vision skills, and image interpretation skills to place a 3D floating mark on the ground surface at each point whose height is to be measured. An example of the image understanding typically used by the operator, is in pushing the floating mark down through vegetation to the actual ground surface. This requires the operator to differentiate between ground surface and vegetation, and to visually interpolate the ground position.

Softcopy photogrammetry has yet to duplicate this level of image understanding, and typically produces a surface that sits on top of any vegetation cover. However the human skill is not completely removed, since the operator can still review and edit the automatically produced contours. The greater speed and facility with which DTMs can be produced using softcopy methods has meant that these systems are replacing stereo plotters in many situations.

5 GEOMETRIC ACCURACY

In the photogrammetric literature, the changes introduced into an image by compression have usually been addressed in terms of radiometric accuracy and geometric accuracy of point location. We shall concern ourselves more with the geometric changes, as they are directly responsible for introducing additional sources of error into a DTM. There has been a number of attempts to address the question of how JPEG compression affects the geometric accuracy of point location. Typically, a least squares adjustment is used to solve for the radiometric and geometric distortion parameters for corresponding patches of the uncompressed and compressed images [1, 4, 11]. These studies, though using very similar techniques, are not easy to compare. This is because even though the experimental methodology seems similar, results are reported in differing ways, and details of the photography parameters and pixel size are not uniformly given. The Novak and Shahin study [4], for example, provides no details on the flying height, focal length, or pixel size, which would allow the results to be meaningfully compared to other studies. Caution is therefore required in drawing any general conclusions from their result. After a least squares adjustment of 2500 defined points, they report that the rms error in locating the points was 0.038 pixels in the x direction, and 0.042 pixels in the y direction for a JPEG compression ratio of 5.9:1.

Jaakola and Orava [1] use a 1:16,000 stereo pair, with focal length of 213.590 mm, which gives an approximate flying height of 3417 m. They compared manual pointing, and an automatic method using least squares to find the absolute errors (difference from ground measurements) and relative errors (difference from points located on the original image). The original image was scanned at 7.5 μm. They found that for compression ratios smaller than 6:1, the rms error in geometric point location was less than 0.4 μm, which works out to 0.053 pixels. This seems in rather good general concordance with the result reported by Novak and Shahin. An additional result was that as the size of the match window increased, the size of the error was reduced. This is to be expected because of the nature of the least squares process. The least squares process does not measure a particular point, but the geometric transformation from the uncompressed to the compressed match window. Therefore, small image patches are more likely to be affected by compression artifacts that introduce a bias in one or another direction. As the match window gets larger, we expect that the random nature of these biases would tend to cancel each other out, reducing the rms error towards zero. We would expect from this that the size of the matching window would similarly affect the accuracy of stereo image matching for compressed images.

A similar methodology is used by Zeng and Ze [11], but it is difficult to make meaningful comparisons with the other two studies because no details are given of the photography. Zeng and Ze also report their results differently, giving the percentage of points where the geometric distortion is less than 0.1 pixels, rather than the rms value of the geometric distortion as in the other studies cited. They conclude that for 6:1 JPEG compression, 90% of the points suffer geometric distortion of less than or equal to 0.1 pixels. If we assume that the errors are normally distributed, then we can use standard tables to calculate that the standard deviation should be $\frac{0.1}{1.28} = 0.078$ pixels. If the errors have zero mean, which seems a reasonable assumption in the lack of any knowledge to the contrary, then this is equivalent to the rms error. This is somewhat more than that reported in the other studies. However, the match window considered was 15×15, compared to 20×20 in the Jaakola and Orava study, which could account for some of the apparent increase.

Given the differences in imagery and procedure, the three studies, summarized in Table 1, agree remarkably well with each other. For JPEG compression of around 6:1, it seems that a geometric pointing error of between 0.05 and 0.1 pixels is introduced. The error is greater for smaller match window sizes, but may vary in unknown ways with respect to other image properties.

Lammi and Sarjakoski [2, 3] have also investigated the pointing accuracy possible with JPEG compressed images, but they used a manual pointing methodology rather than a least squares adjustment. Their imagery was scanned at 600 dpi using a desktop scanner, which is equivalent to a pixel size of approximately 41 μm. No other details of the imagery are given, but from their illustrations it appears to be fairly low level imagery as cars and a pedestrian crossing are easily identified. They conclude that a geometrical pointing accuracy of 0.30 pixels is achieved with a compression ratio of 7:1, and only slightly less, 0.31 pixels, at a ratio of 15:1. This study seems to be at odds with the previous studies. However, this difference may be explained by the difference in method. It seems reasonable that least squares matching would prove to be much more accurate than the human eye.

Table 1: Summary of studies of geometric accuracy of point location for JPEG compressed images, using a least squares method to determine accuracy.

	Novak	Jaakola	Zeng
rms error	0.040	0.053	0.078
window	-	20×20	15×15
Compression	5.9:1	6:1	6:1
Flying Height	-	3417m	-
Focal Length	-	213.590 mm	-
Pixel Size	-	7.5μm	

A problem with these studies is that compression ratio is used to characterise the degree of compression in the image. Previous work [6, 7] has shown that because of the variability in images, the compression ratio does not correlate well with the amount of error introduced by JPEG into DTM construction. Much more meaningful is the degree by which the DCT coefficients are quantized. This is set by the JPEG quantization table. The degree to which the DCT coefficients are quantized is the mechanism for introducing the distortions, so it is not surprising that this shows a much clearer relationship to DTM accuracy across different images. Typical JPEG implementations use a scaling of the standard quantization table to achieve different degrees of compression. Many JPEG implementations use a Quality Factor (QF) which maps to the quantization scaling factor. This means that to meaningfully compare different studies, we should know the quantization table used to achieve each compression ratio. If the quantization table is a result of scaling, then it is sufficient to know the scaling factor, and the original quantization table. Without these details, it is difficult to meaningfully compare results, even if the compression ratios are similar.

6 DTM ACCURACY

DTM construction using compressed stereo image pairs has also received attention in the literature. Robinson et al. [8] studied the effect of compression and pixel size using a single stereo pair of 1:18,000 scale photography with focal length 152mm, giving an approximate flying height of 2736 m. Pixel sizes used were 15, 30, 45 and 60μm. DTMs were constructed on an Intergraph ImageStation Photogrammetric Workstation, which uses feature based matching (MATCH-T). The following points are summarized from their graphical results. For 15μm pixels, and compression less than 8:1, the rms value of the difference between the compressed image DTM and the original DTM is less than 0.05°/$_{oo}$H. For 30μm pixels, it is less than 0.1°/$_{oo}$H. For 45μm, it is less than 0.18°/$_{oo}$H. For 60μm, it is less than 0.24°/$_{oo}$H. These values have been conservatively read from the graphical results in the original paper. It is difficult to compare these results directly to the studies of geometric accuracy in Section 5, but a rough comparison can be made using the relationship

$$\sigma_h = \frac{H}{p}\sigma_d \tag{1}$$

where σ_h is the standard error of the DTM height, σ_d is the standard error of the disparity, and p is the stereo baseline on the photographs, which we can take as 95mm for typical metric cameras and photography with 60% overlap.

We should also take into account the additional errors that contribute to the final accuracy of the DTM. These include the vertical control accuracy, σ_{cn}, the vertical accuracy of triangulation, σ_{vt}, the model orientation accuracy, σ_o, and the spot height accuracy of the model, σ_m. Since these errors are likely to be for all intents and purposes the same whether the model is made with compressed images or not, we can lump them together into one error term, σ_{ef}, containing all the errors which remain *fixed* regardless of the image compression. Although this may not be strictly accurate in all situations, an effort was made in both Robinson's work and our previous work [7] to keep these other error terms constant by retaining the orientation parameters from the original imagery for DTM construction with the compressed images. Including the height error introduced by compression as σ_{ec}, we can represent this as

$$\begin{aligned} \sigma_c^2 &= \sigma_{cn}^2 + \sigma_{vt}^2 + \sigma_o^2 + \sigma_m^2 + \sigma_{ec}^2 && (2) \\ &= \sigma_{ef}^2 + \sigma_{ec}^2 && (3) \end{aligned}$$

where σ_c is the standard error of the DTM made with compressed images.

The error propagation equation can be used to relate the standard deviation of the difference between compressed and uncompressed image DTMs, and the standard errors of each DTM. Letting σ_r represent the standard deviation of the residue between the two DTMs, σ_u the standard error of the DTM made with uncompressed images, and σ_{uc} the cross correlation between the errors,

$$\sigma_r^2 = \sigma_c^2 + \sigma_u^2 - 2\sigma_{uc} \tag{4}$$

Substituting Equation 2 and noting that $\sigma_u^2 = \sigma_{ef}^2$, we obtain

$$\sigma_{ec}^2 = \sigma_r^2 - 2\sigma_{ef}^2 + 2\sigma_{uc} \tag{5}$$

Unfortunately, we can't ignore σ_{uc}, as this typically results in a negative quantity for σ_{ec}^2, which is clearly absurd. Particularly for low values of compression, we expect that σ_{uc} will approximately equal σ_{ef}^2. Therefore as a first approximation, we can say

$$\sigma_{ec}^2 = \sigma_r^2 \tag{6}$$

The actual values of σ_{uc} is something we try to address experimentally Section 7.

To get an estimate of the geometrical pointing precision implied by the standard error of the difference between the two DTMs made with compressed and uncompressed imagery, we can make use of Equation 1. This will allow us to refer the heighting error introduced by compression, to a disparity error. Assuming that an equally distributed independent error in each compressed image contributes to the disparity error, the standard error of geometric point determination in each compressed image, σ_x, is given by

$$\begin{aligned} \sigma_x &= \frac{1}{\sqrt{2}}\frac{p}{H}\sigma_{ec} && (7) \\ &\approx \frac{1}{\sqrt{2}}\frac{p}{H}\sigma_r && (8) \end{aligned}$$

Using Equation 8 we can convert the standard error of the DTM residues into equivalent geometric pointing accuracies for each compressed image. This value is then directly comparable to geometric accuracy reported in Section 5.

Referring again to Robinson's study, they report the rms difference between DTMs as less than 0.05 $^{o}/_{oo}$H for compression less than 8:1, and pixel size of 15μm. Using the relation of Equation 8, σ_x is found to be 3.36μm, or 0.22 pixels. The same value is obtained in the 30μm case, though the value increases for the larger sized pixels. This result is considerably larger than expected from the results cited in Section 5. Robinson's results are summarized in Table 2.

Table 2: Summary of geometric point location accuracy inferred from Robinson for JPEG compression less than or equal to 8:1. Flying height is 2736m, focal length is 152mm.

Pixel Size		15μm	30μm	45μm	60μm
σ_r ($^{o}/_{oo}$H)		0.05	0.1	0.18	0.24
σ_x	μm	3.36	6.72	12.1	16.1
	pixels	0.22	0.22	0.27	0.27

A similar study using a number of different image pairs has been previously published [7, 6] in which we used the Virtuozo softcopy photogrammetry system to construct DTMs. A range of flying heights and compression ratios were considered, for a pixel size of 25μm. Our aim was to see whether the relationship between DTM accuracy and compression held for different imagery, from different heights and of differing terrain. We found that the standard deviation of the residue between the DTM made with compressed imagery and the original DTM varied between approximately 0.1 $^{o}/_{oo}$H and 0.2 $^{o}/_{oo}$H for all of the six stereo pairs that we investigated, as long as the JPEG quality factor was less than 40. This quality factor represented a scaling of the standard quantization table by a factor of 1.25, and a compression ratio of 7:1 up to 13:1. Since the pixel size in our test was either 22.5 μm or 25 μm, this converts, via Equation 8, to a geometric precision of between 0.25 pixels and 0.59 pixels. Though this is somewhat higher than that computed from Robinson's results, it is still sufficiently close to give overall support to those figures. The results show that the accuracy can vary with the imagery, and other photogrammetric properties of the DTM production process. A summary of our results is shown in Table 3.

Both our study and Robinson's indicate a discrepancy between the predicted geometric accuracy, between 0.05 and 0.1 pixels, and the expected geometric accuracy derived from the DTM residue, of between 0.22 and 0.59 pixels. This indicates that either the precision of point location predicted is not achieved in the softcopy workstations which were used, or that there is another dominant source of error which arises from the effects of compression, or that there are deficiencies in the method used to calculate the geometric pointing error from the DTMs residue.

6.1 Alternate Sources of Error

In both Robinson's study and ours, the orientation was kept from the original imagery, and not re-done for each set of compressed images. In the Virtuozo system, this meant performing epi-polar re-sampling, and then image matching to generate the disparity values used to create the DTM. Therefore the error could only have been introduced at these two steps. The epi-polar re-sampling could introduce noise into the process, but it is difficult to see how this would be increased in the case of the compressed images. Therefore we conclude that it is unlikely that JPEG compression introduces another dominant source of error besides a deterioration in geometrical precision.

Table 3: Summary of our findings for DTM accuracy using JPEG compressed images. Six stereo pairs were used with properties as shown. Values for the residue refer to JPEG compression for using the standard's suggested quantization table, scaled by up to 1.25. At this threshold, compression ratios varied from 7:1 to 13:1. Pixel size is 22.5μm, except for Gayndah, which is 25μm

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	Redland	Gayndah	Willunga (H)
H	6503m	245m	7575m
f	303.71mm	152.54mm	153.02mm
σ_r	0.121$^{o}/_{oo}$H	0.094$^{o}/_{oo}$H	0.188$^{o}/_{oo}$H
σ_x	8.13 μm 0.36 pixels	6.31μm 0.25 pixels	12.63μm 0.56 pixels
	Coalstack	Splityard	Willunga (L)
H	622m	532m	3060m
f	153.202mm	152.02mm	153.15mm
σ_r	0.154$^{o}/_{oo}$H	0.198$^{o}/_{oo}$H	0.142$^{o}/_{oo}$H
σ_x	10.34μm 0.46 pixels	13.30μm 0.59 pixels	9.54μm 0.42 pixels

6.2 Deficiencies in Calculation Method

It is quite possible that there are deficiencies in the calculation method, since we assumed that σ_{uc} approximately equals σ_{ef}^2. The only way to test the accuracy of this assumption is to actually measure the quantities and compare them. However, without a ground truth, these quantities can't be exactly evaluated. To gain some kind of understanding of how the co-variance behaves, we used the Planicomp stereo-plotter to construct DTMs for the same stereo pairs as used on the softcopy workstation. We used the Planicomp model as an approximation of the ground truth, and used it to evaluate the co-variance. The results of this experiment are reported in Section 7.

6.3 Workstations not achieving Predicted Accuracy

Another possibility is that the softcopy workstations were not achieving the accuracy of geometric point location predicted in the studies of geometric precision from Section 5. Robinson et al. [8] refer to the theoretical accuracy of the feature based matching of the MATCH-T process used in their research as around 0.33 pixels. This is in good agreement with the result calculated for the geometric precision based on the DTM residue, since we expect

$$\begin{aligned}\sigma_d &= \sqrt{\sigma_x^2 + \sigma_x^2} && (9)\\ &= \sqrt{0.22^2 + 0.22^2} && (10)\\ &= 0.31 && (11)\end{aligned}$$

where σ_d represents the standard error of the disparity measurement. On the face of this, it would seem that the suppo-

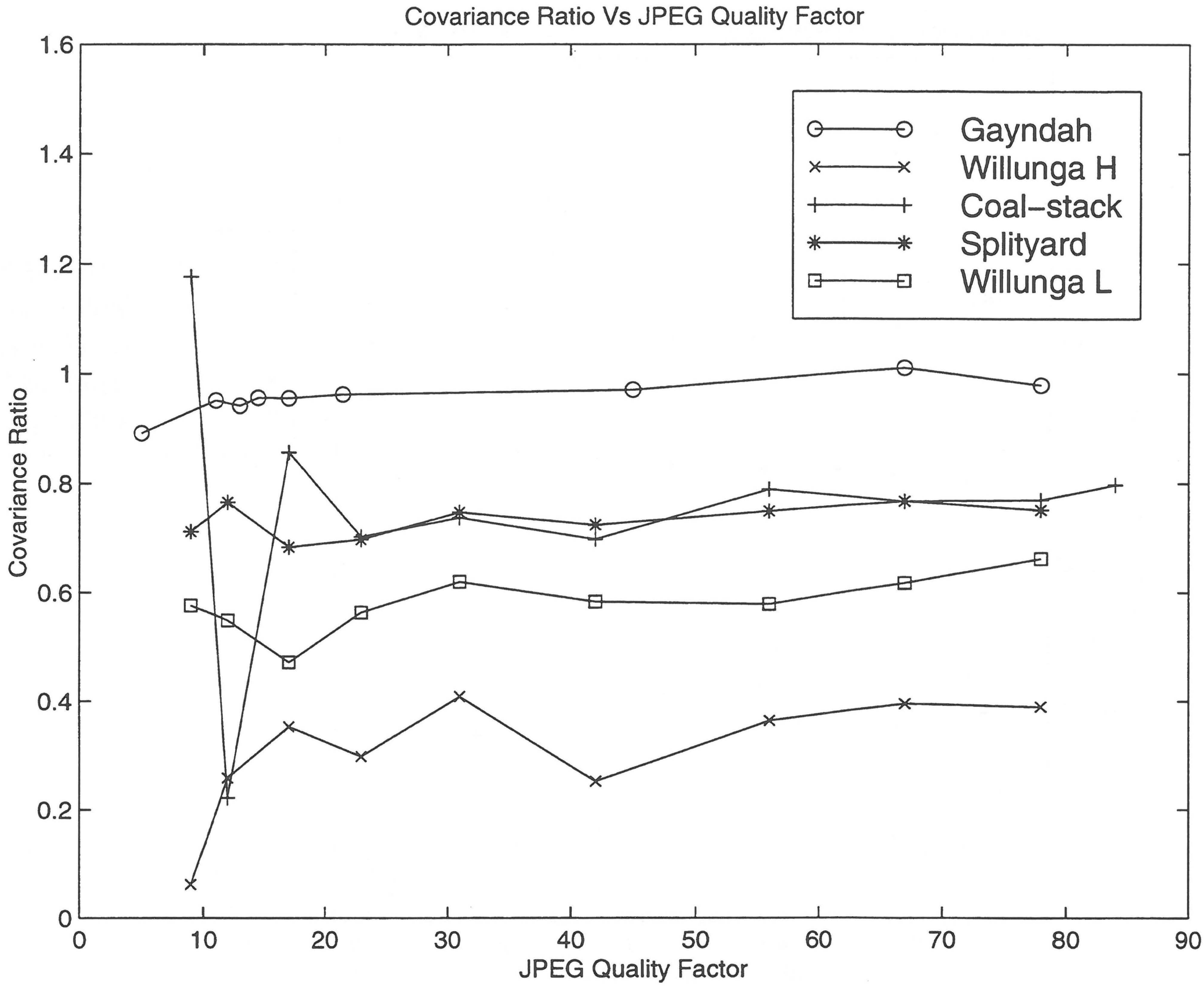

Figure 1: The ratio of the covariance of the residues, $\sigma_{(u-p)(c-p)}$ to the variance of the difference between the softcopy DTM (uncompressed images) and the Planicomp DTM, σ^2_{u-p}.

sition that the softcopy workstations were achieving accuracy in the order of 0.33 pixels in finding the disparity to be quite reasonable. The results of our own experiments indicate that this figure of accuracy can vary according to the imagery. As we will report in the following section, the figures arrived at in this section, and reported in Tables 2 and 3 should be considered an upper bound on the error introduced by JPEG compression, which is likely to be substantially less in many cases.

7 INVESTIGATION OF THE ERROR COVARIANCE

In the previous analysis, it was assumed that the error in DTM accuracy due to image compression was equal to the standard deviation of the residue between the DTMs made with compressed and uncompressed images. However this depended on the assumption that $\sigma_{uc} = \sigma^2_{ef}$. In order to test the reasonableness of this assumption, we constructed DTMs for our test imagery using an analytical stereo-plotter. Though not ideal because the accuracy is likely to be similar or only slightly better than the softcopy DTMs, it should at least give us insight into the behavior of the error covariance, if not its precise value.

The accuracy of the Planicomp DTM can be computed from Equation 2, where the error due to compression, σ_{ec}, is taken to be zero. The resulting accuracies for our imagery are shown in Table 4.

Once the stereo-plotter DTMs had been constructed, the following quantities were evaluated,

- σ_{u-p}, the standard deviation of the difference between the softcopy DTM made with uncompressed imagery and the DTM made on the Planicomp stereo-plotter (approximates σ_{eb}),
- σ_{c-p}, the standard deviation of the difference between the softcopy DTM made with compressed images and the Planicomp DTM,
- $\sigma_{(u-p)(c-p)}$, the covariance of the differences (approximates σ_{uc}) .

These quantities were evaluated at a number of different JPEG quality factors. In Figure 1 we show a plot of

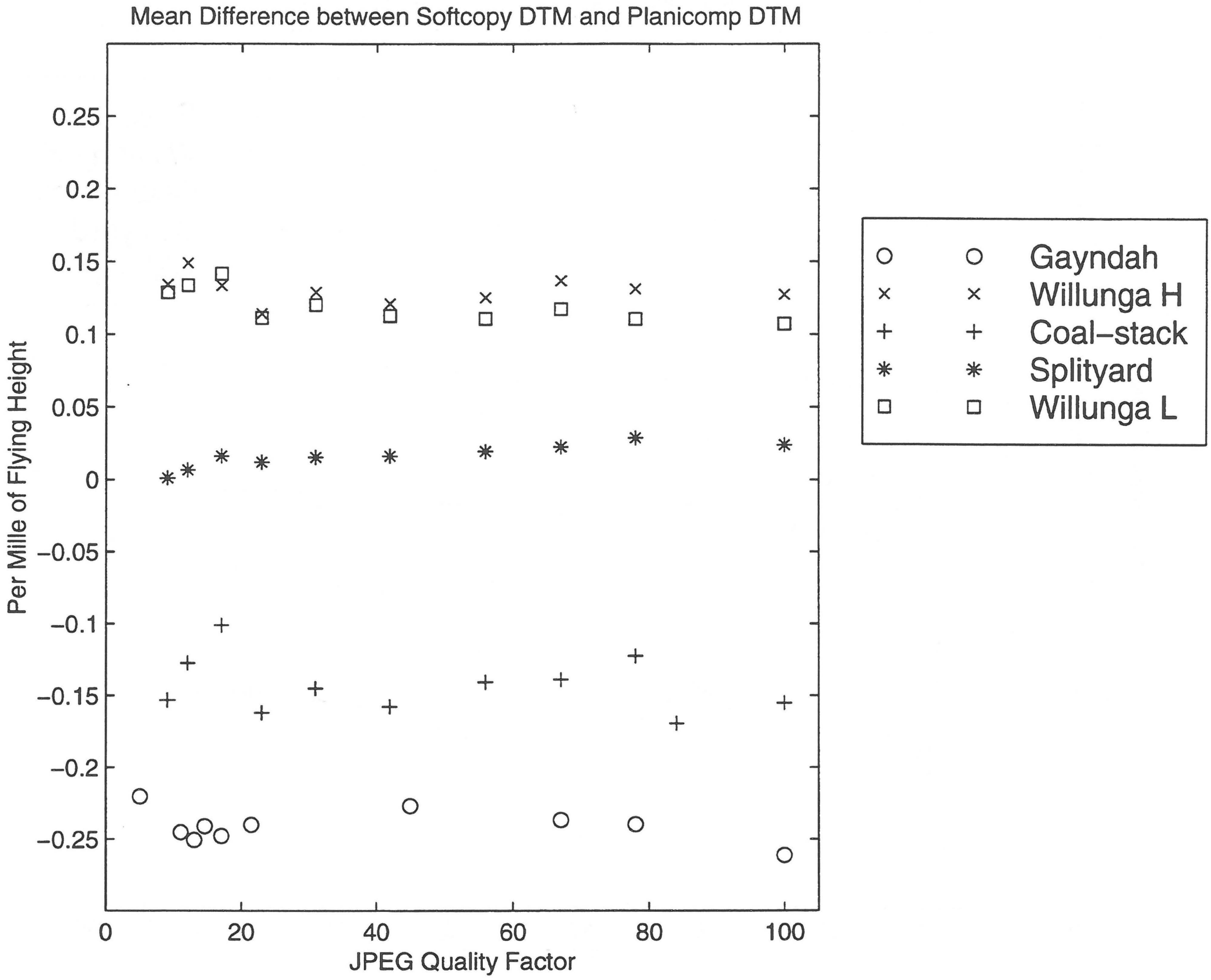

Figure 2: The ratio of the covariance of the residues to the variance of the difference between the softcopy DTM (uncompressed images) and the Planicomp DTM.

Table 4: Estimated accuracy of DTMs constructed on stereoplotter. The vertical control accuracy is as shown, the vertical accuracy triangulation is taken as 0.1 $^{\circ}/_{oo}$H, and the model orientation accuracy and the model spot height accuracy are both taken as 10μm at photoscale. Equation 2 is used to calculate the DTM accuracy.

	Redland	Gayndah	Willunga (H)
Vert. Control	0.05m	0.05m	0.02m
Accuracy	0.110$^{\circ}/_{oo}$H	0.236$^{\circ}/_{oo}$H	0.137$^{\circ}/_{oo}$H
	Coalstack	Splityard	Willunga (L)
Vert. Control	0.05m	0.05m	0.02m
Accuracy	0.158$^{\circ}/_{oo}$H	0.165$^{\circ}/_{oo}$H	0.136$^{\circ}/_{oo}$H

$\frac{\sigma_{(u-p)(c-p)}}{\sigma^2_{u-p}}$, which will allow us to judge how well σ^2_{u-p} approximates $\sigma_{(u-p)(c-p)}$. Figure 1 shows that only in the Gayndah photography is the assumption that $\sigma_{uc} = \sigma^2_{ef}$ likely to be valid. In the other cases $\sigma_{(u-p)(c-p)}$ is less than σ^2_{u-p}, indicating that σ_{uc} is likely to be less than σ^2_{ef}. Equation 5 then implies that the error introduced by compression should be *less* than the standard deviation of the residue. This means that the values of σ_x we found in Section 6 for our test sites are generally too conservative.

8 INVESTIGATION OF BIAS

We have dealt, up to this point, with the standard error as being a measure of the accuracy of a DTM. However, it is not sufficient to simply look at the standard deviation of errors. We must also look at the mean value of the errors, to see whether any bias exists in the DTM. Because we don't have an independently surveyed ground truth, for this study, we once again make use of DTMs made on the analytical stereoplotter as the ground truth. The mean value of the difference between the softcopy DTM and the Planicomp DTM for a number of JPEG quality factors is shown in Figure 2

From this figure two principal findings emerge. Note that the case for no compression is included on the figure, plotted at Quality Factor of 100. From this it can be seen that compression has little impact on the bias. Secondly, the mean values are distributed between approximately -0.25 $^{o}/_{oo}$H and 0.15 $^{o}/_{oo}$H. This is not consistent with the bias being introduced solely due to the softcopy DTM sitting on top of the vegetation cover. If this was the case, we would expect the mean difference to be always positive, reflecting that the softcopy DTM was a little higher than the Planicomp DTM. From our results, we can simply note that the softcopy process can have a bias when compared to the DTM produced on an analytical plotter. Although the number of stereo models is insufficient to form a decent sample, we postulate that the bias can be sufficiently explained by systematic errors introduced into the construction of each model at the relative and absolute orientation stages, and as such unavoidable. It is also possible that scanning could introduce systematic errors, but there is really no basis for saying how the systematic errors are introduced.

9 CONCLUSIONS

Studies of the influence of JPEG compression of about 6:1 on geometric accuracy have shown that an rms error of between 0.04 and 0.078 pixels can be expected, when using a least squares adjustment to find the parameters of transformation. The rms error will increase as the match window size decreases.

A problem comparing different studies is that changes introduced into the image as a result of compression, which effect geometric accuracy, depend on the quantization table used in the compression. The same quantization table can result in widely varying compression ratios in different imagery. The quantization table is usually obtained by scaling the table suggested in the standard. Future studies should provide information on the quantization table and its scaling used to achieve a particular compression ratio. This will assist in comparing different research.

By using well known photogrammetric formulas, the variance of the residue between the compressed image and uncompressed image DTMs can be converted to an equivalent geometric pointing precision. This value can be meaningfully compared to the geometric accuracy found in other studies. We found that the equivalent geometric pointing precision of DTMs made with JPEG compressed images of quality factor 40 or greater was between 0.25 and 0.59 pixels. A quality factor of 40 corresponds to a scaling of the standard's suggested quantization table by 1.25, and results in compression ratios between 7:1 and 13:1 for our imagery. This result was generally supported by an analysis of results reported by Robinson [8]. The resulting geometric accuracy was poorer than expected. This was thought to be because the theoretical pointing accuracy was not achieved by the softcopy workstations, and also because the calculation method tended to overestimate the value. The overestimation was caused by assuming that the covariance of the uncompressed and compressed image DTM errors was roughly equal to the variance of the uncompressed DTM errors.

We used DTMs made on a Planicomp stereo-plotter to evaluate, as far as possible, the actual values of the covariance of the uncompressed and compressed image DTM errors and the variance of the uncompressed DTM errors. This showed that compression had very little effect on the covariance. It also showed that the covariance was typically significantly less than the variance of the uncompressed DTM errors. This means that the standard deviation of the residue between the compressed and uncompressed image DTMs overestimates the error in the DTM due to compression.

We also used the Planicomp DTMs to examine whether any bias is introduced into the softcopy DTMs. However, such bias as there was seemed reasonably explained by systematic errors introduced at the relative and absolute orientation stages of constructing each model, with perhaps a contribution from the scanning process.

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