REFINEMENT OF DENSE DIGITAL ELEVATION MODELS

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ABSTRACT

The Topographical Survey Division of the Surveys and Mapping Branch, Energy, Mines and Resources, Canada, employs dense digital elevation model (DEM) data for the production of hypsographic overlays for conventional and orthophoto maps.

The Gestalt Photomapper (GPM II/3), installed as a production system since summer of 1977, uses computer controlled electronic scanning and image correlation techniques to produce both orthophotos and dense digital elevation models at high speeds. Discontinuities caused by built-up areas and water bodies, poor image quality, shadows, and steep terrain slopes create anomalies in the DEM which require special data filtering and refinement techniques.

A complex DEM post data-processing system has now been developed to remove such anomalies and inlcudes various sub-programs which operate in Interactive and/or Batch processing modes. The key components of the system are:
* interactive filtering of erroneous observations from the raw DEM's produced by GPM II/3, and editing noise from scanning over water surfaces,
* generating of elevations from a global grid oriented to the UTM coordinate system,
* edit of DEM's for elevation biases, and the enhancement of the hypsographic data to achieve cartographically acceptable contour/ stream re-entrants,
* generating of a structured global DEM data base with the capability of integrating height information from other sources,
* production of hypsographic overlays for conventional and ortho-photo maps.

In order to illustrate the advantages of using the refinement process, several samples are included.

INTRODUCTION

The Gestalt Photomapper (GPM-II), installed at the Topographical Survey Division in 1977, use electronic image correlation to measure parallaxes and produces automatically and simultaneously three products: an orthophoto negative, a contour overlay and a digital elevation model (DEM). The GPM divides the stereomodel into about one thousand 9 by 8 mm scanning area. Depending on the mask size used to print the orthophoto and contour overlay, a matrix (40 by 40, 32 by 32, or 24 by 24) of elevations (patch) in each scanned area is generated. The grid spacing of the matrix is fixed at 182 μm at the photo scale.

In other words, the GPM can produce approximately one million grid elevations in each DEM. For topographic mapping applications, this represents a dense grid on the ground, e.g. using photography at a scale of 1:60 000, and a grid spacing of approximately 10.9 metres.

Due to the limitations of the automatic photogrammetric process, erroneous elevations may occur in the DEM in areas covered with large water surfaces, glacial features, elevation biases, shadows and forests.

A system for the post-processing of data was developed in the Division and is fully operational since 1979 to refine the dense DEM and to integrate the DEM's into our digital mapping system for the production of 1:50 000 topographical maps and the National Digital Terrain Elevation Data Base. The main components of the post-processing system are:

- erroneous data inspection and verification
- DEM interactive editing
- DEM standardization
- further refinement to global grid elevations with hypsographical information.

ERRONEOUS DATA INSPECTION AND VERIFICATION

It is the common concern for the DEM data analysts and/or users to know: what is the criteria to determine the erroneous data? where it falls? and how to locate and report it?

To avoid the complex analysis which may require tremendous computational efforts, the Topographical Survey Division has developed the following techniques as part of the DEM inspection/scanning.

Patch-Tie Map

In the process of conversing and transferring the GPM NOVA 800 tape to the in-house PDP 11/70 disk file (Allam, et al, 1980), a patch-tie map as shown in Figure 1 is generated. This is an index listing of the height differences between each patch corner and the mean height of that corner. To avoid printing large numbers, a scaling factor is used, and only absolute integer values between 0 to 9 are printed.

Photographic Contour Overlay and Patch Grid Overlay

A photographic contour overlay is interpolated (on a per patch basis) from the scanned and correlated DEM, and the derived contours are photo-graphically exposed on the GPM contour printer. The patch grid overlay is a transparency with a printed grid, where the spacing between the grid lines are equal to the GPM printing mask dimensions.

By visual inspection of these two overlays on a light table (Figure 2), poorly correlated areas (e.g. isolated contours on the water surface, mis-matched contours between the patches) are easily identified. Further, if only a part of a patch is in error (an edge or corner), its relative location is also determined.

MAP UNIT = 10.　　　　　 ----- COLUMN ----

```
      RMS                                 1
ROW           1  2  3  4  5  6  7  8  9  0  1  2  3  4  5  6  7  8

14           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
14           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       1.9
13           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
13           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       2.2
12           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
12           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       2.0
11           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
11           00 00 10 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       5.8
10           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
10           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       2.8
 9           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 9           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       3.9
 8           10 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 8           00 06 52 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
      12.1
 7           00 07 40 10 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 7           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       2.3
 6           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 6           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       2.0
 5           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 5           00 00 00 00 00 00 00 00 00 00 10 00 00 00 00 00 00 00
       2.6
 4           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 4           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       2.8
 3           00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 3           10 10 00 00 00 00 20 00 00 00 00 00 00 00 00 00 00 00
       6.0
 2           01 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 2           00 00 00 10 00 00 00 00 00 00 00 00 00 00 00 00 00 00
       2.8
 1           00 00 00 10 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 1           00 00 00 30 00 00 00 00 00 00 00 00 00 00 00 00 01 10

      RMS                                 1
ROW           1  2  3  4  5  6  7  8  9  0  1  2  3  4  5  6  7  8
```

MAP UNIT = 10.　　　　　 ----- COLUMN ----

RMS FOR WHOLE PATCH TIE = 2.9

Figure 1.　Patch Tie Map

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Patch Edges Linkage Display

A closer examination of the doubtful patch elevations is made by displaying the data on a video terminal (Figure 3). It shows the elevations along the edges as well as the data of the patch adjacent to it. From the selective profiles, along x-axis or along y-axis, it indicates the general trend surface of the current patch.

DEM INTERACTIVE EDITING

Upon completion of the DEM inspection phase by the operator, the process of DEM editing and filtering is performed by a software system. The software was designed and developed to allow for a controlled interactive editing of DEM data. For this purpose, a video terminal is required for the I/O program operations (see flow chart in Figure 4). Also a graphic display terminal (TEKTRONIX 4015) and a digitizer (TEKTRONIX 4953 graphic tablets) are required to edit a polygon (see figure 5)

The following interactive editing options are available:

Replace a Point with a Known Elevation

If the height value of a terrain point is known, e.g. a ground control point, the corresponding DEM point is replaced.

Replace the Entire Patch with a Known Elevation

If the patch is located over a body of water, e.g. lake with known elevation, the GPM recorded elevations are replaced.

Z-Shift of Entire Patch

In forest areas, if the average height of the trees is known, then the topographic surface of the area could be obtained by applying such Z-shift to the DEM.

Delete Entire Patch Data

If the patch is located in the edge or corner of the model, false elevations may be generated and this patch is usually discarded.

Tilt One Corner of a Patch

Occasionally, some patches lack a good correlation, particularly in the corner area, and it is necessary to edit a patch segment to achieve homogenity in elevations with other patches.

A patch is divided into nine sub-blocks as shown on Figure 3. The poorly correlated corner can be identified easily through the analysis with the help of the values of the adjacent points of neighboring patches.
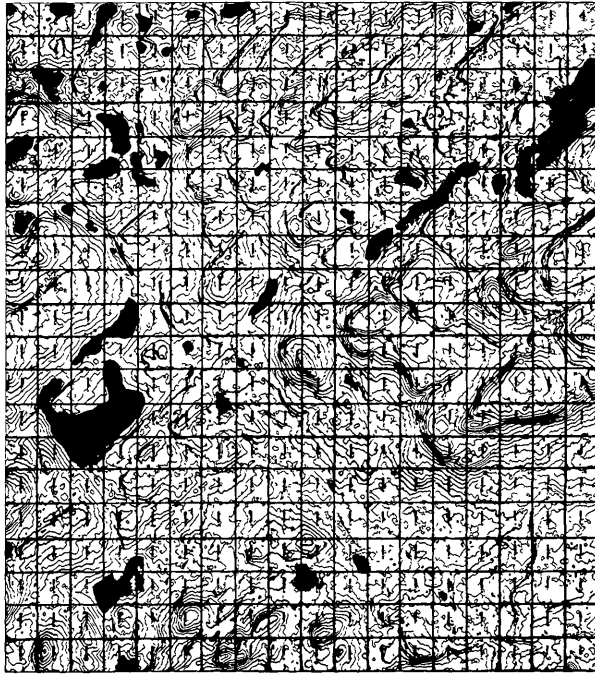
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Figure 2. Photographic Contour Overlay and Patch Grid Overlay

Figure 3. Patch Edges Linkage Display

Assuming S-W corner of the patch has to be tilted due to mis-match of point "D4" with its neighboring points (D3, D6 and D7) in the adjacent patches, and assuming also the profiles C1 to C4 and F1 to F4 are satis-factory, a new elevation $R(1,1)$ for point D4 is interpolated from the acceptable neighboring corners (D3, D6 and D7). New elevations $R(i,j)$ in this sub-block are computed as follows:

For $i = 2$ to $q-1$, and $j = 1$

$R(i,j) = R(1,1) + (i-1) [Z(q,1) - R(1,1)]/(q-1)$

For $j = 2$ to $q-1$, and $i = 1$

$R(1,j) = R(1,1) + (j-1)[Z(1,q) - R(1,1)]/(q-1)$

For $i = 2$ to $q-1$, and $j = 2$ to $q-1$

$R(i,j) = [R(i,1)S1 + Z(i,q)S2 + R(i,j)S3 + Z(q,j)S4]/S$

where

$S1 = 1/(j-1)^2$, n = mask size,
$S2 = 1/(q-i)^2$, $q = 2(n+1)/3$,
$S3 = 1/(i-1)^2$,
$S4 = 1/(q-1)^2$, and
$S = S1 + S2 + S3 + S4$.

If necessary, similar process may be used to modify the Z-values of the other patch corners.

Smoothing of the Linkage of the Adjacent Patches

Due to prior correlation, the Z-values of the patch may represent its topographical characteristics to a certain degree, but these Z-values do not fit to their adjacent patches. Therefore, a Z-adjustment of the patch is needed, and the edge elevations of neighboring patches are used as control values.

The general formula for the trhee-dimensional linear conformal transformation used is:

$E = \lambda AX + C$

in which:

E   is a column vector with the control values of x-, y- and z-coordinates of a point as components,

X   is a column vector with the transformed values of x-, y- and z-coordinates of a point as components,

λ is a scale factor,

A   is an orthogonal matrix that represents a rotation in three-dimensional space, and

C   is a column vector with X-, Y- and Z-shifts as components.

The minimum prerequisites for control configuration for this conformal transformation are selected (four points per edge) as follows:
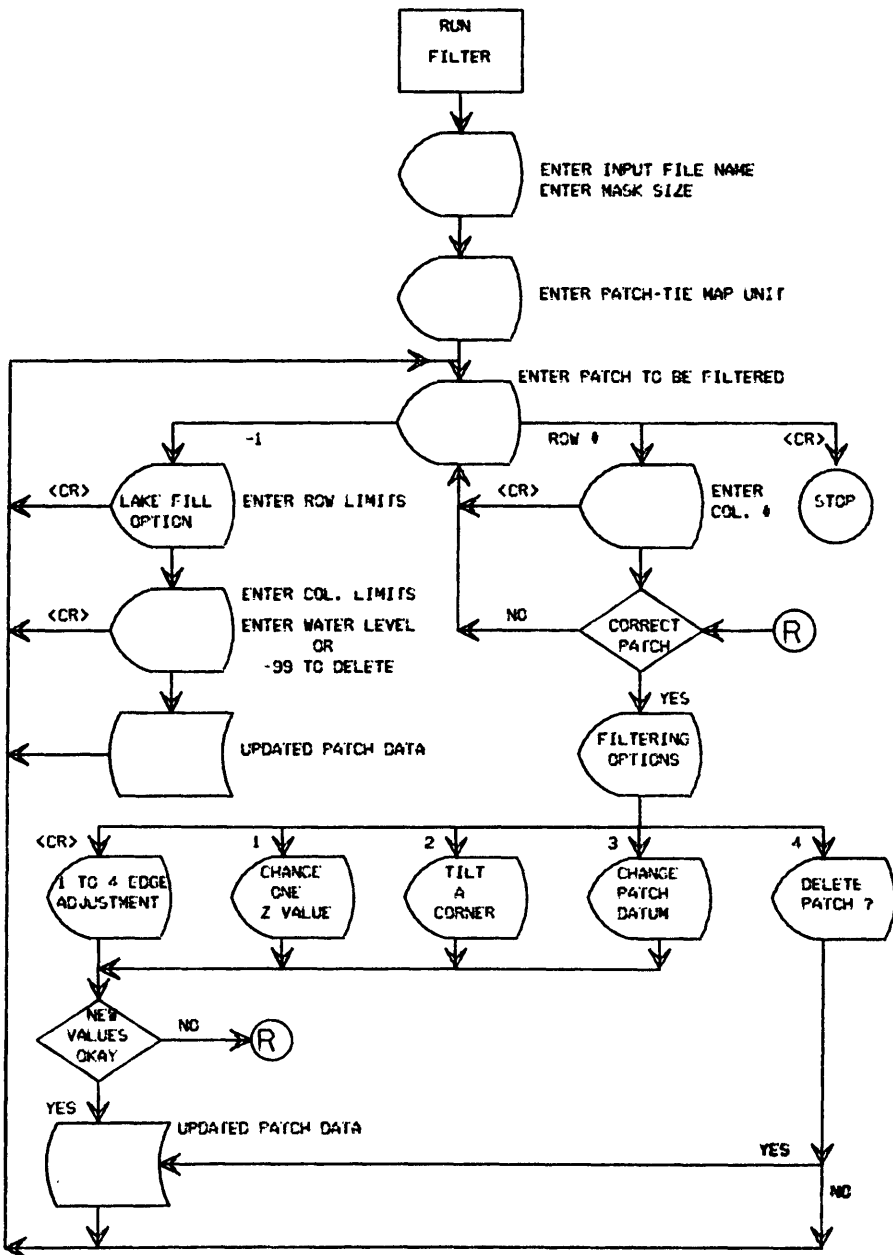
FIGURE 4. OPERATIONAL FLOW CHART OF PROGRAM FILTER

(a) points on two parallel edges indicating a fit to its neighboring patches,

(b) points on two perpendicular edges in the patch indicating a fit, and an auxiliary point at the intersection of the two other edges.

Editing the DEM of a Polygon (Program WAF)

The polygon encompassing poorly correlated areas (e.g. lakes) are digitized from the photographic contour overlay produced by the GPM using TEKTRONIX 4953 Tablet. These X,Y values are expressed in the local coordinate system of the patch matrix. The elevation within this polygon are determined based on terrain coverage and/or external height informations. For example, if the polygon contains a water surface, the elevation is obtained as the mean elevation of all points on the perimeter, or the elevation is known from a map manuscript, hydrographic gauge, or a photogrammetric process. In the case of forest coverage with a known average tree height, a Z-shift is applied within the forest polygon.

This editing process is performed interactively using program WAF, as shown in Figure 5.

DEM STANDARDIZATION

The DEM's produced from the photogrammetric models using the GPM have various elevation grid spacing and orientation based on input imagery. To the DEM users, this diversity may be an obstacle in creating the contours and in selecting terrain elevations from different models on the overlapping area. Therefore, the concept of the global grid elevations, positioned horizontally with the UTM coordinate system, was developed in Topographical Surveys Directorate (Allam, Wong 1976).

Global Grid Elevations (Model)

The DEM is divided into square cells parallel to the UTM coordinate system; each cell has a 10 X 10 grid matrix with a constant grid spacing. The elevation of each grid intersection (node) is interpolated from the DEM patch data by constructing a surface whose weighted sum of the squares of distances to the reference patch points is a minimum (Allam, 1978). The formation of the global grid elevation yields the following advantages:
- produces a uniform digital terrain elevation grid,
- smoothing of the topographic surface,
- provides a means to reduce the quantity and keep the quality of the massive data oriented DEM file.

Global Grid Elevations (Map Sheet)

A global grid elevation in map sheet form is created in order to construct a uniform grid of elevations over a map sheet area, eliminate the problem of matching the model edges, reduce the quantity of elevation data on the model overlapping area, and to provide a better elevation data base in contouring (Allam, Low, 1980).

All global grid elevation (models) in the map sheet area are merged, and mean elevations are computed between the overlapping cells.
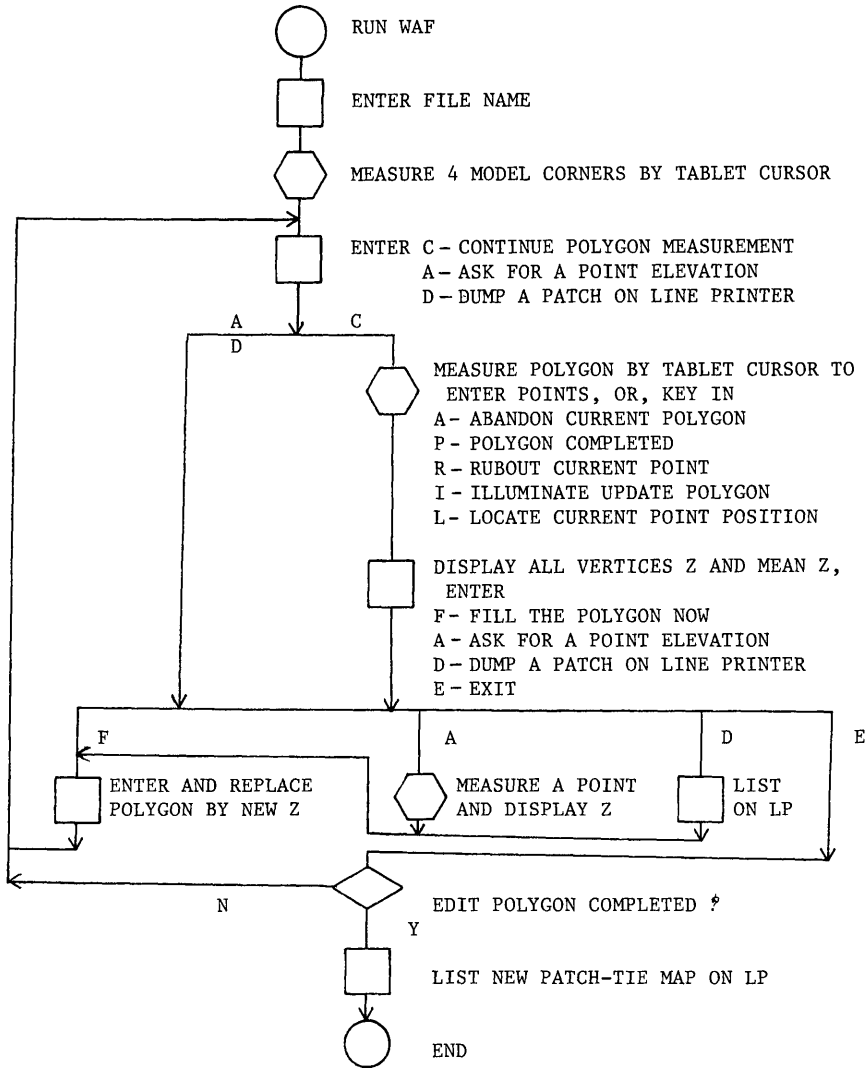
RUN WAF

ENTER FILE NAME

MEASURE 4 MODEL CORNERS BY TABLET CURSOR

ENTER C – CONTINUE POLYGON MEASUREMENT
      A – ASK FOR A POINT ELEVATION
      D – DUMP A PATCH ON LINE PRINTER

A
D   C

MEASURE POLYGON BY TABLET CURSOR TO
  ENTER POINTS, OR, KEY IN
A – ABANDON CURRENT POLYGON
P – POLYGON COMPLETED
R – RUBOUT CURRENT POINT
I – ILLUMINATE UPDATE POLYGON
L – LOCATE CURRENT POINT POSITION

DISPLAY ALL VERTICES Z AND MEAN Z,
  ENTER
F – FILL THE POLYGON NOW
A – ASK FOR A POINT ELEVATION
D – DUMP A PATCH ON LINE PRINTER
E – EXIT

F   A   D   E

ENTER AND REPLACE   MEASURE A POINT   LIST
POLYGON BY NEW Z   AND DISPLAY Z   ON LP

N   EDIT POLYGON COMPLETED ?

Y

LIST NEW PATCH-TIE MAP ON LP

END

Figure 5. Operational Flowchart of Program WAF

REFINEMENT OF GLOBAL GRID ELEVATION WITH HYPSOGRAPHIC DATA

Upon completion of the process of constructing a global grid of elevations per map, the contouring program may be used to interpolate for a graphic contour overlay. In practice, there is a problem of generating cartographically acceptable stream re-entrants with the generated contours. To solve this contour/ drainage problem, usually time-consuming on-line interactive graphic editing or manual processes were used. To improve the efficiency of this process, a batch mode program (SRE) was developed.

Positional coordinates of the stream are digitized from an orthophoto or by a photogrammetric process as shown in Figure 6. Program (SRE) computes the weighted arithmatic mean of the nodal points (e.g. A,B) from the closes four grid elevations, and the elevations of the digitized stream points (1,2,...n) on the grid profile are computed with the linear slope interpolation formula:

$$Z_i = (Z_A + Z_B - Z_A) \cdot d_i/S$$

where

Z_i = elevation of points i, i = 1, ... n,

S = distance between A and B,

d_i = distance between point i and point A,

Z_A, Z_B = elevation of point A and point B.

The grid elevations in the shaded area (2 grid spacing width) along the stream can then be re-defined as follows:

Take point j as example:

$$Z_j = \tfrac{1}{2}[Z_5 + \frac{S_{5-j}}{S_{5-D}} \cdot (Z_D - Z_5) + Z_6 + \frac{S_{6-j}}{S_{6-C}} \cdot (Z_C - Z_6)]$$

where

Z_j = re-defined elevation of point j,

Z_C, Z_D = elevations in DEM file,

Z_5, Z_6 = elevations along the stream, defined by eq.,

S = distance between two points,

To illustrate the advantage of using this method, Figures 7a and 7b show a contour overlay before and after using the program SRE.

CONTOURING AND INTERACTIVE CARTOGRAPHICAL EDITING

Linear interpolation method is used on the global grid elevations (map sheet) to produce graphic contours (Allam, Low, 1980). Since the output contour file is in the same format as that used in Interactive Graphic Design System (IGDS), further graphic editing is feasible.
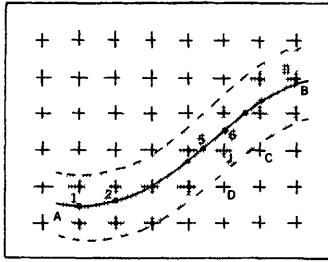
Figure 6.   Segment of a Digitized Stream

CONCLUSION

Refinement of the dense DEM is essential to maintain a high quality
digital elevation data base and digital topographic products.   Inter-
active editing procedures to verify and filter the erroneous elevations
is effective, particularly in a time-sharing, mini-computer processing
environment.   Standardization of the DEM's with the global grid concept
broadens its application and leads to an automatic contouring phase.
Natural topographic features, such as hypsographic information, have to
be considered for the refinement of the dense DEM.

REFERENCES

1. Allam, M.M. and C.K. Wong, "Gridding Topographical Surfaces",
    Presented paper, XIII Congress of the International Society for
    Photogrammetry, Helsinki, July 11-23 1976.

2.   Allam,   M.M.,   "DTM   Application   in   Topographic   Mapping",
    Photogrammetric Engineering and Remote Sensing, Vol, 44, No. 12,
    December 1978, PP. 1513-1520.

3. Allam, M.M., and B.A. Low, "Software Package for the Contouring of
   Massive DEM in a Mini-Computer Environment", 14th ISP Congress, 1980,
   Volume XXIII, Part B3, Hamburg, PP. 19-25.

4. Allam, M.M., "Filtering and Editing of Automatically Generated
    Digital Elevation Models", Presented paper, ISPRS Commission III
    symposium, Helsinki, June 7-11 1982.

5. Zarzycki, J.M., "An Intergrated Digital Mapping System", The
    Canadian Surveyor, Volum 32, No. 4, December 1978, PP. 443-453.
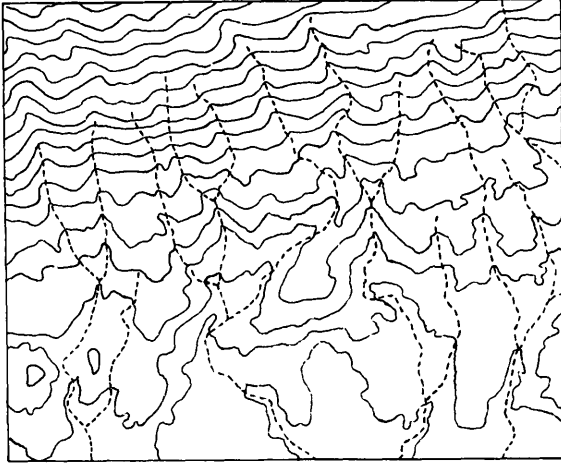
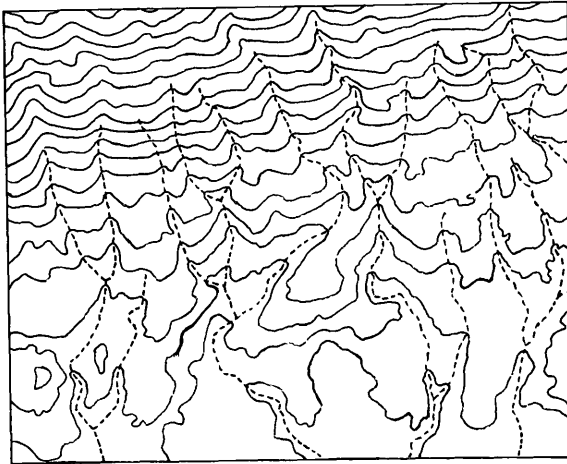FIGURE 7a.   DERIVED CONTOUR OVERLAY
BEFORE "SRE" EDITING

FIGURE 7b.   DERIVED CONTOUR OVERLAY
AFTER "SRE"   EDITING

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