THE MODELLING AND VISUALISATION OF DIGITAL CONTOUR DATA.

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Abstract

Digital contours, the source data for this development work in topographic visualisation, have presented some problems for shading and rendering. Existing methods of modelling contour terrain data reformat either to grid or triangular structures. Both can have disadvantages which include loss of detail in the reconstructed model, poor quality of visualisation, and/or heavy computing overheads.

A method has been devised to construct an alternative elevation model for visualisation which offers advantages. It is based on the calculation of closely packed profiles across the contour model, and the narrow swathes, appropriately smoothed and modified for cross-profile slope, provide the surfaces for shading and rendering. The method has been implemented in a computer system, and the resulting image gives an effective visualisation characterised by accuracy and sharpness of detail.

Utilising this model a range of variables have been investigated for their effectiveness in visualising the terrain on the computer screen and as hardcopy. These include illumination variables - the number, location and colour of a combination of light sources - and reflectance variables - Lambertian and specular. They are applied to a range of landscape types.

1 Introduction

Elevation modelling involves the measurement of a pattern of points on the Earth's surface and the topological structuring of the points for the reconstruction of its simulation. Patterns of sampling of surface points are to an extent influenced by intended fields of application, but are more tightly constrained by acquisition methods and existing source data. The patterns may be grouped into ordered, semi-ordered and random distributions, each with an equivalent characteristic elevation model type.

• The product of ordered sampling of the terrain, the regular grid digital elevation model (DEM), is characterised by simplicity of computer storage (z only) and addressing, and therefore by rapid processing potential. However the density of points does not respond to the complexity of the terrain.

• The pattern of apparently randomly sampled points is governed by the principle of representing critical points and breaks in the terrain, and not by a predetermined distribution. It requires the measurement and full storage of 3-dimensional coordinates, but the principle leads to a much greater economy of point sampling.

• For a semi-ordered sampling one of the coordinate triplets is predetermined - the z in the case of contour lines, and the lines are recorded as strings of x,y coordinates. There is a compromise between memory requirements and fidelity of terrain recording.

Before any surface visualisation and rendering can be achieved it is necessary to reconstruct the surface from the data set which describes it - to quadrilateral facets from the grid, or triangular facets using triangulated irregular network (TIN) algorithms, from the random points. The generation of rendered images from semi-ordered digital contour data has presented difficulties. These arise essentially from the non-uniform topological structure of the data. Linking along contour strings is intrinsically strong, while between them it is non-existent. The problem is compounded by the usually sharp contrast in point sampling density along lines with density across them.

However, as Gittings indicates in his frequently updated Catalogue of Digital Elevation Data [1] this form of elevation data continues to be very widely available, and is the only source for some parts of the world. The conversion of its graphical counterpart on existing paper maps to digital form continues to be a major activity of mapping organisations worldwide.

Unfortunately contours in themselves do not provide a generally effective visualisation tool, particularly for less pronounced relief and for the untrained. Papers by both Phillips [2] and Castner and Wheate [3] in 1979 reported results of tests demonstrating that some form of shading greatly enhanced the visual processing of the relief image. Hence an efficient means of automatically rendering a surface model constructed from this data would clearly be a valuable tool for topographic interpretation.

2 *Current Visualisation Solutions*

Existing visualisation methods which start with contour data convert to one of the other elevation models. They either interpolate a regular grid, typically by some form of bi-linear interpolation (see for example [4], and [5]), or build a triangulated irregular network (TIN) by treating the vertices of the contour strings as a scatter of discrete random points (for example [6]).

The weakness of the former method arises from the regularity of the points and their resultant failure to respond to the complexity of the terrain, and to honour its critical points and breaklines. To minimise this weakness and to create a successful visualisation in which the pixel facets merge to give the impression of a smoothly shaded continuum they must be of small size, and hence of large number. Their processing can entail high computing overheads for both the generation of the grid and the calculation of the visualisation parameters.

The calculation of a triangulated irregular network from the contour strings has presented difficulties in the filtering of the string data. This is necessary to generate a triangulation which is not overloaded with a mass of ill-conditioned microfacets, and yet maintains the character of the topography given by the contour pattern. There are also problems with the triangulation itself where the most equilateral triangles from the widely employed Delaunay method do not always give the most accurate description of the terrain [7]. Flat triangles bounded by vertices on the same contour line may appear in convoluted contour patterns. Computing time for this approach may also be considerable for large data sets [8].

Methods to visualise the reconstructed elevation models are well established, and founded on the simulation of light and shade. The facets so generated, whether grid-based or triangular, are each queried for slope and aspect and are allocated a value on a grey scale which is derived from a simulated illumination model and a reflectance model. The former very commonly relies on a single, distant light source and the latter on a perfectly diffusing reflecting surface. Rendering of the triangular network in particular is often disappointing, because the shading of the facets fails to disguise the triangular structure, leaving polyhedral artefacts accentuated by the 'Mach banding' effect.

3 Development of a Profiles Model

An alternative method, here outlined, has been developed [9] with a view to improve the accuracy of the visualisation, with the further expectation of achieving greater computer efficiency.

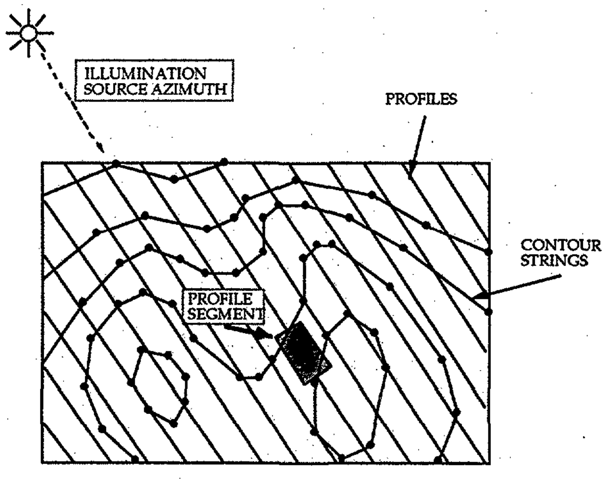

Figure 1. Configuration of Profiles

The method is based on the calculation of profiles across the contour model, so that profile segments of finite but small width become the elements of elevation model reconstruction instead of grid patches or triangles. Clearly for optimum reconstruction the distance separating the profiles should be very small - the practical approach here is to make them small enough that they appear to coalesce smoothly when plotted by thick lines at the chosen representational scale, in the manner of scan lines.

The orientation of the profiles is such that they have the same azimuth as a hypothetical distant light source (Figure 1). This orientation gives the advantage of allowing the gradient components to be reduced to a single variable, thus simplifying and speeding visualisation and related calculations.

The radiance R reflected from the surface element depends on its orientation with respect to the illumination source direction (Figure 2), and on the model of reflectance adopted.

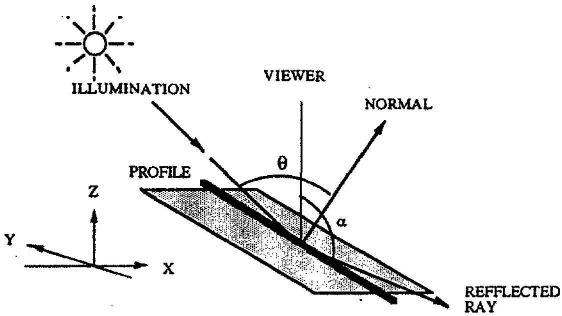

Figure 2. Illumination of a Profile Segment

For a perfectly diffuse (Lambertian) reflecting surface :

$$R = I.\cos\theta$$

where I is the incident irradiance and θ is the angle between the light source direction and the surface normal.

If the surface is considered to be somewhat shiny then a specular reflection component should be included. Several models of specular reflection have been proposed (for example : [10], [11], [12]) from heuristic to increasingly rigorous definitions. For trials based on the Earth's surface an approximate and empirical model is adequate and less computer demanding. Such was that of Phong Bui-Tuong, which modelled the fall-off in radiance by defining a specular reflection exponent n to be applied to cos α (where α is the angle between the reflected ray and the viewing direction) which varies with the reflection characteristics of materials, from 1 for diffuse reflectors to over 100 for mirror-like surfaces. If then a surface has a diffuse reflection coefficient k_d and a specular reflection coefficient k_s (a simplification of Phong's algorithm), then the total radiance from a surface element may be expressed as :

$$R = I[k_d.\cos\theta + k_s.\cos^n\alpha]$$

Hence the radiance R reflected from the slope segment between two contour or other topographic lines can be calculated. These segments have advantages over an interpolated regular grid since they are made to fit precisely between the topographic lines and are as long or short as the relief variation dictates. Data economy follows the principle of 'run-length encoding'.

There is an implied assumption here that the surface normals of the profile swathe all lie in the same plane - the profile plane (Figure 3). This is evidently erroneous and leads to generally insufficient density of shading. The quality of visualisation is further degraded by the assumption of plane facets between contour intersections, especially for more widely spaced contours, giving flat-topped hills and sharp angles to slopes.

To mitigate the second problem intermediate surface normals are interpolated at a given spacing along each segment, based on the Phong method of "Normal-vector interpolation shading" [10]. Interpolation is of course halted at recognised breaks such as shorelines.

To address the first problem of how to incorporate the cross-profile slope component of the surface gradient, each long-profile segment slope is exaggerated as if both the x and y slope components were contained in the y direction. In this way an accurate surface reflection value is retained while at the same time reducing the slope parameters to two - y and z. It is these new false "Qgradients" which are used for the fitting of the interpolated surface (Figure 3). This offers the further advantage of simplifying the application of any vertical exaggeration factor in the relief visualisation, and simplifying specular reflection calculations.

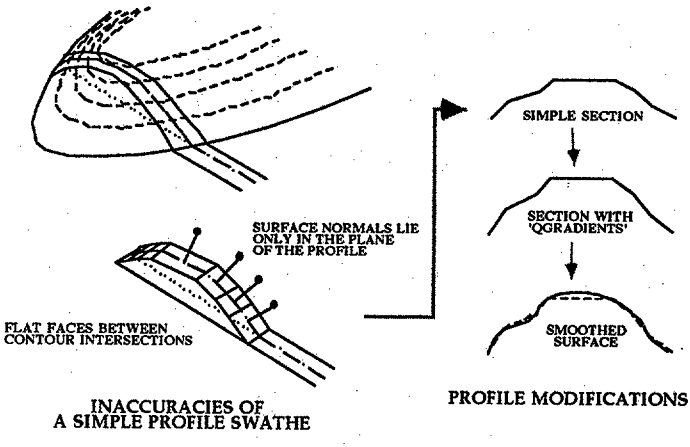

Figure 3.

4 Implementation

The primary source data has been provided by the Ordnance Survey as digitised from their 1:50,000 topographic mapping. It comprises vector data in integer format supplied in 20 Km square tiles in NTF format. Its major content includes:

contours at 10m vertical interval
coastlines with height of 0m attached
lake shorelines given heights 1m below surrounding land
form lines with heights attached.

Programme modules running on an IBM PC platform have been developed to implement the algorithms. The first reformats the O.S. NTF data into a simplified ASCII file. A second module calls for light source azimuth and altitude, and distance between profiles, and processes the ASCII file to build the profiles. Its output is a file of coordinated profile segments with smoothed "Qgradients" attached. A third calculates radiance according to the reflectance model selected, and prepares files for import to Arc/Info as a 'coverage' of line segments.

The profiles data set has been imported into Arc/Info which runs on an HP 9000 Series 700 UNIX workstation to utilise the improved graphic display capabilities, and to convert to raster so that the manipulation and overlay capabilities of Arc/Info can be used. An intensity value is calculated for each segment based on its radiance value. These can then be plotted and displayed as thick adjoining lines given one of perhaps 200 grey values read from a look-up table.

5 Results and Developments

For chiaroscuro to be convincing there should be appropriate value and imperceptible change of intensity for smoothly curving surfaces, and sharp and accurately positioned breaks in intensity for breaks in surface smoothness. The development and manipulation of profiles in the way described enables intensities to be both smoothly changing and sharply delimited at the appropriate points along the profile swathe. Changes from one profile to the next clearly may not be as perceptibly smooth, the visibility of discontinuity of course depending on the swathe width. If this is too great sharp breaklines such as lake shores which cross profiles obliquely will display jagged edges, as they would with the grid model.

The screen image generated on the 20-inch high-resolution workstation monitor with a 200-step grey scale and swathe width of 0.6 mm produces a reasonable compromise between image quality and computing economy. An important contribution to successful visualisation is the subduing of the construction framework, and with these parameters the profile artefacts are not visible and the continuity of the terrain is apparent. The detail of modelling is good, and is found to be better than the shading of a lattice generated from the TIN of the contour data if the lattice interval is set the same as the profile swathe width.

5.1 Addition of Specular Reflection

The Earth's surface, with its great variety of natural and man-made cover types which rarely combine to create a glossy patch of significant extent, is not a ready subject for the realistic application of a general value for specular reflection. Nevertheless the inclusion of this reflection component within the reflectance parameters has produced unexpectedly effective modelling.

It has been found that with a value of 0.6 for k_d, and 0.4 for k_s, and with exponent n kept to a comparatively small value of say 5, then the resulting 'low key glossiness' causes a useful enhancement of the smaller detail while retaining a plausible surface texture - which does not look like a shiny plastic molding. Plates 1 and 2 contrast the effect of excluding or including the specular reflection component, for a mountainous terrain. Plate 3 illustrates the effectiveness of the method - with the same parameters as Plate 2 - for much flatter terrain.

5.2 Composite Colour Shading

Following experimentation with various illumination source positions it has become evident that substantially different interpretations of the topography can result from different light source azimuths. Even when generally remaining within the accepted north-west quadrant, the divergence between an image of 350° light azimuth and one of 280° is sufficient to make strong mountain features in the one become almost unnoticeable in the other.

Traditional manual relief shading applies a local adjustment to the light source direction on features which would otherwise appear flat because of their trend perpendicular to the light, and this has not been successfully automated. However the simulation of a combination of light sources in different positions holds the promise of an improvement in modelling. It has been applied, for example, by Robert Mark in his shaded relief image of the Island of Hawaii, [13].

Here the approach has been to generate three images within Arc/Info from selected light azimuths (and their respective profile models), following the procedure described above. Each of these has then been converted to a single band image for red, green and blue, respectively. This allows combining of the bands for display as a composite multiband image (Figure 5).

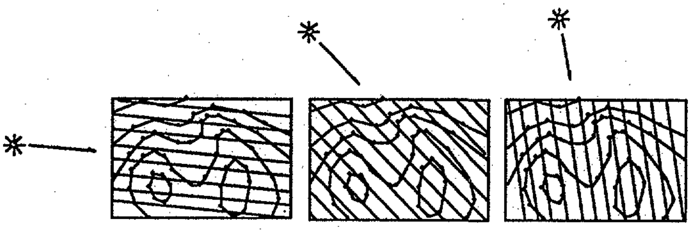

Figure 5. Single Band Images from Three Light Sources

If the selection of azimuths is made to straddle the north-west sector while not aligning exactly with the map edges, and the allocation of the respective bands to these azimuths is guided by intuitive considerations of a warmer westerly (red) light and a colder northerly (blue) light, then the resulting relief depiction not only reveals more sloping surfaces but is considered to more strongly delineate the whole topographic structure. Where the colour scale values of red, green and blue are equal for a pixel it of course displays as a grey tone, and this in fact appears as the predominant colour. Where radiance from the three light sources differs significantly, hues emerge which are related to local slope aspect.

Horn, when investigating the reverse problem of deriving shape from shading [14] stated that if two shaded images created from different light source positions were printed in combination, each with a different coloured ink, then the local gradient could not only be visualised but quantified since both its components are represented. Here the primary objective remains the envisioning of the data, but the technique does appear to offer enhanced information content and improved interpretation.

6 Conclusions

The method has succeeded in generating a visual image of the terrain surface originally encoded as semi-ordered line strings. The accuracy of the image as a faithful representation of the real terrain is difficult to assess. The most satisfactory evaluation would be to complete the cycle from sampled surface to visualisation and back to computed surface by running "Shape from shading" routines, but in the absence of these reliance has to be placed to an extent on intuitive reactions from observers. There has been general agreement that the images, particularly the colour composites with specular reflection, are a significant improvement for the envisioning of terrain data over the products of some existing methods. Plate 4 illustrates a comparison between an enlarged extract of shading of the TIN-lattice developed surface, adopted by many packages, and the same area applying the profiles approach. The lattice interval is made the same as the profile swathe width.

It is recognised that the profile based elevation model has limitations for the solution of some surface analysis problems. Intervisibility calculations across profiles are more difficult than on the grid model, for example, and volumetric calculations than on the TIN. However it does lend itself very well to a number of further processes which could enhance the displayed image quality, and which are particularly facilitated by the bi-dimensional quality of the data model. These include :

• Additional linear data such as stream, ridge or other characteristic lines can be incorporated, if available.

• The addition of cast shadows can be simply achieved since the calculation of surfaces concealed from the light source considers two dimensions only, the y and z. Trials with cast shadows have in fact been found to degrade interpretability when applied to terrain surfaces.

• Generalisation of the shaded image - which for other models presents particular difficulties - can be readily carried out on this model. A standard line simplification algorithm - such as the Douglas-Peucker - can be applied to the profiles before calculating gradients.

References

[1] Gittings, B.,1995. Digital Elevation Data Catalogue on internet. University of Edinburgh. E-mail <bruce@geovax.edinburgh.ac.uk>

[2] Phillips, R.J, 1979. An experiment with contour lines. *Cartographic Journal*, Vol.16,No.2, December 1979.

[3] Castner, H.W, and Wheate, R, 1979. Re-assessing the role played by shaded relief in topographic scale maps. *Cartographic Journal, Vol.16, No.2*, December 1979.

[4] Clarke, A.L., Grün, A, and Loon, J.C., 1982. The application of contour data for generating high fidelity grid digital elevation models. *Proceedings, AutoCarto 5*, 1982, 213 - 222.

[5] Hutchinson, M.F.,1988. Calculation of hydrologically sound digital elevation models. *Proceedings, Third International Symposium on Spatial Data Handling*, Sydney, Australia, 1988.

[6] Christensen, A.H.J., 1987. Fitting a triangulation to contour lines, *Proceedings, Autocarto 8*, 57 - 67.

[7] Heller, M., 1990. Triangulation algorithms for adaptive terrain modelling, *Proceedings, Fourth International Symposium on Spatial Data Handling*, Columbus, Ohio. 163 - 174.

[8] Tsai, V, 1993. Delaunay triangulations in TIN creation: an overview and linear-time algorithm. *International Journal of Geographical Information Systems*, 1993, Vol.7, No.6, 501 - 524.

[9] Hobbs, K.F., 1994. The visualisation of contour data via profiles, *Proceedings, AGI 94*, Association of Geographic Information, 1994.

[10] Phong Bui-Tong, 1975. Illumination for computer generated pictures. *CACM*, 18(6), 311 - 317.

[11] Blinn, J.F., 1977. Models of light reflection for computer-synthesized pictures. *SIGGRAPH* 77, 192-198.

[12] Ikeuchi, K. and Sato, K, 1990. Determining reflectance parameters using range and brightness images. *Proceedings, Third International Conference on Computer Vision (IEEE)*, Osaka, 1990.

[13] Mark, R.K, 1992. A multidirectional, oblique-weighted, shaded-relief image of the Island of Hawaii. *Open-File Report 92-422*. U.S. Department of the Interior, 1992.

[14] Horn, B.K.P., 1981. Hill shading and the reflectance map, *Proceedings, IEEE*, 69(1), 14 - 47.

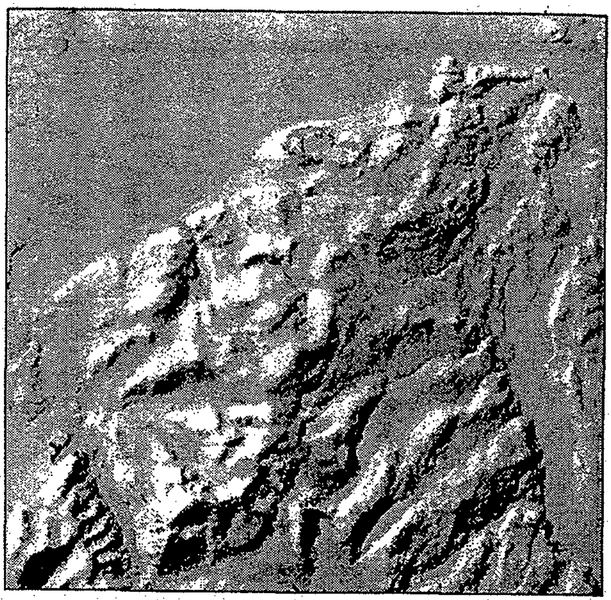

Plate 1

Shaded Profiles Model - Mountain Terrain
Light azimuth 310°
Light altitude 35°
Vertical Exagg. x2

Diffuse reflection only.

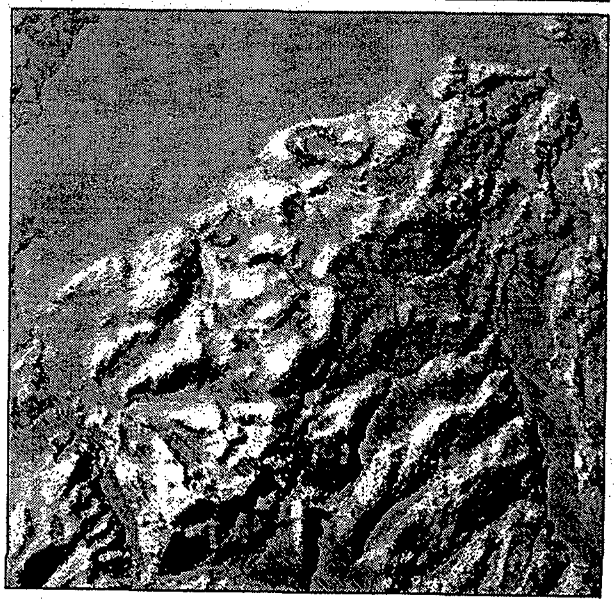

Plate 2.

As for Plate 1, but with Diffuse and Specular reflection

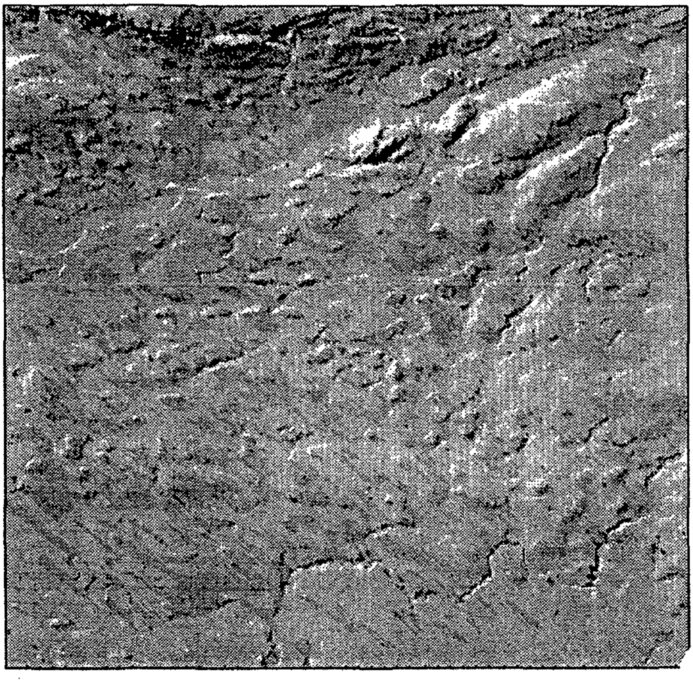

Plate 3. Shaded Profiles Model - Undulating Terrain. Parameters the same as Plate 2

(a) (b)

Plate 4. Enlarged extract of shading based on (a) TIN-Lattice and (b) Profiles