A Comparative Study of Australian Cartometric and Photogrammetric Digital Elevation Model Accuracy

Jeffrey P. Walker and Garry R. Willgoose

Abstract

This paper explores the accuracy of Digital Elevation Models (DEMs), with particular reference to Australian published DEMs. Direct comparisons were made between cartometric and automatically measured photogrammetric DEMs at various grid spacings with an accurate and dense set of ground truth data. The cartometric DEMs were found to be more accurate than the photogrammetric DEMs for the small study site in this paper, with RMS errors in elevation of approximately 3.5 m and 4.5 m, respectively, and maximum absolute errors in elevation of approximately 12 m and 28 m, respectively. An important factor for environmental prediction studies is slope, and RMS errors in slope were approximately 6 percent and 20 percent for the cartometric and photogrammetric DEMs, respectively, with maximum absolute errors in slope of approximately 75 percent and 290 percent, respectively. However, use of suitable post-processing such as filtering may reduce the errors in photogrammetric DEMs to at least the same magnitude as cartometric DEMs. The cartometric DEMs were found to satisfy the USGS specifications for Level 2 data.

Introduction

Current generation computer models for environmental prediction rely heavily on the integrity of Digital Elevation Models (DEMs) (Moore and Grayson, 1991; Moore *et al.*, 1991; Lane *et al.*, 1994). However, there are few publications on the accuracy of DEMs (Bolstad and Stowe, 1994; Robinson, 1994) or the effects introduced on derived geomorphological parameters (Walker *et al*, 1999), with DEMs created, distributed, and used very frequently without any reference to the magnitude of the error implied, or to the methods applied to its disclosure or correction (Felicísimo, 1994).

Generally, raw elevation data in the form of stereo photographs or field surveys are not readily available to potential users of a DEM. Therefore, most users rely on DEMs published by government agencies. The most common form of DEM available in Australia, OEEPE (Organisation Européene d'Etudes Photogrammétriques Expérimentales) member countries and the United States, are those produced by digitizing the contours on existing topographical maps (cartometric DEMs) (Moore *et al.*, 1991; Robinson, 1994). In the state of New South Wales (NSW), Australia this method incorporates a drainage enforcement algorithm developed by Hutchinson (1989), which utilizes the blue lines drawn on topographic maps to represent the permanently flowing or major intermittent streams (Moore *et al.*, 1991). However, there has been an increasing move towards using automated digital correlation techniques to generate DEMs directly from stereoscopic imagery (photogrammetric DEMs), especially where contour data are not available or are not accurate enough (Robinson, 1994). More recent developments have involved DEM generation from space-borne measurements by the interferometric technique, but this data is not yet widely available.

So far as can be ascertained, there are currently no accuracy standards for the production and checking of DEMs in Australia. However, there is an accuracy specification for classification of DEMs in the United States (Moore *et al.*, 1991; Bolstad and Stowe, 1994; U.S. Department of Interior, 1998) and in OEEPE member countries (Robinson, 1994).

The quality of United States Geological Survey (USGS) DEM data is classified as either Level 1, 2, or 3. Level 1 represents a standard format with a maximum absolute vertical error of 50 m and a maximum relative error between adjacent points of 21 m. Level 2 data has been smoothed and edited for errors, with DEMs derived from digitized contours classed under this level. These Level 2 DEMs have a maximum root mean square error (RMSE) of one-half contour interval, and an absolute error no greater than two contour intervals. Level 3 data have a maximum error of one contour interval and a maximum root mean square error of one third of a contour interval, which is not to exceed 7 m. The USGS does not currently produce Level 3 elevation data, and hence the most accurate DEMs produced by the USGS are those generated by complex linear interpolation of digitized contour data using drainage enforcement (Moore *et al.*, 1991).

This paper explores the accuracy of DEMs with particular reference to Australian published DEMs. This is undertaken by making direct comparisons between cartometric and photogrammetric DEMs at various grid spacings with an accurate and dense set of ground truth data. To ensure the

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accuracy of ground truth data, an error assessment of the raw irregularly spaced and grid interpolated ground data was first undertaken.

Cartometric DEM Accuracy Considerations

While no accuracy standards could be found for Australian cartometric DEMs, the standards of accuracy for Australian topographic maps are set by the National Mapping Council (NMC) as "The horizontal accuracy criteria for well-defined map detail require that not more than 10 percent of points tested are to be in error by more than 0.5 mm at map scale. For vertical accuracy, not more than 10 percent of points tested are to be in error by more than half the contour interval of the map" (Manning, 1983). What qualifies as a well-defined point is explained by the 1953 NMC specification as: "Well defined points are those that are easily visible or recoverable on the ground. In general, what is well defined will also be determined by what is plottable on the scale of the map within 0.25 mm" (Manning, 1983).

For topographical maps at a scale of 1:25 000 and a contour interval of 10 m, this translates to an accuracy of 12.5 m in horizontal and 5 m in vertical. Therefore, if two adjacent contours are both in error by 5 m, one higher and one lower than the true value, then the possibility exists for a relative error of 10 m (but only 5 m absolute error). Thus, derived products, such as terrain slope, are likely to exhibit the greatest error.

For the highest accuracy classification of maps, the limiting root mean square error in elevation by contour interpolation is set by the specifications at one-third the indicated contour interval for well-defined points only. Furthermore, spot heights have a specification of limiting root mean square error to one sixth of the contour interval (Fryer *et al.*, 1994). Testing by national mapping agencies for compliance to these standards is optional, with only 3 percent of topographic maps in the U.S. rigorously checked, and approximately 1 percent for Australia (Manning, 1983).

Because of the requirement for uniformity of topographic map formats within a country, a limited number of contour intervals are adopted for these products, often with only a single contour interval available for some areas. This has the result of requiring a compromise for the representation of high and low relief areas. This situation can have serious implications for the creation of DEMs from contour data with greater relative uncertainties in elevation value and greater absolute uncertainties in derived parameters such as slope and aspect in areas of low relief (Robinson, 1994).

Photogrammetric DEM Accuracy Considerations

Textbooks on photogrammetry indicate that heights of *well-defined* points can, conventionally, be obtained with a standard deviation of ± 1 part per 10,000 of the flying height (e.g., Wolf, 1974). However, Fryer *et al.* (1994) question the reliability of the critical parameter 1 part per 10,000 and enunciated that there is a distinct difference between the accuracy which may be obtained by photogrammetry for targeted points, and that for natural features. Most experienced photogrammetric operators believe they can produce targeted heights twice as accurate as those for natural features.

An analysis of the manner in which random and systematic errors in photogrammetric observations may be propagated through a block of aerial photographs was undertaken by Fryer *et al.* (1994) with the results indicating that values of ± 1 and ± 3 parts per 10,000 of the flying height, are the best which may be expected for the standard deviations of spot heights and contours, respectively, in standard mapping. However, if the ground control is sparse and random errors of measurement on the photogrammetric plates are larger than ± 5 μm, then the figures could easily be as high as ± 10 and ± 30 parts per 10,000 of the flying height for spot heights and contour heights, respectively. This translates to 1.5 m and 4.5 m for the typical 1,500 m flying height used in standard aerial photography. The study also pointed out that the use of published map data (digital or not) for producing landform models should be made only after careful assessment of the accuracy of those data, and that some claims currently being made for height accuracy obtained with new photogrammetric equipment, such as forward motion cameras, are valid only in special cases of targeted points.

Ground Truth Data

A "ground truth" data set was obtained for a 1.4 km^2 parcel of land at Pokolbin, NSW, Australia (Figure 1) to enable the accuracy evaluation of published DEM's for that area. Prominent features of the undulating site include a large farm dam, covering of trees on the southern portion of the site (mainly on the sections with higher elevation), vineyards on the northern portion, and a lane dissecting the site separating the northern and southern portions. Steeper slopes are in the southern portion of the site with more gently sloping terrain to the north.

The ground survey data for this site were collected by total station field survey with coordinate evaluation on the Australian Map Grid (AMG). Approximately 3,000 data points were collected with an average spacing of 17.7 m. Data were collected at all changes of grade, allowing linear interpolation between data points to a fine-grid spacing with a high degree of accuracy.

Published Elevation Data

The published DEM data used in this evaluation were provided by the Land Information Centre (LIC) at Bathurst, NSW, Australia. These data were supplied on the AMG coordinate

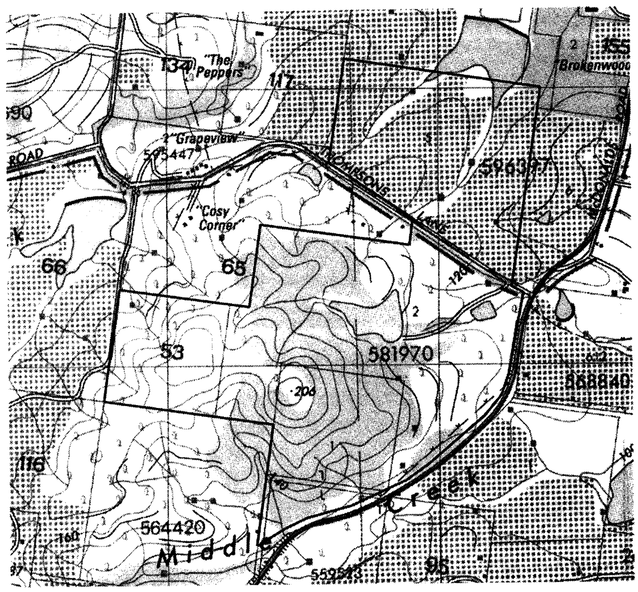

Figure 1. Extract of 1:25 000 scale series topographic map showing the location of the site under investigation (not to scale).

system, thus dispensing with any georeferencing problems in making data comparisons. The published DEM data included the following:

1. Cartometric DEMs: 6.25 m, 12.5 m, and 25.0 m gridded elevation data derived from contours on the 1:25 000 topographical map series (10 m contour interval). Hutchinson (1989) drainage enforcement was used and an auxiliary contour height assigned to the shorelines of the large dams in the area. Use was also made of spot heights shown on the contour maps. In addition, 95 m and 105 m intermediate contours were added by the LIC to help with interpolation in the flatter region located in the south-east corner of the site.
2. Photogrammetric DEMs: 6.25 m and 12.5 m gridded elevation data produced by automatic image correlation of stereo pairs of controlled photography using the Orthomax software which is a subset of the ERDAS Imagine® software package (John Perry, Personal Communication). No editing of the data set was performed, hence in timbered areas correlated points may be at tree-top level or ground level. Slope data extracted from the 6.25 m elevation data and filtered back to 25.0 m resolution were also supplied.

Each of the above DEMs was produced independently from the same source data using the same parameter settings. Hence, even at common points the elevations could be different.

Error Structure of Raw Ground Survey Data

The accuracy of ground truth data points was assessed from error propagation theory (Mikhail and Ackerman, 1976). Error estimates for the observed horizontal and vertical angles and distance were determined by assuming a uniform distribution, as angles were recorded to the nearest minute of arc and distances to the nearest centimetre. The standard deviations on observations used in the error propagation were ±17″ for horizontal and vertical angles, ±0.005 m for slope distance, ±0.001 m for height of instrument and ±0.01 m for height of target.

Results of the error analysis are summarised in Table 1, with average standard deviation in easting and northing approximately the same magnitude, while the standard deviation for elevation was approximately twice as large. The maximum standard deviation in northing and elevation was the same, and approximately twice as large as for the standard deviation in easting. However, the standard deviations obtained were comparatively low with approximately 0.01 m uncertainty in position and 0.02 m uncertainty in elevation, implying that the ground truth data was precise.

Error Structure of Gridded Ground Survey Data

During Delauney triangulation (Sloan, 1993) and interpolation of ground survey data onto a 3.25 m regular grid, so that comparisons could be made with the published DEMs at common points, further error is introduced. To determine the error characteristics of the gridded ground survey data, a Monte Carlo simulation using 100 replicates of the original ground survey data with random perturbations sampled from a multivariate normal distribution (to preserve the correlations, particularly between easting and northing; see Table 1) using the covariance data from error propagation was performed. In addition to elevation accuracy, slope (defined as the maximum downslope by finite difference to the eight surrounding grid points) accuracy and autocorrelation of error in gridded elevation and derived slope were also assessed. As well as giving an estimate of relative error in the DEM, slopes are the main input for many environmental prediction models. The significance of autocorrelation was that errors in DEM-derived slope should be negligible if the correlation length of error in elevation is large relative to the data spacing.

Table 1. Summary of the Standard Deviation and Correlation Between the Coordinates of Each of the Ground Truth Detail Points

	Average	Minimum	Maximum
S.D. of Easting (m)	0.008	0.000	0.037
S.D. of Northing (m)	0.010	0.000	0.076
S.D. of Elevation (m)	0.017	0.000	0.076
Correlation between Easting and Northing	0.08	−0.97	0.99
Correlation between Easting and Elevation	0.02	−0.26	0.61
Correlation between Northing and Elevation	0.01	−0.14	0.31

Elevation Error

The standard deviation of grid elevations are displayed in Figure 2a, where it can be seen that the majority of grid points had a relatively low standard deviation (<0.05 m), with a scattering of larger standard deviations (<0.5 m) spread across the site. Comparison of elevation error with terrain slope showed that grid points with larger errors had lower slopes (<0.3 m/m).

Calculation of autocorrelation between all pairs of grid points yielded a correlation length of 18.4 m, which was only slightly larger than the average data spacing of 17.7 m. This process indicated a strong correlation of error in grid elevation between grid points which had their elevations interpolated from the same three grid points, i.e., grid points lying in the same triangle. It also indicated that weaker correlations existed between grid points in the adjoining triangles, and that effectively, no correlation existed in grid points any further away. These results are in accordance with intuition.

The effect of spatial attributes on autocorrelation was investigated. Correlation lengths for grid points lying in the steepest slope direction and grid points lying in a direction perpendicular to the steepest slope were 21.4 m and 20.9 m, respectively. As these were not significantly different, it was concluded that the direction of steepest slope had no significant effect on the correlation length of errors in elevation. Moreover, the data have an isotropic autocorrelation structure, with correlation lengths ranging from 20.3 m to 21.4 m when binned according to direction. However, the correlation length decreased significantly as the slope between grid points (Figure 3a) and elevation (Figure 3b) increased.

It was believed that the reduction in correlation length with both slope and elevation was due to steeper portions of the site also having the higher elevations. It was also believed that this reduction in correlation length was due to a reduction in data spacing on the steeper (and typically rougher) portions of the site. This is confirmed in Figure 3c, showing that the data spacing for the elevation ranges was similar to the correlation lengths for the corresponding elevation ranges in Figure 3b. Comparison with the correlation lengths according to slope showed a similar trend with steeper areas located on the higher portions of the site. Therefore, it was concluded that the observed correlation, of autocorrelation for error in elevation with slope and elevation, was in fact spurious, and that the true correlation was with data spacing. This analysis has further confirmed that the correlation length of errors in grid elevation was directly proportional to the data spacing. The single exponential correlation function had the best fit to the data in all cases.

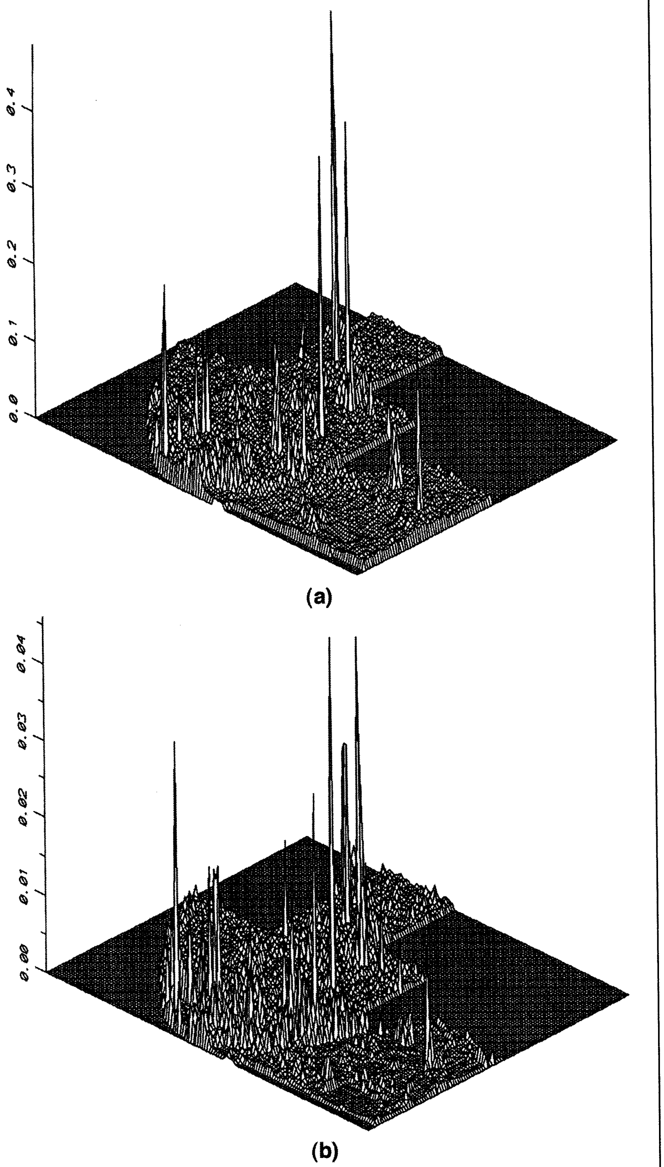

Figure 2. Surface plot of standard deviations in (a) grid elevation (vertical exaggeration 3500) and (b) slope (vertical exaggeration 35000) for the ground truth DEM.

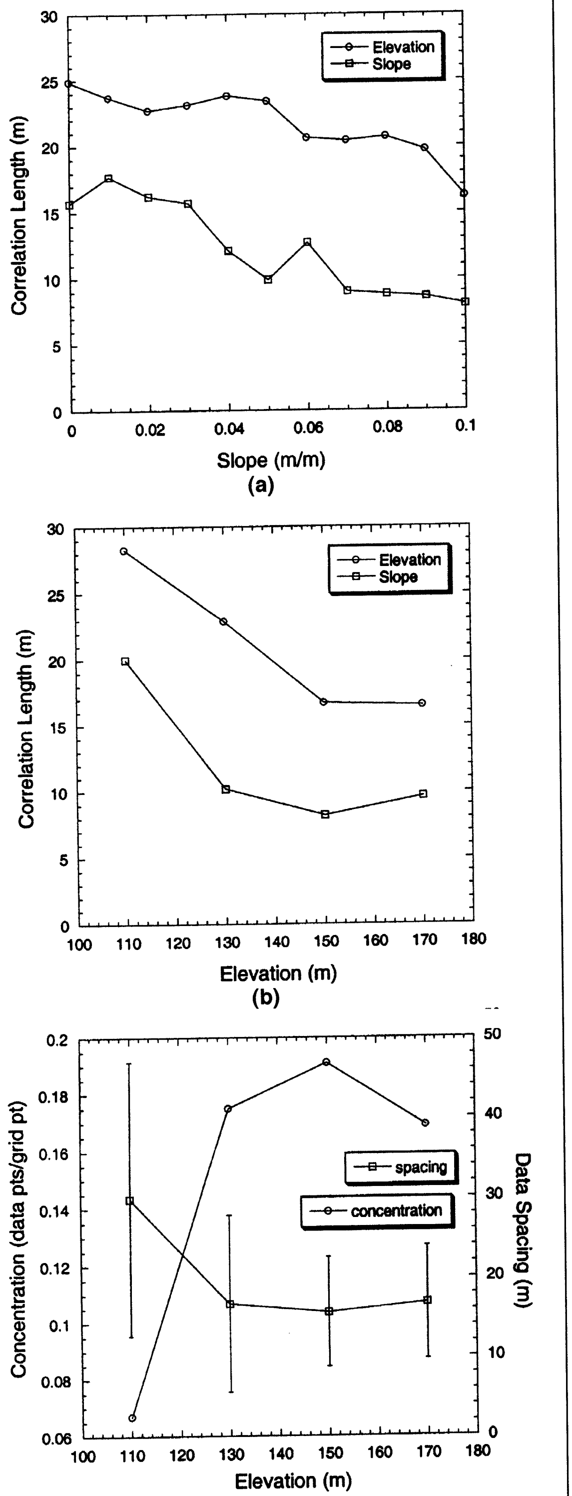

Figure 3. (a) Correlation lengths of errors in grid elevation and slope between grid points for the slope shown between the two points ±0.005 m/m; (b) Correlation lengths of errors in grid elevation and slope between grid points for the elevation at either point ±10 m; and (c) Concentration of data points contributing to each grid point for various elevations ±10 m, as well as the corresponding data spacing.

Slope Error

The standard deviation of slopes are displayed in Figure 2b, where it can be seen that the majority of slope estimates had a relatively low standard deviation (<0.005 m/m), with a scattering of larger standard deviations (<0.05 m/m) across the site. It is notable that in both cases the values for the standard deviations in slope were an order of magnitude less than those from the elevations from which the slopes were derived. Figure 2b also shows that the standard deviation of slope on the flatter region to the north were much more constant and generally less than those on the steeper section to the south.

Calculation of autocorrelation between all pairs of grid points produced a correlation length of 8.9 m, which was only slightly larger than the grid spacing of 6.25 m. This indicated that errors in slopes of the eight surrounding grid points from which the slope was calculated would be strongly correlated to the error in slope at the center grid point. However, the error in slope for the next ring of grid points beyond this would be only slightly correlated, and the error in slope greater than two grid points away would have zero correlation. Thus, it was seen that the length scale over which correlation of errors in slopes existed was much less than the length scale over which correlation of errors in elevation existed and was much less than the spacing of the raw data.

As for elevation, the effects of spatial attributes on autocorrelation were investigated for slope. Unlike errors in elevation, correlation lengths for slope at grid points lying in the steepest slope direction from the origin and slopes at grid points lying in a direction perpendicular to the steepest slope direction from the origin were 7.4 m and 15.9 m, respectively, which are significantly different. However, the autocorrelation was isotropic, with correlation lengths ranging from 10.0 m to 12.6 m when binned according to direction. The correlation length also decreased significantly as the slope between grid points (Figure 3a) and the elevation (Figure 3b) increased. Furthermore, the correlation length for slope errors between points in the maximum slope direction was of similar magnitude to that between points with a relatively steep slope, and the correlation length between points in the direction perpendicular to maximum slope was similar to that between points with a relatively low slope. This indicated that the correlation length of errors in slope was dependent on the slope magnitude between the points rather than direction per se.

Although the spacing of data from which the slopes were calculated was fixed at 6.25 m, the raw data from which this gridded data was derived had greater spacing for flatter lower regions of the site than for steeper regions of the site. Thus, the correlation seen between slope and elevation was spurious, and errors in slope were proportional to the data spacing, but over a shorter length scale than for errors in elevation. Again, the single exponential correlation function had the best fit to the data in all cases.

Error Structure of Published DEM Data

A surface plot of the ground truth data showed a relatively smooth surface with a few fine features clearly visible. These features were the cutting for the lane dissecting the site and the large farm dam. The cartometric DEM was also very smooth with the farm dam being the only fine feature visible. The gullies were still clearly visible, and the overall shape of the site was maintained. However, the photogrammetric DEM was extremely rough with a significant amount of high frequency noise. It was impossible to identify any of the fine detail clearly visible in the previous two DEMS, and even the gullies were hard to identify. The overall shape of the site, however, had been maintained. Figure 4 shows the differences in elevation and slope when compared to the truth DEM, indicating that the greatest variability in differences was for the steeper, timbered section of the site with the difference being fairly constant on the flatter cleared section of the site.

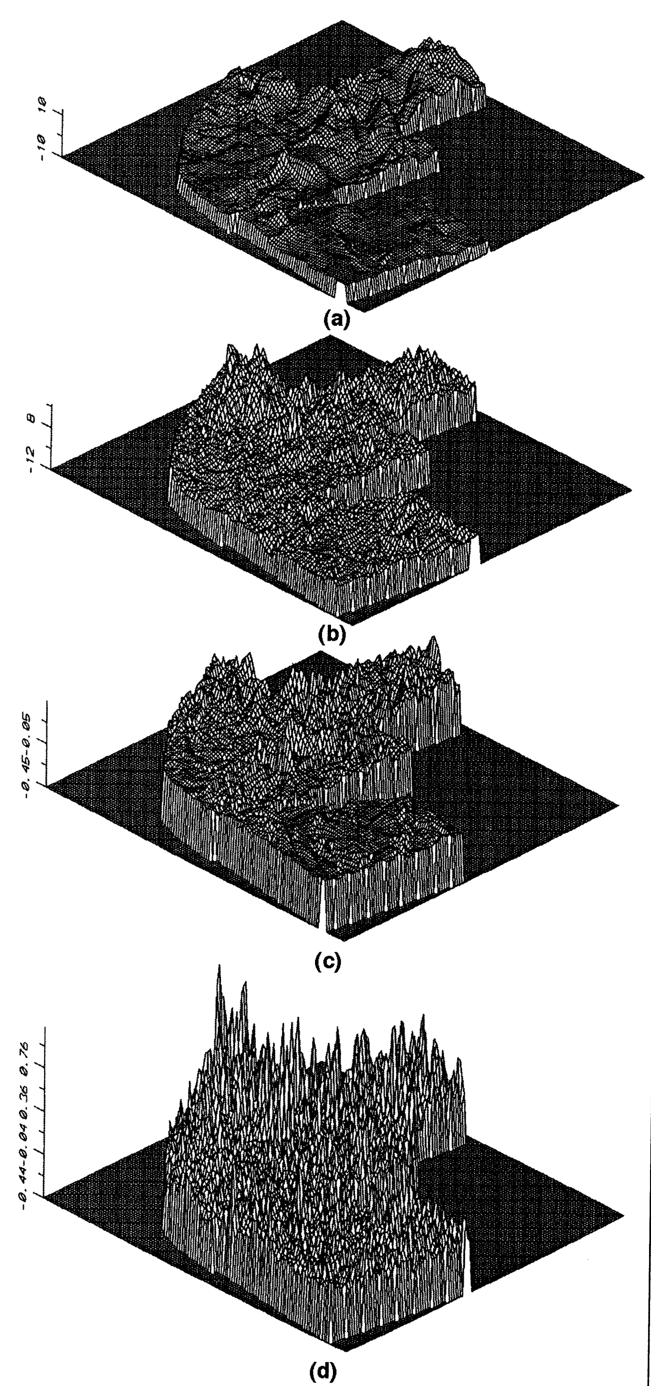

Figure 4. Surface plot of errors in elevation (vertical exaggeration 10): (a) cartometric DEM, (b) photogrammetric DEM: surface plot of errors in slope (vertical exaggeration 500), (c) cartometric DEM, and (d) photogrammetric DEM.

Elevation and Slope Error

Error estimates for the published DEMs were made by comparing elevations at common grid points with those in the ground truth and the results are given in Table 2. These results reinforce the conclusions of the above discussion; that the cartometric DEM had much better statistical properties than the photogrammetric DEM. The maximum negative difference in elevation was approximately the same for both DEM sources on the various grid spacings, with the photogrammetric DEMs being only slightly worse. However, the maximum positive difference in elevation was significantly greater for the photogrammetric DEMs in comparison with the cartometric DEMs, with errors in elevation up to approximately 2.5 times as large for the 6.25 m grid, and errors in slope an order of magnitude greater. These dramatic differences in the photogrammetric DEMs were obviously a result of some grid points being at tree top level, while others were at ground level.

TABLE 2. RESULTS OF STATISTICAL PARAMETERS EVALUATED IN THE COMPARISON OF THE PUBLISHED DEMS WITH THE 3.25 M GROUND TRUTH DEM

Statistical Parameter	Cartometric DEMs			Photogrammetric DEMs		
	6.25 m Grid	12.5 m Grid	25.0 m Grid	6.25 m Grid	12.5 m Grid	12.5 m Grid 5×5 filter
Results for Heights at Common Grid Points						
Mean Difference (m)	−2.018	−2.199	−2.260	2.328	1.851	1.838
Absolute Mean Difference (m)	2.820	3.112	3.135	3.042	2.508	2.296
RMS Error (m)	3.269	3.634	3.540	4.629	3.497	3.165
Standard Deviation (m)	2.572	2.894	2.725	4.001	2.966	2.577
Correlation Length (m)	304.2 ± 11.3	285.8 ± 17.3	142.8 ± 10.4	127.6 ± 1.6	80.0 ± 4.0	173.6 ± 16.6
Maximum Difference (m)	11.039	12.697	12.205	27.682	18.900	14.697
Minimum Difference (m)	−9.978	−10.062	−11.119	−14.225	−12.415	10.858
Results for Heights at All Grid Points (Bi-Linear Surface Interpolation)						
Mean Difference (m)	−2.018	−2.200	−2.261	2.329	1.849	1.836
Absolute Mean Difference (m)	2.819	3.105	3.103	3.020	2.438	2.285
RMS Error (m)	3.268	3.627	3.490	4.596	3.387	3.148
Standard Deviation (m)	2.570	2.884	2.659	3.963	2.838	2.557
Correlation Length (m)	379.0 ± 8.7	522.1 ± 15.7	422.4 ± 14.3	174.6 ± 2.7	218.0 ± 10.0	574.8 ± 27.9
Maximum Difference (m)	11.039	12.822	12.205	27.682	18.900	14.697
Minimum Difference (m)	−10.885	−10.886	−11.259	−14.225	−12.415	−10.858
Results for Heights at All Grid Points (Triangular Facet Interpolation)						
Mean Difference (m)	−2.018	−2.200	−2.260	2.329	1.849	1.836
Absolute Mean Difference (m)	2.819	3.106	3.105	3.021	2.443	2.286
RMS Error (m)	3.268	3.629	3.493	4.598	3.394	3.148
Standard Deviation (m)	2.570	2.886	2.663	3.965	2.846	2.558
Correlation Length (m)	381.1 ± 8.9	529.3 ± 15.7	449.4 ± 14.8	177.3 ± 2.8	220.0 ± 10.1	578.2 ± 27.9
Maximum Difference (m)	11.039	12.907	12.205	27.682	18.900	14.697
Minimum Difference (m)	−10.879	−10.886	−11.259	−14.225	−12.415	−10.858
Results for Slopes at Common Grid Points from the 3.25 m Grid						
Mean Difference (m/m)	−0.011	−0.018	−0.016	0.045	0.041	−.007
Absolute Mean Difference (m/m)	0.030	0.042	0.047	0.089	0.099	0.035
RMS Error (m/m)	0.066	0.069	0.078	0.173	0.153	0.063
Standard Deviation (m/m)	0.065	0.067	0.077	0.167	0.147	0.063
Correlation Length (m/m)	43.7 ± 3.9	27.0 ± 7.5	37.0 ± 10.0	25.1 ± 1.7	36.4 ± 3.8	32.0 ± 13.1
Maximum Difference (m/m)	0.447	0.344	0.316	2.862	1.133	0.429
Minimum Difference (m/m)	−1.371	−1.392	−1.022	−1.440	−1.320	−1.260
Results for Slopes at Common Grid Points from Same Size Grid						
Average Slope (m/m)	0.081	0.112	0.112	0.138	0.171	0.085
Mean Difference (m/m)	−0.012	−0.011	−0.004	0.056	0.040	−0.003
Absolute Mean Difference (m/m)	0.039	0.036	0.035	0.114	0.089	0.044
RMS Error (m/m)	0.063	0.055	0.053	0.197	0.130	0.063
Standard Deviation (m/m)	0.062	0.054	0.053	0.188	0.123	0.063
Correlation Length (m/m)	31.334 ± 1.4	24.2 ± 2.2	29.9 ± 15.9	14.4 ± 1.1	23.2 ± 2.8	40.7 ± 2.6
Maximum Difference (m/m)	0.447	0.344	0.259	2.887	1.137	0.433
Minimum Difference (m/m)	−0.753	−0.453	−0.265	−0.764	−0.444	−.317

The correlation lengths of error in elevation for the cartometric DEMs were also approximately twice that for the photogrammetric DEMs, which is consistent with the high frequency noise in the photogrammetric DEM. It is possible that this correlation length was a characteristic of the data spacing from which the DEMs had been derived. However, when comparing the correlation length of errors in the cartometric DEMs with the horizontal spacing of contours, the correlation length was equivalent to the spacing of contours on the flat regions of the site, but was significantly greater (as much as 5 times) than the spacing of contours on the steep sections of the site.

Table 2 shows that linear interpolation of published DEM data onto a 3.25 m grid did not have any significant effect on the resulting DEM accuracy. While the correlation length increased with interpolation, the form of interpolation for spacings up to 25 m was unimportant, with error statistics from bi-linear interpolation and triangular facets being the same. If the slopes were not calculated from the same size grid, then the maximum negative difference was significantly affected, with the effect being greater as the grid spacing was increased.

The RMS error for the cartometric DEMs was about 3.5 m irrespective of grid spacing, while it was 4.5 m for the photogrammetric DEM on a 6.25 m grid. The mean difference between the published DEM and the ground truth was approximately −2 m for the cartometric DEM, and +2 m for the photogrammetric DEM, indicating that on average the surface of the cartometric DEM was below that of the ground truth, while the photogrammetric DEM was above. The absolute mean difference indicated that the average separation between the two surfaces (either below or above) was approximately 3 m for both DEMs.

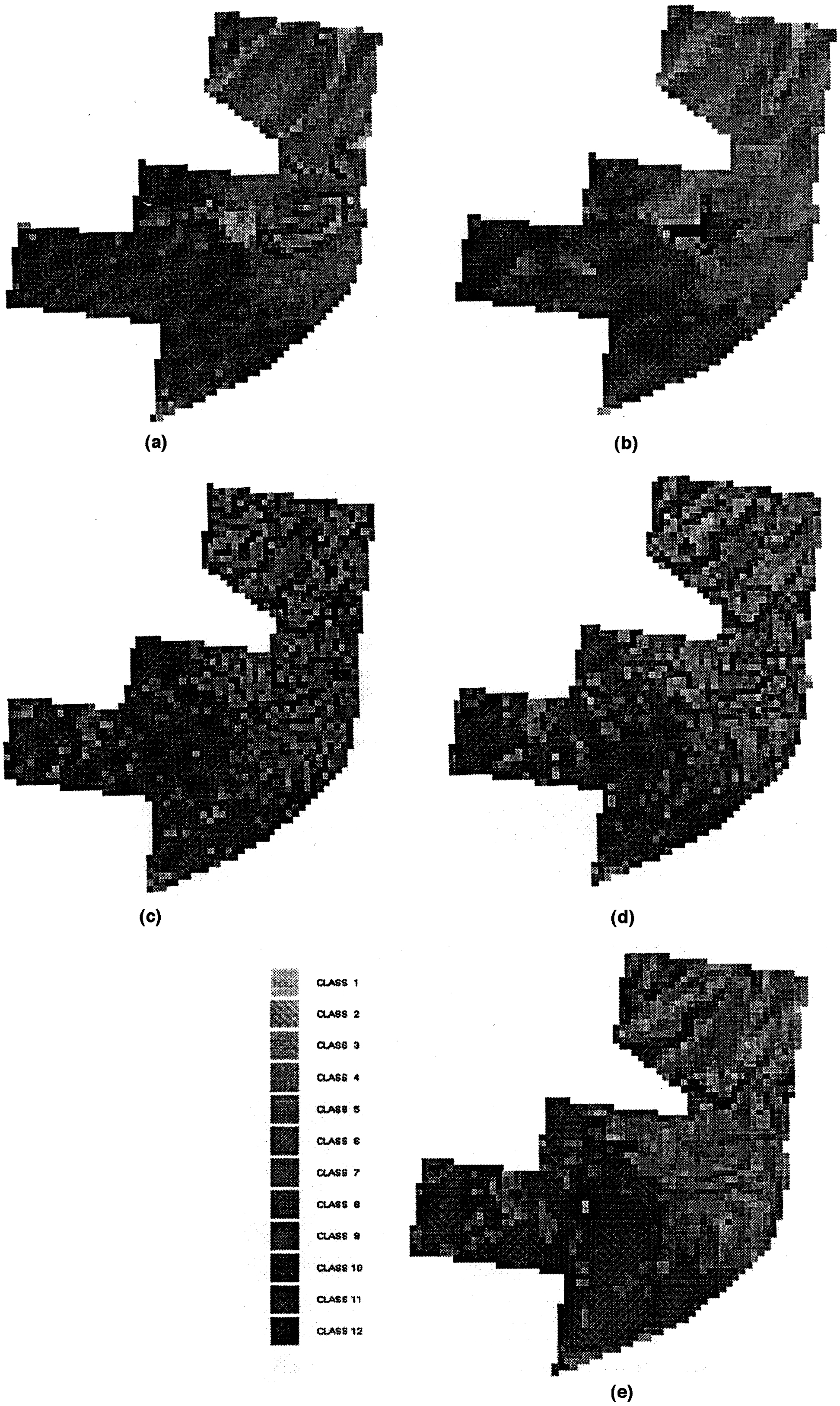

Figure 5. Slope maps for 25 m grid spacing from: (a) ground truth DEM, (b) 25m cartometric DEM, (c) 12.5 m photogrammetric DEM, (d) 6.25 m photogrammetric DEM, and (e) 25 m published slope map.

The RMSE in elevation for the cartometric DEMs was less than one-half a contour interval (i.e., 5 m), and the maximum error in elevation was considerably less than two contour intervals (i.e., 20 m). Thus, the cartometric DEMs satisfied the requirements for Level 2 data, under the USGS specifications.

Filtered Photogrammetric DEM Error

A significant amount of high frequency noise existed in the photogrammetric DEMs. The effect of filtering with a low pass filter to reduce this noise, and hence the relative and absolute errors, was investigated. The analysis undertaken was for the photogrammetric DEM supplied on 12.5 m grid spacing, using a 5 × 5 Gaussian filter. Filters of size 3 × 3, 7 × 7 and 9 × 9 were also trialed.

Even after a single pass of a 3 × 3 filter a significant improvement was made to the visual appearance of the DEM. As the size of the filter was increased, the smoothness of the DEM was also increased. However, once the filter became larger than a 5 × 5, over smoothing of the DEM appeared to occur, with fine detail being lost. Moreover, the farm dam clearly visible in the ground truth and cartometric DEM was still not distinguishable in the photogrammetric DEM after filtering.

Results of statistical analysis showed that errors in the photogrammetric DEM were reduced to the same magnitude as those from the cartometric DEMs with filtering. Thus, with appropriate editing and filtering of the data during production of the DEM, photogrammetric DEMs at least as good as cartometric DEMs may be attained.

Slope Map Error

The accuracy of terrain slope, as well as being a measure of the relative errors in published DEMs, is of major interest to the environmental modelers. A slope map is simply a plot of slope magnitude (grouped into classes) with spatial position, having steeper areas shaded more darkly. This analysis was performed for the cartometric DEM with a 25.0 m spacing, and the photogrammetric DEMs on both the 6.25 m and 12.5 m grids with slopes calculated from points at 25.0 m spacing. This spacing was used in order that a comparison of the plots of slope class with spatial distribution could be made with the slope data provided for the photogrammetic DEM.

The slope maps in Figure 5 showed that the spatial distribution of slope class for the cartometric DEM was reasonably close to that for the ground truth. However, comparisons with the slope maps produced from the photogrammetric DEMs were not so good, with the slope map from the 12.5 m DEM being the worst. With some filtering, it was possible to imagine that a plot similar to that from the cartometric DEM could be obtained for the slope map produced from the 6.25 m grid. This is seen in the slope map in Figure 5e.

Conclusions

The accuracy of both cartometric and automatically measured photogrammetric DEMs have been characterised for a 1.4 km^2 study site by comparison with an accurate and dense set of truth data from ground survey. While this only represents a small area when assessing state and national DEM accuracy, results here should be indicative of accuracy for other regions. However, the conclusions presented are specific to this particular study and may not be characteristic of all cases. We therefore encourage others to undertake similar comparisons using accurate and dense ground truth data sets such as the one used here.

The raw ground survey data used for this analysis had an average standard deviation in position of 0.01 m, and an average standard deviation in elevation of 0.02 m. Gridded elevations from the ground survey data by linear interpolation had an average standard deviation of approximately 0.05 m, and a maximum standard deviation of approximately 0.5 m. Derived slopes from the truth DEM had an average standard deviation of approximately 0.5 percent and a maximum standard deviation of approximately 5 percent. Elevation error in the truth DEM was characterised by an isotropic single exponential correlation function, with a correlation length directly proportional to the raw data spacing. The correlation length of errors in derived slope was less than the correlation length of errors in elevation, being approximately two-thirds the spacing of the raw data.

The cartometric DEMs were as smooth as the truth DEM, with a loss of some fine detail and an RMSE in elevation of approximately 3.5 m, independent of grid spacing. The correlation length of errors in elevation ranged from approximately 300 m to 150 m, as the grid spacing was increased from 6.25 m to 25.0 m. The RMSE for slopes in the cartometric DEMs was approximately 6 percent, with a correlation length of approximately 30 m. The cartometric DEMs also had a maximum absolute error in elevation of approximately 12 m, and a maximum error in derived slope of 75 percent. Furthermore, the cartometric DEMs were found to satisfy the USGS specifications for Level 2 data at all grid spacings.

The photogrammetric DEMs exhibited significant amounts of high frequency noise, having an RMS error in elevation of approximately 4.5 m with a correlation length of 130 m, and 3.5 m with a correlation length of 80 m, for 6.25 m and 12.5 m grid spacings respectively. The RMSE in slopes for the photogrammetric DEMs was approximately 20 percent with a correlation length of 15 m, and 13 percent with a correlation length of 25 m, for 6.25 m and 12.5 m grid spacings, respectively. The maximum absolute error in elevation was approximately 28 m for the 6.25 m grid and 19 m for the 12.5 m grid, with maximum errors in derived slope of 289 percent and 114 percent, respectively. It is believed that the photogrammetric DEMs were so much worse than the cartometric DEMs because some points were at tree top level, while others were at ground level. Therefore, the photogrammetric DEMs require filtering or editing during production. The use of a 5 × 5 Gaussian filter reduced the errors in the photogrammetric DEM to the same level as for the cartometric DEMs, but research into a large number of DEMs for different terrains and different grid sizes with various filters types is required before recommendations may be made about post-processing requirements. Hence, a carefully edited photogrammetric DEM might be of a significantly higher accuracy.

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References

Bolstad, P.V., and T. Stowe, 1994. An evaluation of DEM accuracy: Elevation, slope, and aspect, *Photogrammetric Engineering & Remote Sensing*, 60(11):1327–1332.

Felicísimo, A.M., 1994. Parametric statistical method for error detection in digital elevation models, *Journal of Photogrammetry and Remote Sensing*, 49(4):29–33.

Fryer, J.G., J.H. Chandler, and M.A.R. Cooper, 1994. Short communication on the accuracy of heighting from aerial photographs and maps: Implications to process modellers, *Earth Surface Processes and Landforms*, 19:577–583.

Hutchinson, M.F., 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurous pits, *Journal of Hydrology*, 106:211–232.

Lane, S.N., J.H. Chandler, and K.S. Richards, 1994. Developments in monitoring and modelling small-scale river bed topography, *Earth Surface Processes and Landforms*, 19:349–368.

Li, Zhilin, 1993a. Theoretical models of the accuracy of digital terrain models: An evaluation and some observations, *The Photogrammetric Record*, 14(82):651–660.

Li, Zhilin, 1993b. Mathematical models of the accuracy of digital terrain model surfaces linearly constructed from square gridded data, *The Photogrammetric Record*, 14(82):661–674.

Manning, J., 1983. Accuracy checks on topographic maps, *Proceedings of the 25th Australian Surveyors Conference*, Melbourne, pp. 161–169.

Mikhail, E.M., and F. Ackerman, 1976. *Observations and Least Squares*, IEP, New York, 497 pp.

Moore, I.D., and R.B. GRAYSON, 1991. Terrain-based catchment partitioning and runoff prediction using vector elevation data, *Water Resources Research*, 27(6):1177–1191.

Moore, I.D., R.B. Grayson, and A.R. Ladson, 1991. Digital terrain modelling: A review of hydrological, geomorphological and biological applications, *Hydrological Processes*, 5:3–30

Robinson, G.J., 1994. The accuracy of digital elevation models derived from digitised contour data, *The Photogrammetric Record*, 14(83):805–814.

Sloan, S.W., 1993. A fast algorithm for generating constrained delaunay triangulations, *Computers and Structures*, 47(3): 441–450.

U.S. Department of Interior, 1998. User Guide #5, Standards for Digital Elevation Models, USGS National Mapping Division, URL: http://rockyweb.cr.usgs.gov/nmpstds/demstds.html (last data accessed: 03 April 2006).

Walker, J.P., and G.R. Willgoose, 1999. On the effect of digital elevation model accuracy on hydrology and geomorphology, *Water Resources Research*, 35(7):2259–2268.

Wolf, P.R., 1974. *Elements of Photogrammetry (with Air Photo Interpretation and Remote Sensing)*, McGraw Hill, New York.

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