

THE APPLICATION OF CONTOUR DATA FOR GENERATING HIGH FIDELITY GRID DIGITAL ELEVATION MODELS

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ABSTRACT

Digitized contours are increasingly being applied as a data source for generating regular grid digital elevation models (DEMs). The special characteristics of contours as a DEM data source, and some published contour-specific interpolation algorithms, are reviewed in this paper. Test results for three algorithms are presented, employing both synthetic and real surface data. The algorithms are: linear interpolation with four data points found in the grid axis directions (LIXY), linear interpolation within two data points found in the approximate direction of steepest slope (LISS), and cubic interpolation within four data points found in the approximate direction of steepest slope (CISS). The results indicate that high fidelity DEMs can be generated from contours, particularly when associated terrain features, such as break lines, ridges and spot heights, are incorporated into the input data. The root mean square errors of interpolated heights, relative to the contour data, range from 3% to 27% of the contour interval, depending on the interpolation algorithm, surface structure, and composition of the input data. Error surface contours are employed to illustrate the extent of systematic errors in the interpolated DEMs. The fidelities of the DEMs interpolated by means of the steepest slope algorithms are significantly higher than those resulting from grid axis interpolation.

INTRODUCTION

Contours are currently employed as a data source for the production of grid DEMs by government (civil and military) and commercial mapping organizations (Boyko, 1982; Adams et al, 1980; Leberl and Olson, 1982). Two reasons may be identified for the increasing popularity of this data source. Firstly, contours are either already available in graphic form on topographic maps, or can be readily obtained in a digital or graphic form directly from a stereoplotter. In these cases, the grid DEM can be generated by digitizing the graphic contour data, and applying an appropriate interpolation algorithm. Secondly, the special characteristics of contours as a terrain descriptor may be exploited by an interpolation algorithm for efficient production of a high fidelity DEM.

The fidelity of a DEM is a function of both the accuracy of the individual DEM elevations, and the geomorphological information content of the total model. In this paper, the accuracy of individual elevations are expressed through the

RMSE of interpolated heights, given as a percentage of the original contour interval (% CI), while the extent to which the geomorphological information in the original contours is captured in the DEM is illustrated with error surface contours. (A high fidelity DEM should produce error surface contours with a random horizontal and vertical distribution). Together, the RMSE % CI and error surface contours provide a measure of fidelity which is independent of the DEM density and applications.

CONTOURS AS A DEM DATA SOURCE

In a recent review of DEMs, eight patterns were identified for photogrammetric sampling of elevation data (Torlegard, 1981). These patterns consist of selective, homogeneous, progressive, composite and random sampling, in addition to sampling along profiles, contours, and epipolar lines. The contour line sampling pattern incorporates many of the desirable characteristics of the other patterns. The pattern is selective in that spot heights, break lines, ridges, drainage lines and other significant features are either implicitly or explicitly recorded during contour compilation. Contour sampling may be described as homogenous as all parts of the stereomodel are considered, and as progressive, since the density of the data is increased in areas of rough terrain. The contour pattern may be considered a special case of either composite or profile sampling, with the additional feature that the original data satisfy a wide range of applications without further processing.

These characteristics of contour sampling result from the sampling scheme being defined in terms of elevation differences, which is one of the phenomena being recorded. The structure of the contour lines is dependent on the local geomorphology, while the contour interval places a limit on the range of possible unrecorded elevations. Other commonly applied sampling patterns such as homogenous grids or profiles are not phenomenon based, and so no information on the shape or elevation of the terrain between observed points or lines can be inferred.

CONTOUR-SPECIFIC INTERPOLATION ALGORITHMS

Digital contour data may be processed by any general interpolation algorithm, such as the moving surface or finite elements methods, by considering the data as a set of randomly distributed point observations. However, these methods are generally less efficient and less accurate than contour-specific methods, as the former do not exploit the characteristics of contour data.

The published contour-specific algorithms may be classified into four groups, based on the methods employed to locate contour data points and interpolate within those points. The four groups are:

1. Linear interpolation within data points found in prespecified axis directions (LIXY). The number

of axes may be one, two or four, leading to two, four or eight data points.

2. Linear interpolation within two data points found in the direction of steepest slope through the DEM point (LISS). The directions searched for the steepest slope may be limited to the x, y and two diagonal axes. A variation of this algorithm employs the distance transform method to locate the two data points, hence allowing the local steepest slope profile to change direction at the DEM point (Mordhorst, 1976; Leberl et al, 1980).
3. Cubic polynomial interpolation within four data points found in the direction of steepest slope through the DEM point (CISS). As with LISS, the number of directions searched for the steepest slope may be limited.
4. Other algorithms. This group includes an investigation into the application of least squares interpolation (collocation) on data points found in pre-specified axis directions (Lauer, 1972), and algorithms which employ parallel processing hardware and procedures. The parallel algorithm described by Adams et al, 1980, applies linear interpolation to data points selected from the current processing column, the data to the right of the current column, and from within interpolated DEM points to the left of the column.

A summary of the published algorithms, grouped under these four classifications, is presented in Table 1. The table lists the authors, date of publication, the results of any accuracy tests, and the standard for accuracy testing. The title and source of each publication are listed in the references. Figure 1 illustrates the data points used by a representative algorithm from each classification. Since the published test results are not based on the same input data or test standard, and the algorithms within each group are not identical, the accuracy results cannot be directly compared and should be treated only as an indication of the accuracies which can be obtained with contour data. The published results relating to the geomorphological information content of contour-interpolated DEMs have been limited to comparisons of re-interpolated contours with the originals.

Many of the references listed in Table 1 indicate that the inclusion of supplementary non-contour data, such as spot heights, break lines, and ridge and drainage lines, significantly improves the fidelity of interpolated DEMs. One implementation of the two axis LIXY algorithm computes "phantom" data points to model hill tops, valleys and ridges

TABLE 1

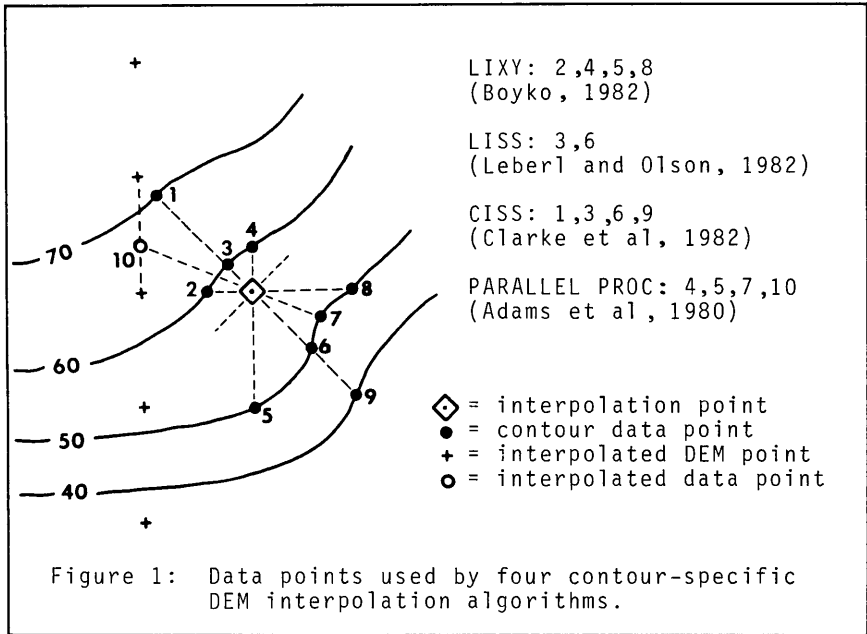
Published Contour-Specific DEM Interpolation Algorithms

Algorithms are grouped according to the method used for locating data points, and performing the interpolation. Accuracy results have been converted to the RMSE of interpolated heights as a % of the contour interval.

<u>AUTHORS</u>	<u>DATE</u>	<u>RMSE % CI</u>	<u>STANDARD</u>
<u>1. Linear along prespecified axes (LIXY).</u>			
Lauer	1972	8%-16%	manual int'n
Schult	1974	19%-34%	*
Finsterwalder	1975	15%-19%	stereo obs'n
Yoeli	1975		
Boyko	1982	<50%	ground obs'n
Leupin and Ettarid	1982		
<u>2. Linear in direction of steepest slope (LISS).</u>			
Hallmen	1969		
Finsterwalder	1975	13%	stereo obs'n
Yoeli	1975		
Mordhorst	1976		
Leberl, Kropatsch & Lipp	1980	5%-10%	manual int'n
Leberl and Olson	1982	10%-20%	manual int'n
<u>3. Cubic in direction of steepest slope (CISS).</u>			
Clarke, Gruen and Loon	1982	3%-10%	synthetic surface
<u>4. Other algorithms.</u>			
Lauer (collocation)	1972	5%-13%	manual int'n
Clark	1980		
Adams, Anderson, et al	1980		(parallel processing)
Baker, Gogineni, et al	1981		

* heights interpolated from the DEM at contour locations

(Boyko, 1982). The CISS algorithm includes a special procedure for interpolation adjacent to a break line, whereby data points beyond the surface discontinuity are not employed for the interpolation. The pre-processing of data for the CISS algorithm includes procedures for incorporating spot heights and structure lines into the interpolation data set. A more detailed description of the published contour-specific interpolation algorithms, and of the development and implementation of the CISS algorithm, may be found in Clarke, 1982.



EXPERIMENTAL RESULTS

Three of the algorithms from Table 1 have been programmed in FORTRAN, employing a raster data format. The algorithms are LIXY with two axes and four data points, LISS with four directions searched for the steepest slope, and CISS, also limited to a four direction search. Results from the application of these algorithms to synthetic surface data have been published previously (Clarke, Gruen and Loon, 1982). In that investigation, the RMSEs of interpolated points were found to be 3% CI for CISS, 15% CI for LISS, and 21% CI for LIXY. The error surface contours from the LISS and LIXY DEMs both exhibited a trend similar to the original surface, while the CISS error contours were randomly distributed, at the 10% CI level.

Two areas from a 1:25,000 scale topographic map (20 m contours) have been digitized with a manual line following digitizer, for the real surface testing of the algorithms. For each 50 mm by 50 mm map area, two raster data sets were created; one containing only contours, and the other containing contours, ridge lines, break lines (streams) and spot heights. Elevations along the non-contour linear features were computed during the vector to raster conversion, employing contour intersections as the data points for natural cubic spline interpolation. Spot heights were incorporated into the "all-data" rasters by interpolating a line of elevations between the spot height and surrounding contour. This procedure ensures that the spot height information will be encountered during the limited direction data searches performed by the interpolation algorithms. Grid

DEMs with a 25 m ground spacing were interpolated from the four data sets, with each of the CISS, LISS and LIXY algorithms. To isolate the effect on DEM fidelity of different terrain features and the effect of the inclusion of the supplementary data, five sub-areas were selected for detailed analysis. Figure 2 shows the vector data and DEM locations within each sub-area. Grid DEM heights were compared to manually interpolated heights to produce the accuracy statistics in Table 2. Error surface contour plots have been produced for each of the algorithms, data sets and sub-areas (Clarke, 1982). The plots for sub-area 5 are shown in Figure 3. Sample computation times for the three algorithms are shown in Table 3. The shorter times when all data are included are due to the lower number of pixels which must be examined in the raster data during the search for supporting points for the interpolation at each DEM point.

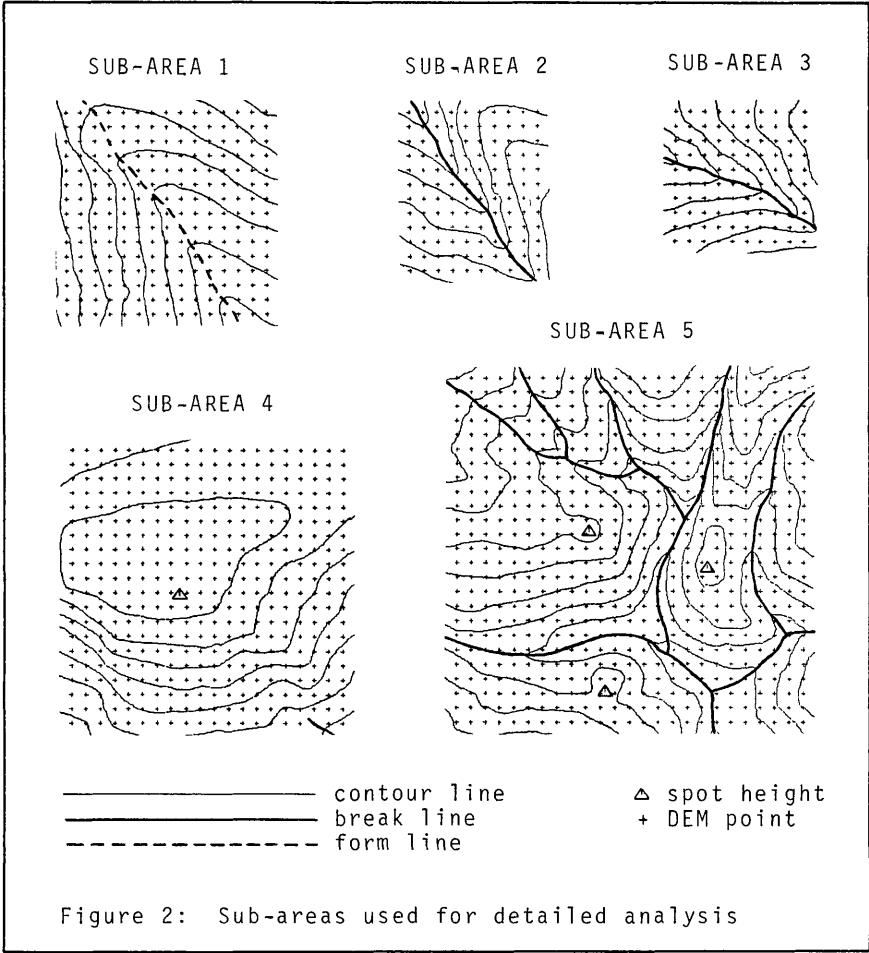


TABLE 2

DEM Accuracy Statistics using Topographic Map Data

Input data contour interval (CI) is 20 metres.
 Absolute maximum errors and RMSEs are given in metres.
 See Figure 2 for the original contours in sub-areas.

ALGORITHM:	CISS		LISS		LIXY	
INPUT DATA:	CONTOUR ALL		CONTOUR ALL		CONTOUR ALL	

<u>Sub-area #1 (225 points)</u>						
Abs max error	7.0	4.2	5.0	3.4	13.0	5.3
R M S E	1.4	1.2	1.0	0.9	3.2	1.5
RMSE as % CI	7%	6%	5%	5%	16%	8%
<u>Sub-area #2 (120 points)</u>						
Abs max error	4.1	3.5	5.3	3.0	13.0	10.0
R M S E	1.2	0.9	1.0	0.9	3.8	2.9
RMSE as % CI	6%	5%	5%	5%	14%	9%
<u>Sub-area #3 (100 points)</u>						
Abs max error	6.4	3.6	5.0	3.7	9.3	9.2
R M S E	1.5	1.2	1.2	1.1	2.8	2.1
RMSE as % CI	8%	6%	6%	5%	14%	9%
<u>Sub-area #4 (400 points)</u>						
Abs max error	12.1	8.7	14.0	10.2	17.0	17.0
R M S E	1.9	1.6	3.8	1.8	5.4	4.6
RMSE as % CI	9%	8%	19%	9%	27%	23%
<u>Sub-area #5 (625 points)</u>						
Abs max error	15.3	4.1	12.0	5.0	16.0	11.5
R M S E	2.4	1.3	2.1	1.1	3.9	2.9
RMSE as % CI	12%	6%	10%	6%	20%	14%

TABLE 3

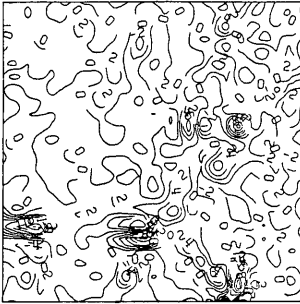
Sample Computing Times for DEM Interpolation

The times shown are the CPU times in seconds for the interpolation of 2601 DEM points within a 251 x 251 data matrix, using an Amdahl 470 V6-II computer. Program compilation and input/output are not included.

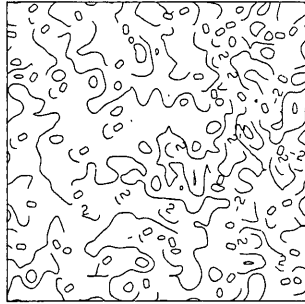
ALGORITHM:	CISS	LISS	LIXY

USING CONTOURS ONLY:	6.25	3.22	2.01
USING ALL DATA:	5.90	3.08	1.88

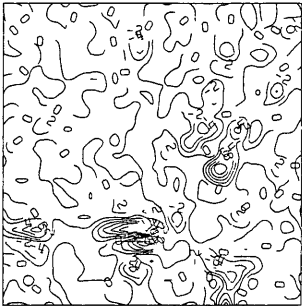
C I S S / CONTOUR DATA



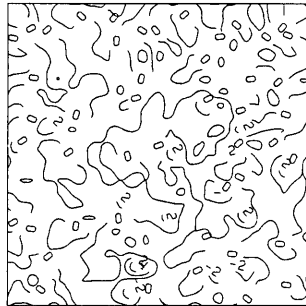
C I S S / ALL DATA



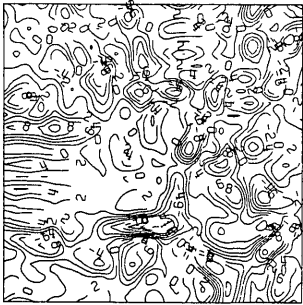
L I S S / CONTOUR DATA



L I S S / ALL DATA



L I X Y / CONTOUR DATA



L I X Y / ALL DATA

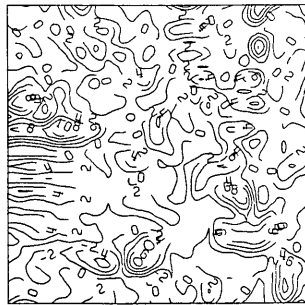


Figure 3: Sub-area #5: Error surface contours (10%CI)
Original contours are shown in Figure 2.

CONCLUSIONS

The topographic map data testing has not produced the clear ranking of algorithms, in terms of DEM fidelity, that was possible from the synthetic surface results. Overall, the two steepest slope algorithms have performed equally well, and always better than LIXY. The only situation which

demonstrates a clear difference between CISS and LISS is sub-area 4, where without supplementary data, the CISS algorithm was able to retain the mountain top geomorphology in the interpolated DEM. In all other cases, the statistics from the LISS algorithm were equal to or slightly better than those from CISS, although the differences are not generally perceptible in the 10% CI error surface contour plots. (The extent to which the comparison is influenced by the use of manually interpolated heights as "true" values could only be determined by more objective testing).

A clear trend in the topographic map tests is the improvement in DEM fidelity which results from the inclusion of supplementary data. The additional data have a large effect on the accuracy statistics of the LIXY algorithm, but do not eliminate the trends from the LIXY 10% CI error surface contours. The improved point accuracies however, do not equal those resulting from the application of the steepest slope algorithms to the "contours-only" data. The additional data have a lesser effect on the steepest slope accuracy statistics, but eliminate the trends in the 10% CI error contours, indicating a high retention of the geomorphological information contained in the original data. From the contour data employed in this study, the expected RMSE of DEM heights, relative to the original data, is 5% to 15% CI when steepest slope algorithms are applied, and 14% to 27% CI when the x,y axes algorithm is applied. Smaller errors and a higher retention of geomorphological information may be expected when supplementary non-contour data are included. These results are consistent with the previously reported findings shown in Table 1.

Further investigations in this area will include modifying the CISS algorithm to search more directions from the DEM point, and to locate the outer two data points by steepest slope searches from the inner two points. (Currently, the outer two points are located by a linear extrapolation in the direction of the inner steepest slope profile). These modifications should produce more stable distributions of data points for the cubic interpolation. Additional testing will incorporate a variety of landforms, including moderately flat terrain, and employ stereomodel observations as the standard for comparison.

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