Quality assessment of digital elevation models produced by automatic stereo matchers from SPOT image pairs.

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ISPRS COMMISSION III

Abstract

A number of published stereo matching algorithms have been implemented and tested on SPOT images of areas for which we have gridded digital elevation models (DEMs) available with spacings of $80m$ or less as well as ground control checkpoints.

Results will be presented for a comparison of stereo matched output with the DEMs and an analysis of the errors arising and their causes. Results will be discussed for planimetrically geocoded and epipolar resampled data. An error budget describing effects due to orientation, feature localisation and matching will be discussed and conclusions drawn for future work in this area.

1 Introduction

The automated generation of Digital Elevation Models (DEMs) from SPOT images has been a primary goal of several different groups (see review by [Dowman, 1987]) around the world from private sector companies (see [Simard et al., 1987] [Swann et al., 1987] [Vincent, 1987]) to mapping organisations [Guichard, 1987]. All of these attempts use resampled epipolar image data [O'Neill and Dowman, 1988] [Otto, 1988] as inputs to the stereo matching process to restrict the search space severely.

The Alvey MMI-137 joint university-industry-government project [Muller and Day, 1987] is concerned with producing accurate DEMs from level 1A ("raw") SPOT image data within a couple of hours for the whole 6000 by 6000 pixel images (loc.cit.) and at video refresh-rates for windows within the image (loc.cit.) using a transputer-based parallel MIMD machine (loc.cit.). One of the primary objectives of this investigation has been to perform an evaluation both in terms of speed and quality. Results for speed (loc.cit.) indicate that existing algorithms can be significantly speeded up using modifications of existing stereo matching algorithms. This paper describes some preliminary results of quality assessment of DEMs generated by three different stereo matchers on SPOT image data.

Previous assessments of quality of automated stereo matchers can be grouped into three categories :

- Theoretical noise models [Foerstner, 1982] [Foerstner, 1984].
- Empirical studies with noise-correlated data [Ehlers, 1985] [Paine, 1986] or limited area data [Li, 1986].
- Empirical studies with satellite data and a priori data of dubious quality [Cooper et al., 1986] [Cooper et al., 1987] [Ley, 1987].

Previous photogrammetric quality assessment techniques based on the use of isolated random checkpoints is clearly nonsensical when stereo matchers produce millions of point pairs and when stereo matcher output will be primarily assessed on the basis of the blunder rate (as many authors have shown sub-pixel acuity for stereo matching).

In this work, we decided to attempt to take a purely empirical approach which had several novel aspects :

- Comparison of accuracy, reliability and sampling densities of three stereo matchers : one epipolar-based (PMF), one non-epipolar (Barnard and Thompson) and one quasi-epipolar (Gruen).
- Use of a gridded reference DEM independently obtained from underflight photography using manual photogrammetric measurements of almost 100,000 spot heights with a 30m planimetric

grid and exterior orientation from independent control.

- Difference statistics for both "raw" stereo matcher output and grid-point triangulated/interpolated measurements at the same planimetric grid-points as our reference DEM.
- Investigation of any correlation of blunders with (i) changes in image content (clouds) or contrast (harvested fields); (ii) mean slope; (iii) water features with low Signal-to-Noise Ratio (SNR) [Ehlers, 1985].

2 Description of Data

2.1 SPOT Images

We have so far been working entirely with a set of three SPOT images (scene number 50–252) of the Aix-en-Provence region in the South of France, kindly provided as part of the SPOT-PEPS experiment [Muller and Day, 1987].

While the vertical image is free of any noticeable atmospheric effects, the left is affected by haze which acts as multiplicative noise and lowers the contrast range of features considerably. The right image contains several completely opaque clouds, but is as of as high quality as the vertical image away from these. The images are also affected by horizontal and vertical stripes; artifacts of the pushbroom sensor. Although this problem has been solved by SPOT for images originating after July '85, images produced before then apparently cannot be corrected [Begni, 1987].

2.2 Ground Control DEM Data

All the images cover Montagne Sainte Victoire, an area for which we have two detailed DEMs :

- A $12.42km$ by $6.9km$ DEM with $30m$ spacing produced in the department by manual photogrammetric measurement of spot heights from contemporaneous underflight aerial photography. This DEM is unusual in that the operator measured the top of the tree canopy, where it was present, rather than attempting to estimate ground elevation, therefore it should be directly comparable with stereo-matcher output. The accuracy of the measurements was estimated by multiple set-up and observation of several blocks within the DEM (see below).
- A $12.4km$ by $12.4km$ DEM with $80m$ spacing provided as part of the SPOT-PEPS programme, which was produced from interpolation of digitised contours by IGN. No information on the quality of this dataset was provided, and it was considered to be of too poor quality to be used here after comparison with coinciding points in the 30m DEM revealed differences between $-51.5m$ and $74.6m$, with a standard deviation of $14.7m$ [Muller and Day, 1987].

An analysis of 830 duplicate (i.e. set up and measured twice) points of the $30m$ DEM gives the following results:

- Mean difference $= -0.026m$
- Standard deviation $\sigma = 1.837m$
- Maximum absolute difference $= 14.658m$
- 1.7 % of duplicate points have absolute difference greater than 3σ

So, assuming these are typical of all 95865 points of the DEM (though obviously the maximum absolute error can be expected to rise with more points), the $30m$ DEM should be adequate for testing stereo-matchers up to our target accuracy of an RMS error of $5m$ in height. However, we must beware of classifying individual points as erroneous, due the possibility of a few large ($> 15m$) errors in the DEM.

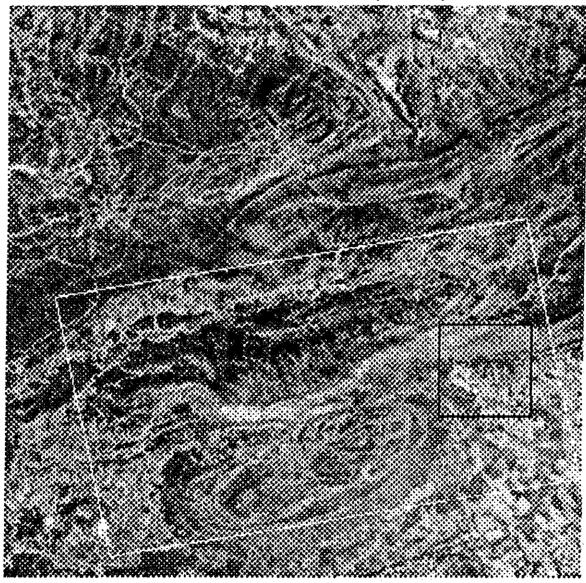
2.3 Stereo Matchers Tested

All the stereo matchers used are adaptations of existing published algorithms, and were implemented by project collaborators (PMF and Gruen on conventional hardware by UCL's department of computer science [Chau, 1987] [Chau and Otto, 1987a] and Barnard and Thompson on transputers by the Royal Signals and Radar Establishment at Malvern [Collins et al., 1987], [Muller et al., 1988a]).

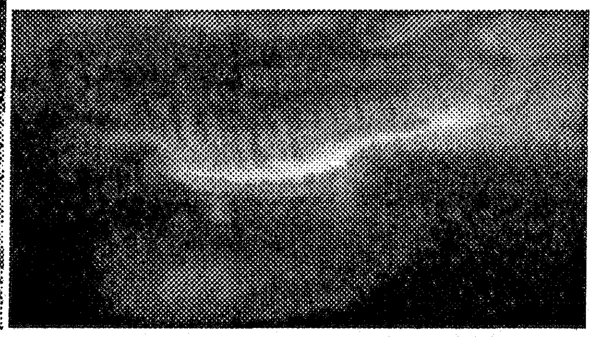
2.3.1 PMF

This is an edge-based matcher developed at Sheffield as part of Alvey IKBS-025 (3D surface representations and 3D model based vision from stereo) [Pollard et al., 1985]. It operates only along scan lines, and therefore requires epipolar images. SPOT images of the same area are generally rotated

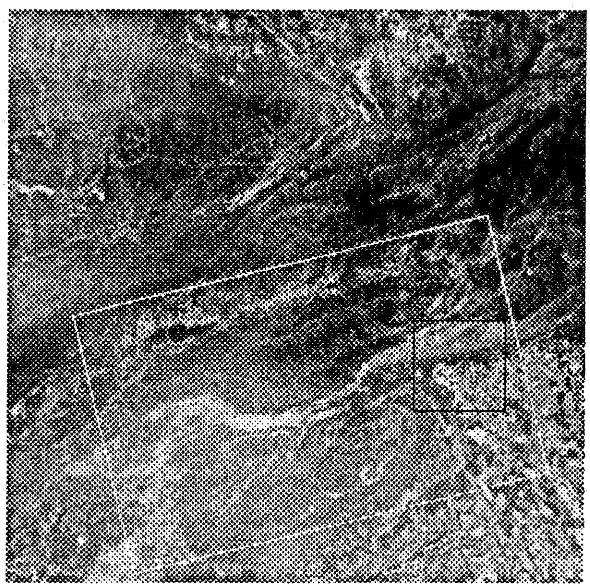
Figure 1: Extracts from left, vertical and right images showing the location of the 30m DEM (white) and 240 by 240 pixel test areas (black).



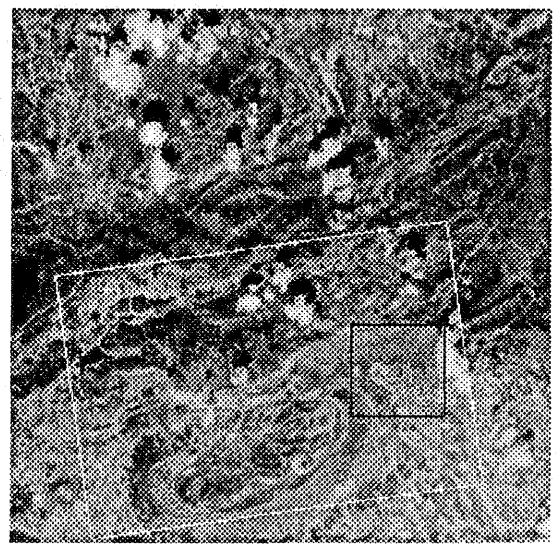
Vertical image



Intensity range image of 30*m DEM*
Elevation range: 191.7*m to* 1011.0*m*



Left image



Right image

with respect to each other (i.e. different scene orientation angles) so we can use an affine transform to warp our images to near-epipolar [Muller and Day, 1987]. In practice it appears we cannot resample to true epipolar without iterative adjustment [Otto, 1988].

2.3.2 Gruen

This is an area-based adaptive least-squares correlator [Gruen, 1982], claimed to be of extremely high accuracy (approximately 0.05 pixels, based on figures reported for aerial photography [Gruen, 1986]). The correlator can only correct an initial estimate of the disparity at a point, and has a limited pull-in range (on the order of two pixels). However, it also produces shaping information which can be used to estimate the disparity locally and thus the matcher can sheet-grow out from some initial seed points [Chau and Otto, 1987b]. These could be obtained either by manual observation or from some other suitable automatic stereo matcher (e.g Barnard & Thompson).

2.3.3 Barnard and Thompson

This is an interest operator based matcher [Barnard and Thompson, 1980]. The Moravec operator [Moravec, 1977] is applied to each image as a feature extractor. A match-network is constructed using disparity limits, then iteratively refined using similarity between raw grey-levels in a 5 by 5 pixel window centred on the feature.

Since the Moravec operator does not locate locate features to sub-pixel accuracies, the stereo-matcher is unable to resolve elevations in smaller steps than the elevation change due to one pixel disparity (e.g $30m$ for the left and vertical image pair used below). However, the points obtained can be used as seed points to the Gruen algorithm, which requires an initial estimate of the disparity at a point.

3 Quality Assessment Procedures

Quality is defined in this study as

Accuracy: Accuracy is defined with respect to a dense DEM measured independently from larger scale underflight photographs (see 2.2) using three techniques described below.

Reliability: Defined as the proportion of points with elevation errors (or disparity errors for image-space analysis) greater in magnitude than 3σ (σ = standard deviation of errors).

Sampling density: Defined by number of points matched (compared with number of possible matches).

3.1 Disparity-Space Analysis of Stereo-Matcher Output

This involves transforming each point of our DEM into image space to obtain a digital disparity model (DDM). There is a different DDM for each image pair. The stereo matcher's output can then be compared with the DDM in some manner; we initially used "of stereo-matched points within N pixels of a DDM point, the percentage with disparities within M pixels of the DDM value" as a statistic. This is a quick way of assessing stereo-matcher output because we can test the stereo-matcher output immediately without applying the camera-model.

3.2 Raw Transformed Output vs. Reference DEM

Each stereo matched point is transformed through the camera model [Gugan, 1987] into ground co-ordinates, and compared with the planimetrically nearest point in the reference DEM, provided one exists within a prescribed distance. Ideally we would like to make this distance small to minimize the error due to terrain variation away from the DEM point; however, this will in turn limit the number of points we actually compare. We can analyse the variation of terrain away from a known point by examining the DEM's variogram (see analysis of error sources below).

3.3 Interpolated Grid vs. Reference DEM

Each point is transformed through the camera model into ground co-ordinates, and a gridded DEM is interpolated from them (we use Laserscan's "Panacea" package for this [McCullagh and Ross, 1980]). If the grid of the stereo-matcher derived DEM co-incides with the grid of the reference DEM then we can compare coinciding points from each DEM. Although we will have introduced additional errors in the interpolation process, if the stereo-matcher is to be a primary source of gridded DEMs or contours then we must assess the quality of the end-product.

A problem with the previous methods is that, while they test the quality of stereo-matcher output, they are only testing whichever points the stereo-matcher chose to output, which can be dependent on many other factors [Barnard and Fischler, 1982]. If those points are not well distributed, then the quality measure obtained tells us little about the quality of a gridded DEM derived from them. For example, we can easily filter PMF output to produce just a few (less than 100) very high quality points, but these would be inadequate for generating a DEM of anywhere except completely flat terrain.

4 Quality Assessment Results : Small Test Area

To compare the performance of each stereo-matcher implemented we have applied each one to a pair of 240 pixel by 240 pixel images extracted from the left and vertical images (see fig. 1 & 2). These were chosen to be free of homogeneous areas and atmospheric effects, though there is a slight intrusion of haze at the south-west corner of the left image. The base to height ratio for the image pair (0.32) is such that one pixel disparity is equivalent to approximately $29m$ elevation.

From the output of each stereo-matcher (except Barnard and Thompson) we interpolate a $1.8km$ by $1.8km$ DEM on the same grid as our reference DEM; the corresponding part of the reference DEM can then be subtracted from the stereo-matcher derived DEM to determine errors ('DEM' column in the following tables). Error statistics are also given for the stereo-matcher output points before interpolation ('Points' column in the following tables).

4.1 PMF

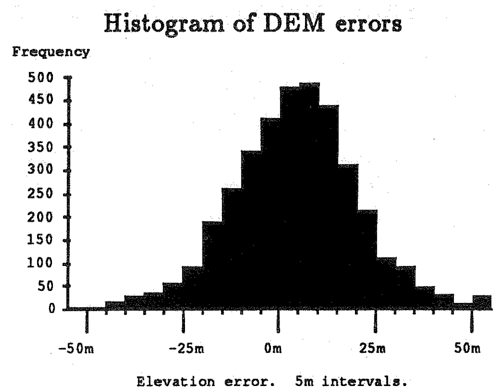
The striping in the SPOT images presents an obstacle to edge-detector based matching, and we have yet to find a combination of edge-detector and matcher parameters which will ignore these artifacts while still accurately locating genuine edges. However, we have had some success with images subsampled so each pixel corresponds to approximately $24.3m$ in ground co-ordinates [Muller and Day, 1987]. One pixel disparity corresponds to approximately $70m$ elevation. Note that the results below are extracted from output for a larger area (see 5.1), are after post-processing with a noise filter, and that PMF was supplied with disparity limits and a disparity gradient limit based on a maximum terrain gradient of 45°.

Table 1: PMF error histogram and statistics.

Elevation error statistics. 718 points matched over image pair		
	Points [a]	*DEM* [b]
Number of points	384	3721
Mean μ	$4.45m$	$4.06m$
S.D σ	$17.49m$	$16.78m$
R.M.S	$18.05m$	$17.26m$
Max.	$70.142m$	$70.47m$
Min.	$-49.90m$	$-95.67m$
$\mid error - \mu \mid > 3\sigma$	1.04%	0.73%

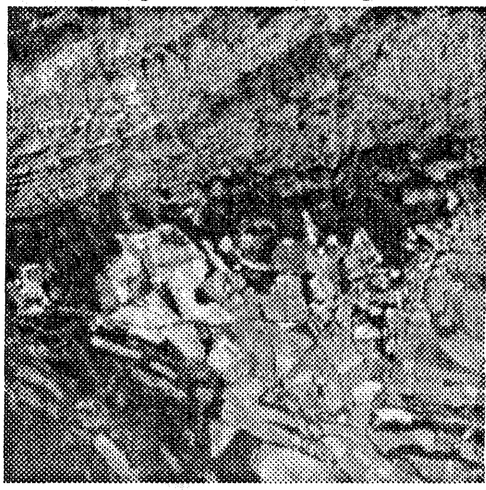
[a] Statistics of elevation differences between uninterpolated stereo-matcher points and nearest point in 30m reference DEM (if one exists within $22m$).

[b] Statistics of elevation differences between stereo-matcher derived DEM and 30m reference DEM.

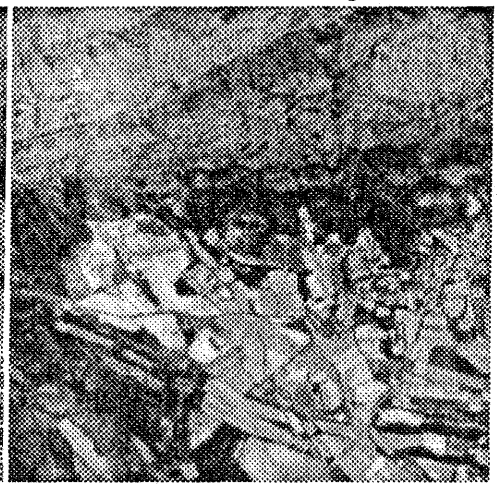


Inspection of table 1 shows that PMF edgels are present with a density of approximately 1.19% (based on 384 points in the DEM area, which covers an approximately 180 by 180 pixel region in the vertical image). Figure 4 shows a visualisation [Muller et al., 1988b] of the area.

Figure 2: 240 by 240 pixel extracts from left and vertical images.

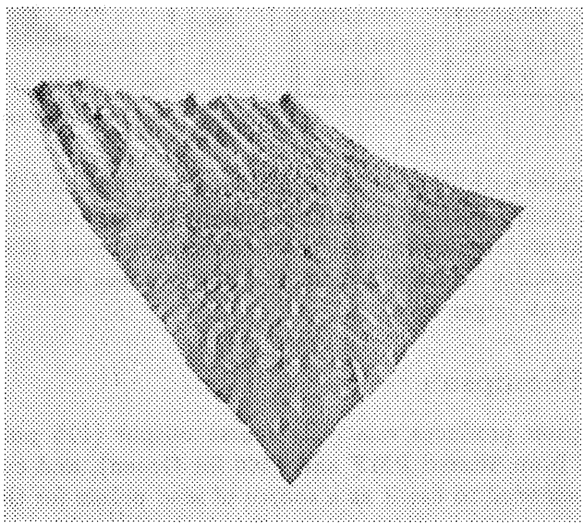


Left image



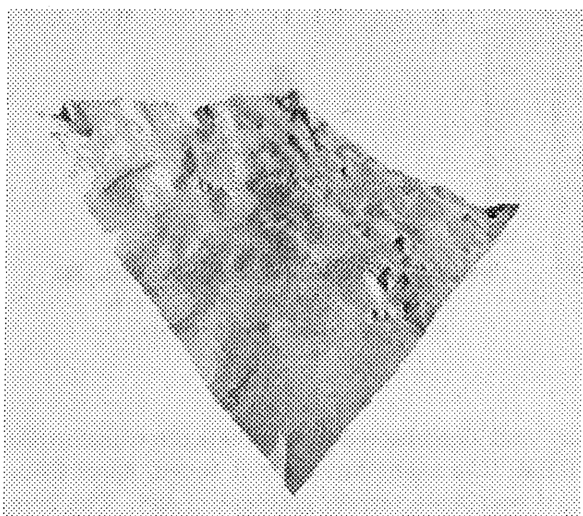
Vertical image

Figure 3: Visualisation (from South-West) of $1.8km$ by $1.8km$ test region extracted from 30m DEM.

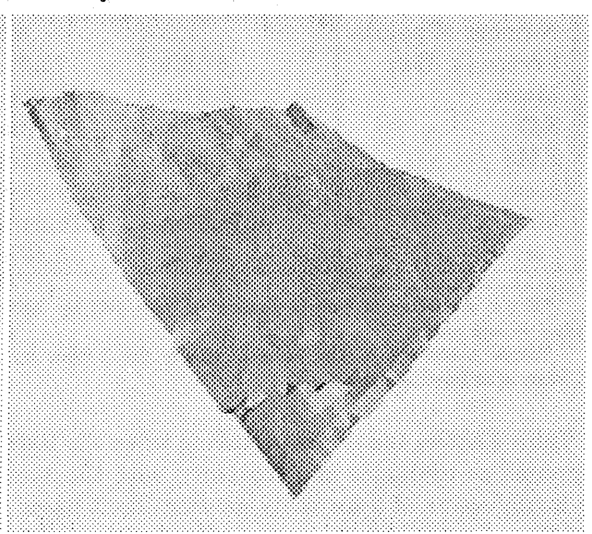


Elevation range : $310.8m$ *to* $846.2m$

Figure 4: Visualisations (from South-West) of $1.8km$ by $1.8km$ PMF & Gruen derived DEMs.



PMF derived DEM



Gruen derived DEM

4.2 Gruen

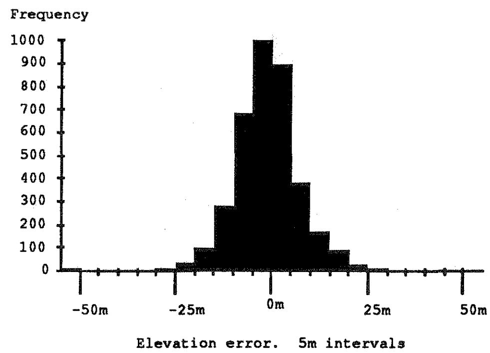
For the results below four manually chosen seed points were supplied, and sheet grown outwards at three pixel intervals. No tuning of algorithm parameters was done. In fig. 4 note the smoothness of the DEM in comparison with our reference data in fig. 3. This may be due to the large size of correlation patch used (21 pixels square; approximately $210m$ on the ground), which obviously misses features such as the ravines running off the ridge which are around $180m$ across. The correlator simply averages them out. This could possibly be overcome by using a smaller patch, or by allowing higher order shaping than the affine transform in the current implementation.

Gruen produces estimates for 3069 points within the $1.8km$ square test area, out of a maximum possible (given the sheet grid spacing) of around 3600, i.e 85% density.

Table 2: Gruen error histogram and statistics.

Elevation error statistics. 4460 points matched over image pair		
	Points	*DEM*
Number of points	3069	3721
Mean	$-1.01m$	$-1.36m$
S.D	$9.70m$	$10.09m$
R.M.S	$9.75m$	$10.18m$
Max.	$88.66m$	$89.12m$
Min.	$-118.20m$	$-123.34m$
$\mid error - \mu \mid > 3\sigma$	0.85%	0.99%

Histogram of DEM errors



Comparison of these results with PMF show an RMS error almost half the size. However, the PMF results were obtained from images with pixels approximately 2.4 times the size of those used for Gruen. It is not yet clear how great an increase in quality we can expect from PMF applied to full resolution SPOT images, since the disparity limits will increase. However, see section 5 for further comparison of these stereo matchers over a larger area.

4.3 Barnard and Thompson

Since Barnard and Thompson produces relatively sparse output (115 points on the 240*240 pixel image, compared with 718 from filtered PMF and 4460 for Gruen), and currently does not produce sub-pixel disparities, it is intended to use it as a source of seed points for the Gruen matcher.

Table 3: Barnard and Thompson error histogram and statistics.

Elevation error statistics		
	Whole image[a]	*DEM area*[b]
Number of points	115	88
$\mid error \mid < 35m$	67.8%	73.8%
Mean	$5.62m$	$-16.47m$
S.D	$96.70m$	$78.72m$
RMS	$96.86m$	$80.43m$
Max.	$322.67m$	$219.96m$
Min.	$-375.84m$	$-375.84m$
$\mid error - \mu \mid > 3\sigma$	3.48%	3.40%

[a] Error statistics of points generated over 240 by 240 pixel image pair.
[b] Error statistics of the subset within the $1.8km$ by $1.8km$ area used above

Error histogram for 115 points

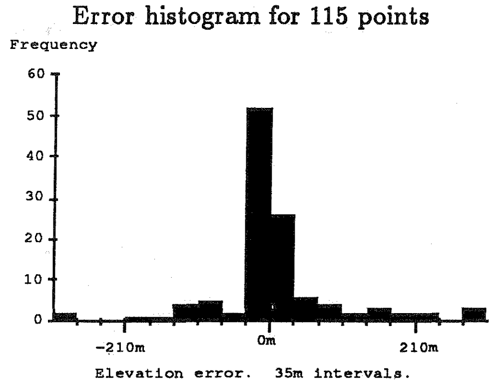


Table 3 shows the errors occurring when the Barnard and Thompson output points are transformed to ground co-ordinates and compared with the 30m DEM. The algorithm was not tuned, apart from the introduction of a disparity gradient limit based on a maximum terrain gradient of 45°. The $29m$ elevation per pixel disparity ratio implies that that the majority of the points within the two central intervals ($-35m \leq error < 35m$) can be considered due to matches accurate to a pixel and suitable for use as seedpoints for Gruen. The Gruen implementation itself should detect erroneous Barnard and Thompson points, which will violate the geometric constraint, fail to converge within the number of iterations allowed, or correlate badly.

This has been performed, and Gruen output quality was almost identical to that given above for manual seed points. However, since the image pair used is a single 'domain' (i.e a sheet can grow to cover it from a single seed point) larger image pairs need to be considered before we can draw any definite conclusions.

[Muller et al., 1988a] discuss the broader range of disparities that B&T has to handle (x=45,y=17) compared with PMF (x=14) and especially Gruen (x=2,y=2). Hence these preliminary results should be seen in this context and represent a very effective way of reducing the pull-in range within the limits that Gruen can handle.

5 Quality Assessment Results: Larger Areas

5.1 PMF

The PMF output obtained above appeared to be of reasonable quality. However, on examination of the quality of the larger area from which it was taken (corresponding to the whole of the 30m DEM), we find the following results. Again, this is a left and vertical image pair, resampled to near-epipolar with $24.3m$ pixels (1 pixel disparity corresponds to approximately $70m$ elevation). [Muller and Day, 1987] showed that the errors were highly correlated with non-epipolarity (see [Otto, 1988] [O'Neill and Dowman, 1988]).

Table 4: PMF errors (full 30m DEM area)

Elevation error statistics.		
	Points	*DEM*
Number of points	8425	95865
Mean	$3.34m$	$-2.26m$
S.D	$45.31m$	$63.26m$
RMS	$45.43m$	$63.30m$
Max.	$548.67m$	$549.14m$
Min.	$-683.10m$	$-684.86m$
$\mid error - \mu \mid > 3\sigma$	1.16%	2.19%

Intensity range image of PMF derived DEM
Scaling as for fig. 1

5.2 Gruen

Because of the currently terminal effects of multiplicative noise in the left image we used a 1400 by 1400 pixel segment of the vertical and right images shown in Fig. 1.

The distribution of Gruen output points and blunders (see figure 5) should be compared with the location of cumulo-nimbus clouds (and their shadows) in the right image. Note that the range of errors has increased by a factor of five due to the concentration of blunders around the clouds in the image, particularly the approximately central cloud and shadow. This cloud is very close to the ridge, which is itself itself a region of high blunder density, and hence the error may be amplified. The systematic error indicated by the large mean may be due to camera model errors.

6 Discussion

6.1 Error Sources

We have identified several stages at which error is introduced in the stereo-matcher to DEM process.

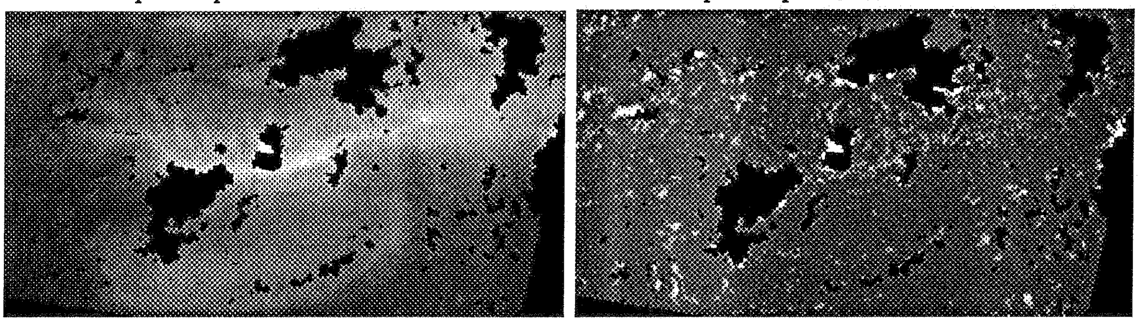
Table 5: Gruen errors (full 30m DEM area)

Elevation error statistics	
Number of points	27835
Mean	$10.84m$
S.D	$18.19m$
RMS	$21.18m$
Max.	$639.84m$
Min.	$-529.92m$
$\mid error - \mu \mid > 3\sigma$	0.88%

Figure 5: Gruen blunders (full 30m DEM area)

Intensity range image of Gruen output points
No points produced in black areas

Intensity image of Gruen blunders
No points produced in black areas



Scaling as for fig. 1

Grey-levels correspond to
$\mid error - \mu \mid < \sigma, < 2\sigma, < 3\sigma$ & $\geq 3\sigma$

- Errors from the stereo-matcher itself. This includes both incorrect matches of completely different features, and small sub-pixel errors when features are correctly matched, but not perfectly, due to fuzzy edges or insufficient texture.
- Errors from the camera-model itself. Our model is known to have deficiencies since it only approximates a polynomial distortion for the effect of attitude variations. Such errors manifest themselves as systematic shifts when we compare stereo-matcher output with the reference DEM.
- Errors from interpolating stereo-matcher output to generate a DEM (or, in the quality assessment process, errors from attempting to compare stereo-matcher output with reference points some distance away).

6.1.1 Stereo Matcher Errors

Each of the stereo-matchers tested has it's own characteristic failure modes. However, in all cases, differences between images taken weeks apart (due to changes in surface appearance and atmospheric effects) present difficulties.

B & T: Particular problems include failure to identify the same feature in each image, and multiple interest-points being generated for a feature due to image tiling [Muller and Anthony, 1987].

PMF: Blunder rate increases with non-epipolarity in images warped to near-epipolar due to bad matches (features lying on different scan lines cannot be matched with each other), and innaccurate matches of different parts of the same feature (e.g consider an edge running down the image at an angle to the scan-line direction). Further problem areas are inconsistent edge detection and differing edge-strengths between images, increasing the likelihood of bad matches. Fuzzy edges may also introduce sub-pixel errors due to uncertainty in positioning edgels.

Gruen: Correlation will be inaccurate, or will fail completely, in areas with a low signal-to-noise ratio (e.g lakes) [Ehlers, 1985]. The sheet growing technique may fail to estimate a disparity within the pull-in range where there is a high rate-of-change shaping parameters (e.g ridge crests).

6.1.2 Camera Model Errors

The camera model we have been using was set up with 10 ground control points distributed over the 6000 by 6000 image. RMS plan accuracies at 20 checkpoints were $15.3m$, and height accuracies at

53 check points were $8.4m$ [Dowman et al., 1987]. Due to the relatively small image patches we have been using (compared with the distances over which major attitude variations take place) we expect these errors to appear as systematic offsets to our stereo-matched points (e.g the $10m$ mean elevation error in section 5.2). The planimetric offset we would expect to introduce additional elevation error variance, with size equal to the value of the terrain's variogram [Davis, 1973] at that lag-distance.

Although these slowly-varying errors should not detract from the geomorphological information content of the DEMs derived, we must seek to reduce them if our stereo-matcher derived data is to be used for accurate mapping.

6.1.3 Interpolation Errors

When we compare the height of a stereo-matcher derived point (transformed to ground co-ordinates), with a DEM point some distance away, we are introducing an additional error because the terrain will vary increasingly with distance from the DEM point. We estimate the variance of this error from the variogram of the terrain [Frederiksen and Jacobi, 1986]. For our $30m$ DEM we obtain a variogram rising from $7.6m^2$ (the observation error) at zero planimetric distance to $74.2m^2$ at $21.2m$ distance (the furthest a stereo-matched point can be from a DEM point on a $30m$ grid).

However, we do not observe this effect when we classify and test our stereo-matched points by distance from the point with which they were compared.

For PMF and Barnard & Thompson, the variance already present (due to bad matches) dominates (on the order of $4000m^2$ for PMF, $9000m^2$ for B&T) and we cannot see the relatively small effect of increasing errors due to distance.

The Gruen stereo-matcher can achieve (on certain image segments) an error variance on the same order as the effect we anticipate, but because it is an *area* correlator operating over a 21 pixel window (corresponding to approximately $210m$ on the ground) each stereo-matched point is effectively a moving-average of the relief within this distance. We do not therefore observe the above effect because the Gruen derived height at a point is not just the true terrain height plus some random error due to the stereo-matching process.

7 Conclusions

Our preliminary results of our ongoing research programme indicate that a two-stage stereo matcher may be required for SPOT data - the first to bring the convergence range down to the integer pixel level and the second to pull the correlation surface down to sub-pixel level. The non-epipolar nature of our stereo matcher means that high accuracies for geocoding/resampling to epipolars is not required (see [Otto, 1988] on the difficulties of creating epipolar data for SPOT) and our stereo matchers may be tuned to deal with a very broad spectrum of non-epipolar data. The low quality of the edge-based epipolar matcher confirms previous results on noise-correlated data [Paine, 1986].

8 Acknowledgements

This work was funded by the U.K. Science and Engineering Research Council under the Alvey MMI-137 Project on "Real-time 2.5D Vision Systems". This project is a collaboration with the Department of Computer Science, University College London, Thorn EMI Central Research Laboratories, Laser-Scan Laboratories Limited and the Royal Signals and Radar Establishment, Malvern. We would like to thank Mike Pitkin for making the DEM measurements; Paul Otto, Mike Recce, Kevin Collins and Tony Chau for providing the stereo matcher implementations and useful discussions and M. P Foin, IGN for providing the SPOT data; underflight photographs and control through the aegis of the SPOT-PEPS campaign.

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