Digital Representations of Topographic Surfaces

James R. Carter
Geography Department, University of Tennessee, Knoxville, TN 37996

ABSTRACT: Although the topographic surface is generally considered to be a mathematically continuous surface, it differs from most other continuous surfaces in that it is visible in its details and relatively stable over time. Because we can see these surfaces and thus compare the actual topographic surface with the maps we create, we have high standards for our topographic maps. To create topographic maps, we subjectively select sample points from a surface we can see and shape contours to fit the surface. By contrast, what we know about most mathematically continuous surfaces we obtain from samples positioned independently of the shape of the surface. From these sample points we have to infer a complete surface. Large-scale topographic maps are created by either field surveys or photogrammetric compilation. Digital representations of the topography may be in the form of gridded matrices of elevations, series of parallel profiles, digitized contours, or triangulated irregular networks (TINs). Gridded matrices of elevations may give adequate representations of the coarse surface form in areas of high relief, but often do a poor job of defining the details of the land surface in areas of low relief. Digitized contours, profiles, and TINs, by contrast, can take into account the finer resolution needed to define small but important details, and, for this reason, digitized contours, profiles, and TINs are the preferred way to store large-scale topographic surfaces.

INTRODUCTION

As MAPPING HAS BECOME AUTOMATED, many new processes, procedures, and packages have been developed. Each approach is more appropriate for one type of map capture and display than for another. There are no universal procedures or packages that serve equally well for all forms of data capture, storage, transformation, and display, nor should we expect there to be. Before automation many scales and types of maps were constructed using a wide range of procedures and techniques, built around various combinations of field survey, stereocompilation, photointerpretation, statistical analysis, and small-scale thematic compilation. For any given type of map, there were certain expected procedures and practices that would be followed in making the map, and most experienced persons knew which procedures and practices were appropriate for each type of map. With automation it has become less clear in many cases as to which procedures and practices are most appropriate for any given map type, in part because a contour-like map can be produced with many of the mapping packages in existence. This paper looks at some of the procedures and practices employed in mapping topographic surfaces digitally.

The isoline or contour in its many names is the symbol commonly used to represent the form of a mathematically continuous surface. On such surfaces there is one and only one value at any point and there are no discontinuities in the surface so that a slope can be defined everywhere. In spite of the fact that we can all think of overhangs and caves in nature, and abutments and walls in the built-up area, where there are breaks in the land surface, topography is generally considered to be a continuous surface. Software packages for the processing and display of mathematically continuous surfaces have been with us for many years. Programs to interpolate regular grids of Z-values from an irregular array of Z-values and to construct isoline maps were introduced early in the development of computer mapping and graphics packages. By 1967 the SYMAP program from the Harvard Laboratory for Computer Graphics and Spatial Analysis had an interpolation procedure to permit the generation of isoline maps. The part of the program that produced such maps was called the 'CONTOUR PACKAGE.' The SYMAP program was a very popular package in academic circles, and many students cut their teeth on this program (Carter, 1984).

Today, software packages for the interpolation and display of continuous surfaces are quite common. CalComp, for example, has long had an interpolation and contour drawing program to output to their vector plotters. SURFACE II is a similar package that has been available for more than a decade. Radian Corporation, Dynamic Graphics, Inc., and Zycor, Inc., produce packages of this type targeted largely at the geologic and petroleum communities. The atmospheric sciences have long employed interpolation and contour drawing programs. Most of the mainframe graphics packages such as CA-DISSPLA, DI-3000, SAS/GRAPH, and UNIRAS have interpolation functionality. Although the above represent a small sample of such packages, it is evident that there has been and still is a sizeable market for computer programs that will interpolate a surface from an irregular array of Z-values and produce contour maps and three-dimensional perspective plots.

Many surveyors and topographic cartographers have been critical of some of these programs because they do not think the programs produce topographic surfaces that look like what they think such surfaces should look like. This dissatisfaction is perhaps best captured in the advertisement of the Contour Mapping package of Houseman & Associates (n.d.): ". . .the computer programmers somehow came up with a method called the grid cell method for contouring. After surveyors used these programs a couple times, they generally trashed the program." Houseman & Associates go on to give five problems with such programs including ". . .maps with buildings, creeks, and highways would rarely be contoured correctly. . ."

TWO DIFFERENT TYPES OF CONTINUOUS SURFACES

The problem is not with the quality of the programs or the mathematics, but with the application of the programs to inappropriate data. It can be argued that there are two basic types of mathematically continuous surfaces. The topographic surface is a surface that is visible and shows little change over a period of days, weeks, months, or even years. All of us have had the experience of hiking over topographic surfaces and walking along contours. We have observed the patterns that streams carve into the topographic surface. Rules for describing the nature of the topographic surface have been developed (e.g., 'contours point upstream.') We take overlapping aerial photographs of the land surface with which we can view the surface stereoscopically to see an exaggerated portrayal of the relief. We know topographic

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surfaces very well and we expect topographic maps to show these surfaces as we know them. This is particularly true of larger-scale maps (1:25,000 scale and larger). These demands are less applicable to the smaller-scale topographic maps where surfaces have to be generalized and are thus seen in a more abstract form.

There are other types of mathematically continuous surfaces that we choose to map with contours, however, that we cannot see and that we only know something about by sampling. These include, for instance, the water table, topographic surfaces of buried stratigraphy or of relict landscapes. What we know about such surfaces we know from well cores. Another set of surfaces of this type are meteorological and climatological surfaces. Atmospheric pressure is measured at a very limited number of points around the world, both at the surface and at heights throughout the atmosphere. These surfaces, moveover, are dynamic. Even though it may take only an hour to assemble a set of synoptic observations at one site to make the contour map of atmospheric pressure, the surface will have changed in some significant ways by the time the map is made. It would be impossible to go back and collect a few more values to fill in gaps in the sample array used to interpolate the pressure surface. A monthly temperature map or an annual precipitation map can only be generated by using values from the few sample sites where data were collected. Even more abstract are surfaces of population potential or income gradients, for these values are derived for a point rather than being observed at the point.

For surfaces of the second type there are not as many rules describing what the surfaces should look like. None of us has seen a 500 millibar pressure surface or a groundwater surface, so we are more willing to accept a mapped surface if it appears to be reasonable. With surfaces that we cannot see, we cannot tell precisely where the ridgelines are or where the valleys are. We have to assume our highest sample values appear along the ridgelines and our lowest values define the valleys, but we cannot prove it without collecting much more data and that we cannot do. We hope to know enough about the phenomena that we are mapping so that we can detect gross aberrations in maps of these surfaces, but we have no basis to argue over small details. As Monmonier (1982) noted "Interpolation is a highly subjective process, and an estimation procedure is not right or wrong, but merely plausible or absurd."

It is important to realize that the topographic surface stands apart from all of the other mathematically smooth map surfaces in terms of how we can collect data about these surfaces, what we know about these surfaces, and what we expect these surfaces to look like. Consequently, many of the computer programs that may serve well to interpolate surfaces and draw isoline maps from any irregular array of z-values are not appropriate for use with topographic data. The only programs that we should expect to do a good job of representing the topographic surface are those programs designed to produce digital terrain models from a very large array of critical points subjectively selected in the field or from aerial photographs (e.g., points defining breaks in slope, peaks, ridge lines, stream courses, and low points.) Today there are programs of this type, and some even have the ability to incorporate breaklines where true discontinuities exist (Thorpe, 1988)

DIGITAL TERRAIN / ELEVATION MODELS

Historically the term Digital Terrain Model (DTM) has been the generic term used to refer to any digital representation of a topographic surface (Miller and Leflamme, 1958). Burrough (1986) argues that the term Digital Elevation Model (DEM) is preferrable "for models containing only elevation data" because "'terrain' often implies attributes of a landscape other than the altitude of the landsurface. . .." Evans (1980) used the term Digital Ground Model (DGM) for such data sets.

Whether called DEMs, DTMs, or DGMs, these data sets exist in many forms (Burrough, 1986). Figure 1 illustrates the four generic forms of elevation data capture and storage. The U.S. Geological Survey (USGS, 1987a) produces and distributes gridded matrices of elevations formatted in the coverages of topographic maps. Elevations in the 1:24,000-scale series are spaced in a square grid 30 metres on a side (called the planar format). The 1:250,000-scale series of DEMs were produced by the Defense Mapping Agency and are distributed by USGS. The elevations in this series are in the so-called arc-second format because they are spaced 3 arc-seconds apart. The arc-second is nonsquare except at the equator where a unit of latitude and longitude are equal. USGS has chosen to call both series of files Digital Elevation Models, or DEMs. Similar matrices have also been called Altitude Matrices (Evans, 1980) and surface matrices (Strumbo, 1985).

Another form of elevation data capture is the Triangulated Irregular Network, or TIN. The TIN is a set of triangular patches fit to the topographic surface and is based on the principle that a flat plane can be fit to any three non-collinear points. TINs are made up of irregular triangles connecting what should be critical points on the surface. In broad areas lacking distinct breaks in slope, mass points are collected to give the general form of the surface. The topographic surface may also be captured as a series of profiles showing elevations along parallel strips. When built from a stereo-photo model, the points along the profile strips should be taken at all critical points as well as scattered across the surface. When built from an existing topographic map, points along the profile can only be taken where the profile intersects a contour line. And finally, the surface may be represented by the digital definition of contour lines with points captured at bends and flexures in the contour lines. Programs exist to go from one form of data storage to another, but with each transformation information is lost and the definition of the surface becomes more generalized.

ACCURACY OF DIGITAL MODELS

It is fair to assume that the DTM/DEM in whatever form should provide an accurate representation of the real world land surface. It is difficult, however, to test how accurately any digital model actually captures the real world, for normally we do not have an independent model of the real world to test our digital model against. To evaluate the accuracy of a DTM/DEM requires consideration of how the DTM/DEM is made. One process is to create the DTM/DEM by digitizing from existing topographic maps. The other process is to create the DTM/DEM directly from field surveys or from stereocompilation with aerial photography.

The DTM/DEM created directly from a topographic map can be no more accurate than the map from which it was derived. And, because a few errors will always occur in processing data, any DTM/DEM derived from digitizing a topographic map will be less accurate than the source map. How accurate are the contours on topographic maps? The National Map Accuracy Standards state: "At least 90 percent of all elevations determined from solid-line contours shall be accurate within one-half the contour interval, and the remaining 10 percent shall be accurate within one contour interval. Any contour that could be brought within this accuracy tolerance by shifting its location 1/40th inch (the allowable horizontal error) will be considered to be acceptable." (U.S. Geological Survey, 1987b). Obviously, it is quite difficult to test the accuracy of contours without extensive field surveys.

There are enough first-hand stories by topographic map compilers to confirm that most topographic maps have some human subjectivity in them where the compiler could not get a good reading from the stereo model or where the contours were shaped to "look like contours are suppose to look." This subjectivity, in addition to the inherent sources of error, means that our topographic maps are but an approximation of the real world.

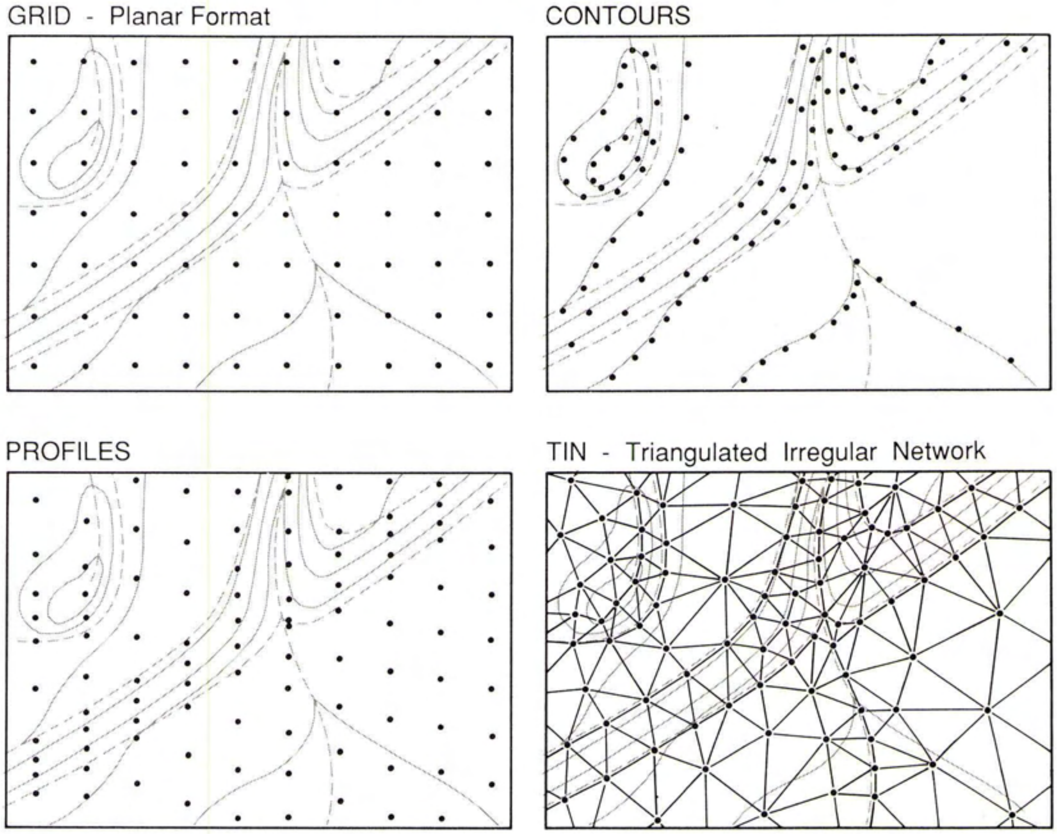

FIG. 1. The four basic forms of capture and storage of digital elevation data. The gray solid lines are contours and the dashed lines delineate distinct breaks in slope.

Any DTM/DEM derived from digitizing a topographic map then must be an approximation of an approximation of the real world. Lest the reader get a wrong impression, such approximations may be most adequate and sufficiently accurate for the tasks for which they are designed.

The alternative method of capturing the elevation data is to measure it directly in the field or scale it from aerial photos. These procedures will eliminate the inherent errors in the digitizing process, but they may introduce others. If the digital model is captured in the field using proper instruments and a trained crew, then the crew is in a position to select where the elevations are to be taken and, hopefully, they will select points that represent the critical points along ridgelines, stream courses, valleys, and at breaks in slope.The surveyor then has the responsibility to ensure that the DTM/DEM derived from fieldwork adequately represents the surface observed first hand.

A large number of the early U.S. Geological Survey 1:24,000-scale DEMs were created directly from National High Altitude Photography (NHAP) imagery using the Gestalt Photo Mapper II. In the process of correlating the many separate points on the photos to build orthophotos, a matrix of elevations was generated. The 1:24,000-scale DEMs are direct derivatives of these matrices (U.S. Geological Survey, 1987a), having been derived photo-mechanically with no human intervention. But when humans examined the models, major problems were sometimes found, particularly over water where sun glint made it difficult to correlate the images on two photos. Subsequent processing was required to edit out the major blunders. USGS is no longer using the Gestalt Photo Mapper system for the generation of DEMs.

To go directly from a stereo photo model to either a TIN, a series of profiles, or strings of digitized contours requires that the points and lines to be digitized be determined by a skilled operator. Such photogrammetric procedures are employed to produce most of the very large-scale topographic data bases (e.g., 1:1200) developed for municipal mapping activities and engineering site analysis. As in compiling analog topographic maps, the operator of the stereo compiler must float a dot across the land surface while determining the basic shape of a portion of the land surface. In this process the operator must interpret the form of that land surface. If the output is to be strings of digital contours, then the operator has only to trace out the contours as would be done in making the analog products. If the product is to be a set of points to be used in a TIN or a profile, then the operator has to identify and digitize the critical points. A dense network of points is required where the land surface is complex and detailed, but, where the land surface is uniformly flat or gently sloping, far fewer points must be captured.

ADDITIONAL CONSIDERATIONS

The spatial frequency of the sample elevations and the precision of the data are two other factors that must be considered with respect to the accuracy of a DTM/DEM. Sampling theory tells us that spatial patterns possessing periods less than twice the size of a regular data collection grid will be lost (Muehrcke, 1972). Thus, to capture details in the land surface, a large number of data values must be digitized. If a person requires a DTM/DEM that will capture the finest details in the landscape, then he or she should be ready to pay the high price of creating a detailed database. The precision with which the data are recorded may also be a concern, particularly in areas of low relief.

If elevations are specified only to the nearest metre, then the details of fairly gentle slopes may be lost or over emphasized by rounding to a whole number. As with the spatial frequency, the greater the precision demanded the greater the cost.

Finally, the availability, cost, and friendliness of software required to convert the data from whatever form the DTM/DEM is in into useful products and to integrate the DTM/DEM in with other elements in a GIS must be considered. Whether the digital model exists as a TIN, a series of profiles, strings of digitized contours, or matrices of elevations, users need to be able to derive indices and maps that can be used to address specific questions. A variety of indices can be derived from a DTM/DEM, including measures of slope, aspect, and elevation in many combinations. The DTM/DEM can also provide information on visibility of one place from another (viewsheds), site and route selection, cut and fill volumes, surface water routing, and areas of potential flooding if appropriate software is available.

CONCLUSION

Our ability to observe, photograph, and walk over the land surface makes it different from all of the other mathematically continuous surfaces we map. We know, or at least we think we know, what topographic surfaces look like. For this reason computer programs written to interpolate a surface from an irregular array of sample points are generally not appropriate for defining and representing the land surface.

Digital Terrain/Elevation Models may be created by either digitizing existing topographic maps, collecting elevations with field surveys, or as a product of photogrammetric stereocompilation. The elevations in a DTM/DEM may be stored as a rectangular matrix (elevation, altitude, or surface matrix), as a Triangulated Irregular Network (TIN), as a series of profiles, or as digitized strings of contour lines. TINs, profiles, and digitized contours reflect some of the subjectivity exercised by the person doing the stereocompilation or the surveyor who captured points as he or she interpreted the land form in creating the digital model. Regular grids of elevations, because they do not contain this subjectivity and because they cannot vary in spatial resolution, may poorly define the land form in areas of gentle slope or complex relief.

The purpose to which the digital model will be applied should govern the resolution, accuracy, and precision of the DTM/DEM. In the U.S., the Geological Survey has a program to make digital elevation models available for the entire country at two scales of resolution. For large-scale municipal mapping these models will generally have little utility. Therefore, designers of large-scale geographic information systems will probably have to contract to have digital terrain/elevation models created. The software available to the user should be considered when deciding whether to have the digital model delivered as a TIN, series of profiles, elevation matrix, or strings of contours.

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