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DTM Application in Topographic Mapping*

The Gestalt Photomapper and sophisticated computer software provide for a high-speed DTM production system.

(Abstract appears on following page)

INTRODUCTION

DIGITAL TERRAIN MODEL (DTM) may be defined as the digital representation of terrain relief. The Topographical Survey Division is currently engaged in a program for digital mapping using DTMs. For this reason a Gestalt Photomapper (GPM-2) system was acquired and installed in the Division. In the Photogrammetric Engineering Section a computer system was developed for the post-processing of the DTMs produced by the GPM-2 system for the production of

- a digital contour overlay for topographic maps, and
- a digital terrain elevation data base on a UTM coordinate system.

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The point pattern for relief representation in the DTM is a grid. The density of the grid point is fixed at $\simeq 182\mu$m expressed at the photo scale.

The processing of DTM data for the purposes of producing digital contour overlay and/or digital terrain elevation data base can be considered as a conversion of one data form into another. The main components of the DTM data processing system are

- The standardization of the DTM data structure and creation of global grid elevation data superimposed on the UTM coordinate system,
- Verification and filtering of the DTM data, and
- Interpolation for contours.

ACQUISITION OF THE DTM

In the Topographical Survey Division, DTM data are obtained from the Gestalt Photomapper System. The GPM-2 is a highly automated photogrammetric system designed to produce DTMs, orthophotos, and photographic contours by using electronic image correla-

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tion to measure parallaxes. The system consists of a pair of flying spot scanners, a digital correlator module, computer and magnetic tape units, orthophoto and contour printer units, and an operator console unit.

The scanners are the measuring units for the image coordinates in the diapositives. A CRT inside the scanner acts as the light source over a square, linearly scanned *X-Y* raster. The light transmitted through the diapositives is collected and converted into an electrical signal by a photomultiplier. The resulting video signal is then transmitted to all the other subsystems of the GPM-2.

The most complex unit of the GPM-2 is the correlator which measures the spatial displacements of points in the left and right video signals. The correlator module has a semiconductor memory to store the results of all parallax calculations. The overlapping area of the input diapositives is divided into about 1000 9 by 8 mm patches. After the initial raster shaping, each pair of left and right patches is identical, except for parallaxes due to differences in heights. The correlator analyzes these differences for 2444 182-micrometer square areas in each patch, calculates their heights, and alters the scanning pattern to remove the expected parallax. This process is iterative at the rate of 50 iterations per second. The correlator measures the image parallaxes at each iteration and thereby provides current height estimates. These height estimates are used to differentially transform each scanner's raster according to the projective transformation relating map to image coordinates. Convergence of the iterative sequence is accompanied by the effective flattening of the perceived stereo model on the monitor. The height values at convergence are the basis for the DTM. After a patch is measured, the height data are transferred to the computer, where a second transfer takes the data to the magnetic tape unit. With the completion of all the tasks for this patch, the present model coordinates of the floating mark are updated by increments $\Delta X, \Delta Y$. By extracting the appropriate information from the correlator's memory, the next patch is usually reached with the correlator keeping the transports locked to the ground at the floating mark. Once the transports are at rest at the coordinates of the new patch center, the Gestalt cycle repeats.

ABSTRACT: *The Topographical Survey Division recently acquired the Gestalt Photomapper GPM-2/3 system for the production of DTMs. The analytical model is scanned and continuously transformed according to electronic correlator measurements until the corresponding images from both cameras for a 9 by 8 mm patch are in register. A single DTM normally contains one million elevations.*

A computer system was developed for the post-processing of the Digital Terrain Models and the production of

- *digital contour overlays for the 1:50 000 topographic maps; and*
- *digital terrain elevation data base on a UTM grid.*

The DTM post-processing system includes the following main tasks:

- *standardization of DTM structure using various interpolation algorithms,*
- *verification and filtering of the generated map elevation grid, and*
- *linear interpolation for contours on a per-map-sheet basis.*

Problems of uncorrelated patches over water surfaces have been resolved and the software was developed for a minicomputer environment. Problems of mass data application were resolved by developing algorithms that actually simulate virtual memory to maintain continuity of contour line, and still require a reasonable amount of computer system time. Results of DTM processing are included.

Only a sub-set of the 9 by 8 mm scanned area is used at each correlation/record/step cycle. A physical mask close to the image plane selects a portion of the 9 by 8 mm scanned area for printing. The stepping increments ΔX, ΔY, from patch to patch are related to the mask size. This redundancy or overlap in scanning is essential for "continuity" in the ortho/contour/DTM products. The data are recorded patch by patch on computer compatible 9 track magnetic tape at 800 BPI. Each patch corresponds to a square submatrix of the DTM. The model is recorded column by column and each column consists of the same number of rows. Columns are parallel to the y-axis, rows parallel to the x-axis. The result is a rectangular DTM with straight line borders. Depending on the mask size, the dimension of the submatrix is 40 by 40, 32 by 32, or 24 by 24. The selection of patch size depends on the steepness of the terrain, larger patches being appropriate for flatter terrain. The spacing between the rows or columns in the patch or between the patches is 182μm expressed at the photo scale. The total number of elevation data in each DTM is a matrix containing approximately one million points divided into patches (or submatrices). For a 1:50 000 scale map the total number of DTMs to cover the area is approximately 25 models giving a total of 25 million elevations per map.

GPM-2 DTM Format

The DTM tape is divided into blocks, in which the first two blocks are the model header and the recording specifications. The model header identifies the model and contains the photogrammetric information such as the parameters of transformation of model to ground, the orientation parameters, focal length, base, scale, RMS errors, and the ground and model coordinates for control points. The recording specification header contains the number of data records per patch, the dimension of the elevation submatrix, the spacing between elements in microns at photo scale.

Each patch data record contains the patch number, column and row number, the number of elevations data, the patch center and origin in model and ground units, the number of times of operator's intervention during correlation, and terrain condition setting. The amount of vertical parallax measured for the patch and patch link error to the adjacent leading and lagging column edges and the leading row edge also are recorded.

The last patch record is followed by the end of model record that contains the number of patches recorded, the number of times operator forceprinted patches due to lack of correlation, and the elapsed time taken to record the model. The entire DTM is terminated by an end-of-file mark.

Data Processing

Processing of DTM data produced by the GPM-2 system for the production of digital contour overlays for the 1:50 000 topographic maps is regarded as a conversion of one data form into another. The columns and rows in each DTM are oriented to the base of the photogrammetric model. As shown in Figure 1, for a 1:50 000 map sheet and depending on the flight line, the DTM matrix of each model has a different orientation with respect to the UTM coordinate system. The scanning pattern for each DTM is shown in Figure 2. If each DTM is processed separately, the contours generated in the overlapping areas between the DTMs will be duplicated and there is a problem of matching contours without extensive editing. Even within the DTM there is a problem between the patches themselves.

The accuracy of the generated elevations depends on correlating the video signals and measuring the phase shift. With a complex system such as the GPM-2 achieving a perfect correlation is virtually impossible due to numerous factors such as the density of photogrammetric imagery, steepness of terrain, and problems of scanning and correlating over large water bodies (e.g., lakes), ice fields, forests, urban areas, etc. In addition to that, there is the problem of the massive amount of data required to cover a 1:50 000 map sheet. A topographic map sheet at a scale 1:50 000 is normally covered with approximately 25 DTMs (25 million elevations), each with a different orientation, i.e., each DTM has its own local coordinate system.

In the Photogrammetric Engineering Section, Topographical Survey Division, a software system was developed for the processing of DTMs and the production of digital contours. To complete the map sheet, the planimetry data (lakes, rivers, culture, roads, etc.) will be

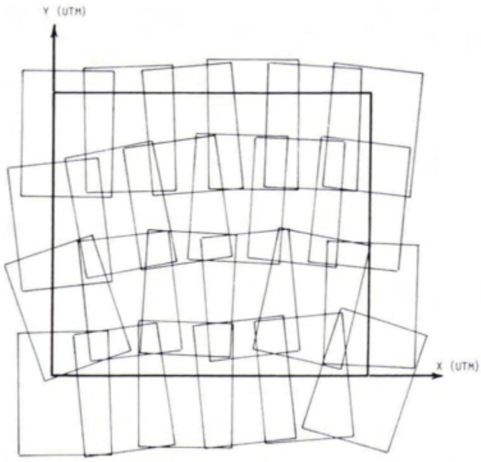

FIG. 1. Layout of photogrammetric models covering 1:50 000 topographic map.

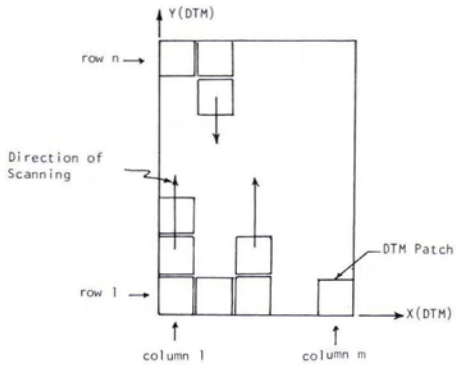

FIG. 2. DTM scanning pattern.

digitized from photogrammetric models using digital map compilation and an on-line edit system. Lakes and streams will be digitized in x, y, and z for further use in the DTM processing system. The main components of the system perform the following tasks:

- Verifying and filtering of DTM data,
- Interpolating the DTM patches and the construction of a global grid coinciding with the UTM coordinate system,
- Smoothing (filtering) of global grid cells,
- Extracting lake and stream information (x, y, z coordinates) from a previously digitized planimetry data file,
- Superimposing the lake and stream information on to the global grid and redefining heights in the cells,
- Interpolating for the contour overlay, and
- Merging of the contour and planimetry data files.

To check the quality of the digitally produced topographic map a proof plot will be drawn.

The second phase of operation involves interactive editing of the digital file and consists of the following tasks:

- Interactive editing of the digital map file and the production of error-free digital data (data base definition file),
- Interactive cartographic editing of the data base definition file, and
- Preparation of a plot file for color separation overlays.

CONSTRUCTION OF GLOBAL GRID ELEVATIONS (GGE)

The concept of the global grid positioned horizontally with the UTM coordinate system was adopted for the following reasons:

- To avoid the problem of contouring DTMs with different orientations in each map sheet;
- To eliminate the problem of matching model edges;
- To eliminate duplicated patches between models and therefore reduce the amount of elevation data;
- The constructed global grid will have a predefined spacing between the elements of rows and columns, thus producing a uniform digital terrain elevation grid; and
- The interpolation for global grid elevations allows for smoothing of the topographic surface and provides the means for detecting and eliminating blunders.

For the computation of the GGE, the map sheet is divided into square cells (Figure 3). Each cell is covered by a group of DTM patches, i.e., submatrices of elevations. The grid intersections (nodes) of the GGE cell are interpolated from the DTM patch data by constructing a surface whose weighted sum of squares of distances to the reference patch points is a minimum. The topographic surface will be represented by a tilted plane or a second degree surface and can be defined by appropriate choice of terms of the equation

$$h = a_0 + a_1x + a_2y + a_3xy + a_4x^2 + a_5y^2 \quad (1)$$

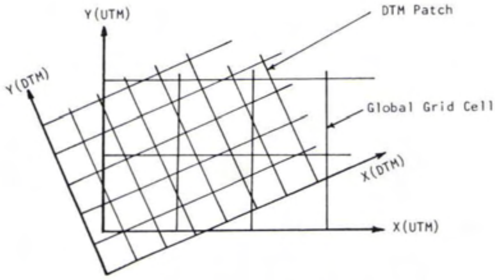

FIG. 3. DTM patches superimposed on the map sheet grid.

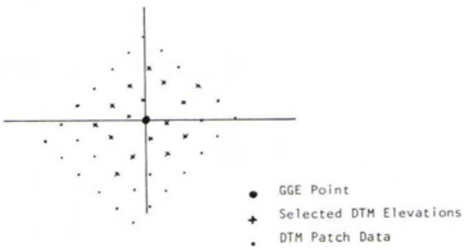

FIG. 4. DTM elevations used for GGE point interpolation.

To fit these surfaces, from eight to sixteen observed points should be selected. Observed points closest to the area of interest are chosen for the surface fit as shown in Figure 4. Two points are usually selected in each octant. The observation equations for the surface are

Second Degree Polynomial →
Bilinear Polynomial
Plane →

$$\begin{bmatrix} 1 & x_1 & y_1 & x_1 y_1 & x_1^2 & y_1^2 \\ 1 & x_2 & y_2 & x_2 y_2 & x_2^2 & y_2^2 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 1 & x_i & y_i & x_i y_i & x_i^2 & y_i^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ \cdot \\ \cdot \\ \cdot \\ z_i \end{bmatrix} \quad (2)$$

or

$$\mathbf{A}\ \mathbf{V} = \mathbf{S}.$$

The weights are defined as $x = 1 / r^2$ where r is the radial distance.
The weight matrix is

$$\mathbf{W} = \begin{bmatrix} w_1 & & & & & \\ & w_2 & & & & \\ & & \cdot & & & \\ & & & \cdot & & \\ & & & & \cdot & \\ & & & & & w_i \end{bmatrix} \quad (3)$$

The normal equation can be given as

$$\mathbf{A}^T\mathbf{W}\mathbf{A}\ (\mathbf{V}) = \mathbf{A}^T\mathbf{W}\mathbf{S} \quad (4)$$

The solution is

$$(\mathbf{V}) = (\mathbf{A}^T\mathbf{W}\mathbf{A})^{-1}\ \mathbf{A}^T\mathbf{W}\mathbf{S}. \quad (5)$$

In Equation 1 the selection of one or more terms gives several interpolation formulae for the evaluation of the GGE point from the observed (patch) data points. If the linear interpolation technique is selected, only the three terms a_0, a_1x, and a_2y will be used. For a bilinear polynomial the fourth term, a_3xy, will be added. The last two terms will be used if a second degree polynomial is required.

Since every GGE node is covered by a regular submatrix of the DTM patch data elevations, it is also possible to compute the required elevation using the weighted arithmetic mean.

The use of the linear interpolation, bilinear polynomial, second degree polynomial, or weighted arithmetic mean depends on the topography of the area around the GGE node and its location with reference to DTM patch coverage. The moving surface method provided a good estimate for elevations close to the edges of the DTM patches and in areas with considerable relief. The bilinear polynomial is best suited for hilly terrain or terrain of moderate relief. The linear interpolation fits a plane surface to areas with low terrain slope and the arithmetic mean was found better for flat terrain where the difference in elevations between the closest points to the GGE node is less than one contour interval.

FILTERING OF GLOBAL GRID ELEVATIONS

The examination of elevation data in the DTM patches showed that the mean elevation inside the patch is relatively smaller than the mean elevation along the boundaries of the patch, indicating the existence of noise between the DTM patch data. If the DTM patch data is contoured, break lines will be noticed between the patches. Also, if the patches in the DTM are profiled along the x- or y- axis of the model, a sudden change in the elevation data is usually observed where the profile crosses one patch to another. The same phenomena usually are found between neighboring DTM's.

Filtering is done on the global grid elevations in two dimensions by applying a one dimensional operator in each dimension. In order to avoid damping of elevation data, filtering is limited to those components most affected by instability, that is, those of high frequency. Since excessive filtering can entirely alter the character of the input data, this operation will be performed once. The filtering of the millions of elevations in the global grid could be tedious if smoothing is done by Fourier, least square polynomial, or min-max methods. Due to the nature of the topographic surface and the expected change of relief in the global grid nodes, filtering is done where the change in terrain slope is more than twice the mean slope along the direction of filtering. The method of moving averages is used in smoothing or damping the noise in the global grid elevations; two points on each side of the elevation to be smoothed are selected to define the simple five point symmetrical operation:

$$Z^*_{i,j} = \frac{1}{K}[K_3(Z_{i-2,j} + Z_{i+2,j}) + K_2(Z_{i-1,j} + Z_{i+1,j}) + K_1 Z_{i,j}]; \tag{6}$$

where $Z^*_{i,j}$ is the smoothed substitute for $Z_{i,j}$.

In Equation 6 the value of K is given by

$$K = K_3 + 2\,(K_1 + K_2). \tag{7}$$

The selection of factors K_1, K_2, and K_3 depends on the required degree of smoothing or magnitude of damping of the noise. For a five-point operation, the ratio of 4:2:1 for K_1 and K_3, respectively, produced a smoothing operator that damps only the physically significant elevation data. Another smoothing operator based on a three point operation can produce smoother elevation data without misrepresenting the character of the terrain.

EDITING CORRELATION NOISE OVER LAKES

When scanning over water surfaces the correlator cannot properly measure the spatial displacement of similar points in the left and right video signals. This causes a random noise

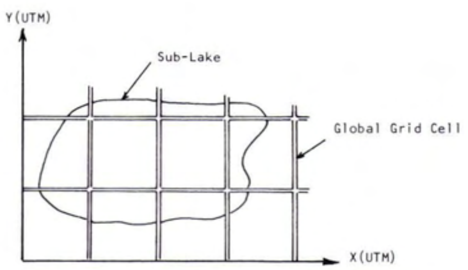

FIG. 5. Superimposing lake on global grid cells.

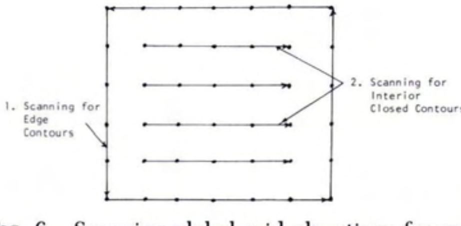

FIG. 6. Scanning global grid elevations for contour overlay.

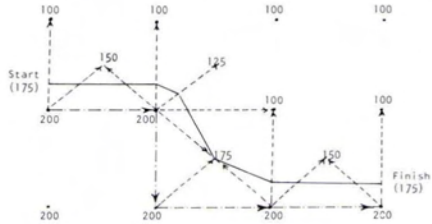

FIG. 7. Example of tracing contour 175 on global grid elevations.

in the elevations or a DTM with false elevation over water surface. If lake elevations recorded by the GPM-2 system are not edited, false contours are generated over the lake, creating a situation which is cartographically intolerable. To overcome this problem, the water surface boundaries (e.g., lakes) are digitized from the photogrammetric models in digital form (X, Y, and Z coordinates in the UTM coordinate system). If any digitized surface covers more than one global grid elevation cell, the lake is divided into sub-lakes as shown in Figure 5.

The subdivision of the lake is necessary so that each time only one global grid cell is brought to core memory for processing. The intersections of each sub-lake polygon with the global grid rows are determined and one single elevation replaces all the recorded GPM-2 elevations in this area.

CONTOURING GLOBAL GRID ELEVATIONS

The plot points are calculated from the grid elevations by linear interpolation. The global grid is searched for contours by scanning, first around the edges and second along the center of the matrix as shown in Figure 6. Any contour starting on an edge terminates on an edge and the entire contour is traced in one pass. The search is conducted in a counterclockwise direction around the grid. If a contour point passes between two grid points one of the grid elevations must have a value greater than the contour (reference point) and the other must have a value less than the contour (sub-point). Using the reference point as center, plot points are found at successive angles of 45° along the lines extending to the eight points immediately adjacent. For the points on the diagonals, the elevation at the center point of each grid square is calculated as the average of the values at the corners. With the introduction of the center point, the grid square may be broken up into four triangles and a contour can pass through each triangle in a unique way. When the contour line does not pass between the points, the reference point is transferred to the second point around which contour points at 45° angles continue to be found. A simple illustrative matrix with one contour line at elevation 175 is shown in Figure 7. Once a reference point has been used for any specific contour, it is flagged to ensure that contours are traced once only.

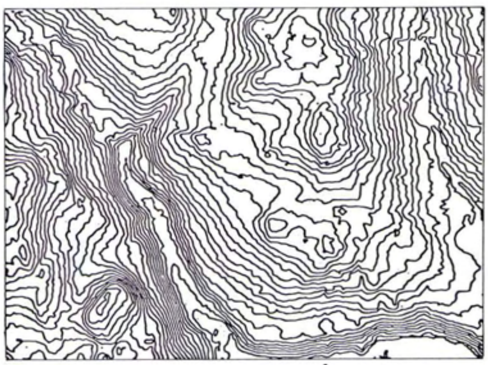

FIG. 8. Sample of digital contours from DTMs.

FIG. 9. Sample of conventially compiled contours.

While this method is not totally new (Coulthard, W. J., Contouring a Grid, U.B.C., Vancouver, Canada, 1975), the approach to the problem of mass data application required a fresh start on an age-old problem of data processing. It was necessary to develop an algorithm that actually simulates virtual memory to maintain continuity of contour line and still maintain a reasonable computer system occupancy.

COMPUTER SYSTEM

As outlined above, a series of programs has been developed for the processing of DTM's produced by the GPM-2 system for the production of

- global elevation grid in the UTM coordinate system, and
- digital contour overlay for 1:50 000 topographic maps.

The computer system was developed initially on the CDC-CYBER 74 computer. Twenty DTMs covering a 1:50 000 topographic map sheet were used for testing. Each DTM contained approximately one million elevations. The global grid elevation covering the map sheet was contoured and compared to the contours compiled on a stereo-photogrammetric plotter. Figures 8 and 9 illustrate a sample of digitally produced contours and the compiled contours respectively. It is expected that, by the time this paper is published, the implementation of the data processing programs on a PDP 11/70 minicomputer will be completed. Further testing and development will be made on the minicomputer environment.

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