Digital Terrain Models:
An Overview*

The definition, origin, acquisition, preprocessing, storage and management, applications, and future directions of DTM data are discussed.

**DEFINITION**

A DIGITAL TERRAIN MODEL (DTM) is an ordered array of numbers that represents the spatial distribution of terrain characteristics. In the most usual case, the spatial distribution is represented by an XY horizontal coordinate system and the terrain characteristic which is recorded is the terrain elevation, \( Z \). An alternate approach is to define position by latitude, \( \phi \), and longitude, \( \lambda \), and the terrain elevation by \( h \). Recent literature has referred to these distributions as Digital Elevation Models (DEM) to distinguish them from other models which describe different characteristics of the terrain. The data can be organized as a matrix array of coordinate triplets or as equations of surface defined by polynomials or Fourier series. It is important to note that characteristics other than elevation may also be included in the DTM. These characteristics may include such items as land value, ownership, soil type, depth to bedrock, land use, etc.

**ORIGIN**

The term Digital Terrain Model apparently had its origin in work performed by Prof. Charles L. Miller at Massachusetts Institute of Technology about 1955-60 (Miller, 1957; Miller and Laflamme, 1958a, 1958b). Prof. Miller and his colleagues were conducting research for the Massachusetts Department of Public Works and the U.S. Bureau of Public Roads. The objective was to expedite highway design by digital computation based upon photogrammetrically acquired terrain data.

Within each stereomodel, an XY horizontal coordinate system was established with the X-axis in the general direction of the proposed highway alignment. This coordinate system was tied to the State Plane Coordinate System by suitable control points. Profiles in the Y direction were taken at regular intervals, and the Z elevation along these profiles was recorded either at regular intervals of \( Y \) or at significant breaks in terrain slope, or both. Data acquisition was by means of a jury rig attached to Kelsh plotters. Initially coordinates were recorded by manual punch, but later paper tape recording was introduced. Conceptually, at least, other terrain attributes, such as soil type and land value, could be recorded in addition to the elevation at each point. In actuality this concept was never implemented, and only elevation was recorded.

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Several computer programs were prepared to utilize the data.

- The operator would input a trial highway alignment and the computer output would be the center line profile.
- The operator would input a trial grade line, and the program would output the resulting grade line geometry with vertical curves and annotations of cut and fill.
- The operator would input typical highway cross sections in both cut and fill, and the program would output station cross section areas, together with earthwork computations, such as haul distances and mass diagrams.
- The most advanced program automatically determined the optimum profile design based upon limiting grades and curves, site distances, and earthwork computations.

The computer employed was the IBM 650, which had a maximum storage of 2,000 words.

Although fairly simple according to today's standards, the MIT approach embodied all of the major elements of a DTM system:

- Data acquisition,
- Data preprocessing,
- Data storage and management, and
- Data applications.

**Digital Data Acquisition**

DTM data may be acquired from existing maps, from photogrammetric stereomodels, from ground surveys, or from other systems such as altimeters carried in aircraft and spacecraft.

The usual method of acquiring DTM data from existing maps is by manually following contour lines on one of the several digitizing tables which are available commercially. Though advertising brochures usually show a pretty girl happily at work, manual following of contour lines is actually a very tedious and boring operation with a high probability of errors, and either duplicating or omitting information.

To alleviate this situation, automatic line following instruments have been devised. The usual procedure is to work with the original contour plate from an existing map. The plate must be prepared by removing all numbers from the contours and filling in the gaps in the lines. This plate is then scanned by the instrument which latches on to a line at the edge of the sheet and follows it to its conclusion. Data density may be 10 to 20 points per millimetre of line. Operator assistance may be needed for closed contours within the sheet. The machine may have difficulty with lines of different weights, such as index contours. There is also difficulty in automatically assigning elevations to each digitized line. However, rapid progress is being made in this field, and new and more powerful instruments may be expected in the near future.

A second approach to automatic data acquisition from existing maps is to use a scanning device. The contour sheet is placed on a drum which either rotates under a fixed light source or has the light source rotating with respect to the drum. Each time a line is crossed, the X and Y position is recorded. These devices are excellent for acquiring and playing back digital data for purely graphical recording. However, if the objective is to file contour lines as continuous strings of digital data, an extensive amount of computer processing is required to vectorize the data and assign elevations to the digitized contours.

Still another approach to automatic acquisition of line data is to scan the map sheet with a linear array. On a single scan, this will record all the line data within a band several centimetres wide. The next scan will cover the adjacent band until the entire map sheet has been covered. This approach also requires a fair amount of computer processing to connect together the individual segments of lines and assign the proper elevations.

The second major source of digital data is from photogrammetric stereomodels. Digitizing systems based upon linear or rotary encoders can be had for most photogrammetric plotting instruments. The most recent generation of photogrammetric instruments have these encoding devices built in, and record the data on paper or magnetic tape. Usually stereomodel coordinates are recorded, but for some applications it is more advantageous to record the photographic image coordinates. Elevation data can be formatted either as contour lines, profiles with elevations recorded at regular intervals or at breaks in terrain slope, or as geomorphic points along drainage lines, hillcrests, etc.

Some photogrammetric instruments are equipped with automatic image correlators, and produce a high density of elevation points along scan profiles. The sampling strategy may be to record elevations at constant increments, $\Delta Y$, along the profile, at constant increments, $\Delta Z$, in elevation, or at constant increments, $\Delta t$, in time. One notable instrument (Gestalt Photomapper) performs correlation on small image patches and outputs an array of digital elevation data.
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Direct sources of digital elevation data are radar and laser altimeters carried in aircraft and spacecraft. Seasat-1, for example, presently in Earth orbit carries a laser altimeter which has the potential of providing worldwide coverage within the lifetime of the satellite.* To date, photogrammetrists have not been particularly concerned with processing these types of data, but it will certainly become a requirement in the future.

**Digital Data Preprocessing**

DTM data, however acquired, is rarely in form for immediate application, and extensive computer preprocessing may be required to arrange the data in the appropriate format.

The first requirement is usually data editing. This may be done either by producing a graphic product on a digitally controlled plotting table, or by displaying the data on a digitally controlled cathode ray tube (CRT). The operator can then determine overlapping, erroneous, or missing data and either send the copy back for redigitizing or make the corrections directly on the CRT. Most acquisition schemes acquire far more data than are actually required in the final files. Therefore, techniques of data compression must be employed to reduce the amount of data to a manageable quantity.

Another requirement of the preprocessing system is format conversion. It is usually necessary to provide programs to convert data interchangeably between contours, profiles, and regular grids of recorded elevation. For data acquired by raster scanning devices, it is usually necessary to transform to linear data by vectorization.

Coordinate transformations are another important part of data preprocessing. Data acquired in a stereomodel coordinate system, for example, may have to be converted to a State Plane Coordinate System; or data acquired in the State Plane Coordinate System may have to be transformed to Universal Transverse Mercator coordinates or into latitude and longitude before storage.

Some applications of DTM require that the surface be expressed as a mathematical function. The parameters of such a function may be found by any of the mathematical techniques of surface fitting.

Still another purpose of preprocessing is interpolation. Even after coordinate transformation, elevation data may not be in the proper location for the final file. For example, elevation data may have been acquired as profiles whereas the final file should be a regular grid of elevation data in the final coordinate system. Interpolation techniques may be as simple as bilinear interpolation or as complicated as multiparameter surface fitting by polynomials or series.

**Data Storage and Management**

One of the characteristics of digital cartographic systems is that they produce enormous amounts of data. In order to be useful, these data must be organized and carry sufficient collateral information so that they can be identified, stored, and retrieved in an efficient manner.

For most modern systems, the basic storage medium is magnetic tape. Header information on each tape will identify the map area, type of information, and the format in which it is recorded. For some applications it is necessary to transfer the information from tape to disk files.

In order to manage the data files, they must be cross-indexed by content and coverage.

There is an increasing awareness that DTM data have much more value than simply producing products within an organization. If this were the sole purpose, relatively simple formats compatible with the output plotting devices would be adequate. But if the DTM information acquired by one organization is to be used for any of a number of applications in other organizations, it will usually be necessary to adjust the storage format. By the time it becomes aware of the benefits of interchangeability, an organization will usually have such a large block of data that it becomes very difficult and expensive to change. The most that can be hoped for is to specify what the information contents of a file must be. Then, either the supplying organization or the using organization can prepare relatively simple software to transform one file format into another.

**Applications of DTM Data**

The mathematical operations involved in the application of DTM data can be summarized as follows:

- Given \( XY \), find \( Z \).
- Given an array of \( XYZ \) coordinates, fit a mathematical surface which will define \( Z \) as a function of \( XY \).
- Given an array of \( XYZ \) coordinate sets at fixed intervals, interpolate to find the value of \( Z \) at any other value of \( XY \).

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* Seasat-1 ceased operation in October 1978.
• Determine the intersection of straight or curved lines with a mathematically defined surface.
• Determine the intersection of horizontal, vertical, or inclined planes with the mathematically defined surface.
• Determine the volume between defined surfaces.

Some of the direct applications of DTM are as follows:

• Determination of contour lines. This can be done either by interpolation or by intersection of a horizontal plane with a mathematically defined surface. A number of programs are currently available for producing contours. A principal problem with digital contouring is obtaining adequate cartographic expression, particularly for details like highway and railroad cuts and fills, overpasses, stream re-entrants, etc.
• Generation of profiles. Profiles may be required for controlling orthophoto printing instruments, for transportation planning, for assuring adequate clearance of power lines, etc. Profiles can be obtained by intersecting the DTM with vertical planes.
• Determining intervisibility of points. This procedure has application to the determination of coverage patterns from ground radar or other tracking systems, to the placement of microwave transmission towers and similar problems.
• Generation of perspective views. A perspective center and direction of view can be defined mathematically in the same coordinate system as the DTM. The perspective view is then generated by the intersection of lines from the DTM points to the perspective center with a plane perpendicular to the viewing direction. Techniques are available for eliminating areas in the DTM which would not be visible from the selected viewpoint. The U.S. Forest Service applies this technique to determine the effect of forest operations on the view from scenic highways. It was also employed by NASA to generate simulated views of the lunar surface for the Apollo crews, both during their descent trajectory and their travels in the Lunar Roving Vehicle.
• Earthwork calculations. As indicated earlier, this was one of the first applications of DTM data. A number of highway departments now use this as a routine procedure. It is also employed for monitoring stock piles, volume calculations in reservoirs, etc.
• Navigation control systems. A typical example is the minimum safe altitude warning system (MSAW). This program establishes the position and elevation of all obstructions within a specified distance of principal airports.
• Terrain simulation. Programs have been developed to produce shaded relief by specifying the direction of illumination and the reflection of the terrain. The program then assigns density levels at every point depending on the aspect of the terrain with respect to the direction of illumination. The program output can then control a scanner-printer to make the final rendition. A similar program is used to produce simulated radar scenes. The flight path of the aircraft and the scan pattern of the radar are described mathematically. Again, density levels are assigned to each point dependent upon the aspect of the terrain with respect to the radar illumination. Still another application is to produce stereo pairs from Landsat data. Here the DTM elevation data are used to compute parallaxes which would have been generated on an image made from a different exposure station. The original Landsat pixels are then displaced according to these parallaxes to produce the simulated stereo pair.
• Terrain models. DTM data has been used to control milling machines which carve a three-dimensional plaster model for later production of plastic relief maps.

Regardless of the application, an important part of DTM computations is to produce the final output data in a suitable form for controlling the output device, whether it be a plotting table, an image scanner-printer, or a milling machine.

DTM Future Directions

Some of the prospects for future applications of DTM data are as follows:

National and World Data Banks

The Defense Mapping Agency has digitized the contour data on the 1:250,000-scale maps of the entire United States. These data have been turned over to the U.S. Geological Survey for storage, maintenance, and dissemination to users. Despite known inadequacies in the data, there is a constant demand to meet a wide variety of applications.

The U.S. Geological Survey has undertaken the long-range objective of producing a digital cartographic data base which will contain essentially all of the information now shown on the existing 1:24,000-scale topographic quadrangle maps. This includes not only the elevation data but also all of the planimetric data. The Survey has paid particular attention to formatting the data in a way which will make it accessible to the widest variety of users.

Other national mapping organizations, notably in Canada, Great Britain, and Aus-
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Many other kinds of data are now being accumulated in digital files by a variety of organizations. A representative project combining several forms of digital data is the Forest Service project Firescope. The objective of this project is to make the optimum deployment of teams for fighting forest fires in the southern part of the State of California.

The basic digital data files contain topography, access routes, hydrology, vegetation cover, land value, and building type and value. The variable input data files include weather patterns, particularly wind direction and velocity and predicted rain fall, personnel availability, current equipment location, and location and intensity of fire. When all of this information is massaged by the central computer, the output gives the optimum deployment of the firefighting forces to bring the fire under control in the minimum amount of time and with minimum loss of property values.

Other types of terrain characteristics—land use for example—are more efficiently stored by digitizing the boundaries of polygons rather than on a point-by-point basis. The techniques of combining these two types of files are largely unexplored.

Combination of DTM with Digital Imagery

Landsat and other space systems are currently producing imagery in digital form. Mention has already been made of the use of DTM data to produce stereo views from Landsat. With an adequate DTM model, the reverse procedure could be applied to remove all relief displacements from Landsat-type data, with the expectation of producing cartographically accurate image maps very rapidly. Furthermore, the demonstrated applicability of multispectral digital imagery for land classification can be appreciably enhanced by consideration of other terrain features, such as slope, aspect with respect to illumination, hydrology, etc., which can be formatted in digital files.

Computer-Controlled Cartography

A number of organizations, both government and commercial, are rapidly developing techniques for computer controlled cartography which will employ DTM data. One can reasonably expect that most of the time consuming laborious manual operations will soon be superseded by a completely automated system. Intervention of human operators will be limited to those functions requiring interpretation and judgement. Hopefully this will result in major economies in the cost and time required to produce maps. A major expected benefit is the ability to keep map data current on a nearly real-time basis.

Conclusion

The rapid development in the ability to handle terrain data in a completely digital form holds forth the promise of reducing the drudgery of cartographic operations, of providing a wide variety of data interactions, and of reducing time and cost so that managers and decision makers will know how to make the maximum utility of the resources of the world.

References

