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An Investigation of Kernels for Shading of Elevation Data

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This report examines the results of enhancing displays of an elevation array by using mathematical shading. The variable examined in this report is the shape of the primitive region by which shading is calculated. This primitive region is called a kernel. Three kernels are examined; triangles, quadrilaterals (actually squares), and a hybrid shape that seemed as though it might have fewer artifacts. The result is that shaded quadrilaterals seem to be more isotropic and to have fewer artifacts than the other shapes examined. Shading using quadrilateral kernels is also the easiest to calculate. All shading was done using the Gouraud technique.

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PREFACE

This study was conducted under DA Project 4A161102B52C, "Artificial Intelligence Concepts for Terrain Analysis."

The study was conducted under the supervision of John Benton, Chief, Artificial Intelligence Division; and John Hansen, Director, Research Institute Laboratory, U.S. Army Topographic Engineering Center.

Walter E. Boge is the Director and Lt. Col. Louis R. DeSanzo is the Commander and Deputy Director of the U.S. Army Topographic Engineering Center.

AN INVESTIGATION OF KERNELS FOR SHADING OF ELEVATION DATA

INTRODUCTION

Shading is the graphical simulation of surface relief in an image derived from an elevation matrix by means of variations in lightness of tone over the surface. Shading is useful in displays of 3-D surfaces because it gives viewers a cue to allow them to determine the conformation of the displayed surface. Displays so generated are much more intuitive than simpler schemes, such as using brighter shades for higher elevation (hypsometric shading). Shading can also be used to modify a display of map data to give the viewer a sense of the underlying terrain elevations. There are several methods of shading that have been recommended, such as slope shading[1] in which an area is shaded darker as its local slope increases, but these methods do not produce a realistic effect to the same degree that physically-based shading methods can provide.

In the next section, the basic model for shading will be presented and variations on this model will be described in detail. Finally, an assessment of these results and a recommendation will be presented.

SHADING MODELS

Physical modeling of a 3-D illumination situation is the method that will be used in this investigation. A good reference is Rogers[2], which is the source of the equations used to write the shading programs for this study. In the next section, the various methods of shading will be described in detail. All of these methods are based on the physical model of sun-illuminated terrain shown schematically in Figure 1, which is derived from Rogers[3]. Figure 1 shows the basic geometry for physically-modeled shading. The surface normal vector is especially important for calculating shading.

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[1] Edward Imhof, *Cartographic Relief Presentation*, Walter de Gruyter 1982. See especially Chapter 9 *Shading and Shadows*.

[2] David F. Rogers, *Procedural Elements for Computer Graphics*, McGraw-Hill 1985. See especially Chapter 5, *Rendering*.

[3] Ibid. Figure 5-5, p. 314.

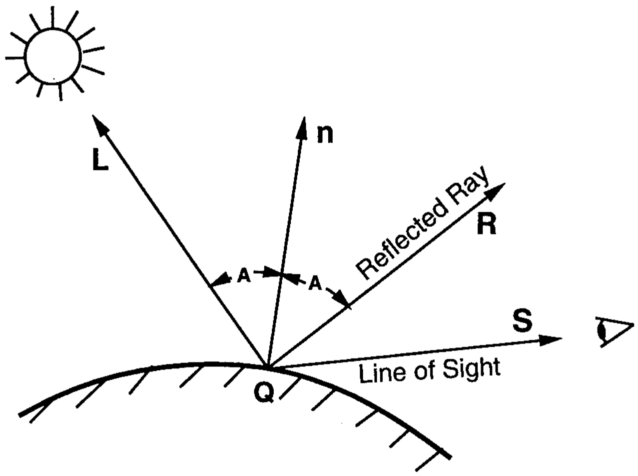

Figure 1. Schematic of a Viewing Situation. Here we see the basic geometric elements needed for a shading calculation. The surface can have its own characteristics, such as a map pattern, and this will be reproduced in the shaded image. Vector **L** is toward the light source, and vector **S** is toward the observer. Vector **n** is a normalized vector perpendicular to surface **Q** at the point for which shading is being calculated. **n** is the surface normal vector. Mirror or *specular* reflection is in the direction shown by **R**. For convincing terrain shading there should be little or no specular reflection.

Shading of terrain elevations by using a physical model of the surface and of the illumination gives superior results when compared to simple slope shading in which higher slopes appear darker; however more calculation is required to physically model a surface. Previously, computers did not have enough speed to perform these more sophisticated calculations, but this is no longer a problem. Thus, we must find superior methods to give the viewer a better sense of the terrain.

SHADING CALCULATIONS

Surface Subdivision

All shading methods start by dividing the surface to be shaded into many small regions, such as triangles or squares. These small regions have known elevation points at their corners. Each of these little areas then is shaded according to a mathematical model based on physical modeling.

The input data for shading are a set of point elevation readings that are called *postings* in surveying terminology. The data for this investigation was generated in-house at the U.S. Army Topographic Engineering Center (TEC) by digital correlation of a stereo pair of aerial photos. Postings on a square (Cartesian) grid, such as is found in most current digital elevation data, were used for this report. But the results given here are equally applicable to irregularly-spaced postings. Such irregularly-spaced postings are sometimes referred to as TINS, an acronym for Triangulated Irregular NetworkS. As this report shows, it is not necessary or even desirable to triangulate irregularly-spaced postings to generate good surface shading.

For those regions of terrain that are to be displayed in between the elevation postings, we must define surfaces and determine their three-dimensional surface normal vectors so that their brightness can be calculated using the model shown in Figure 1. The simplest type of surface to define is a triangle, as shown in Figure 2. As Figure 2 also shows, there must be a convention adopted to set the direction in which a triangular subdivision will take place.

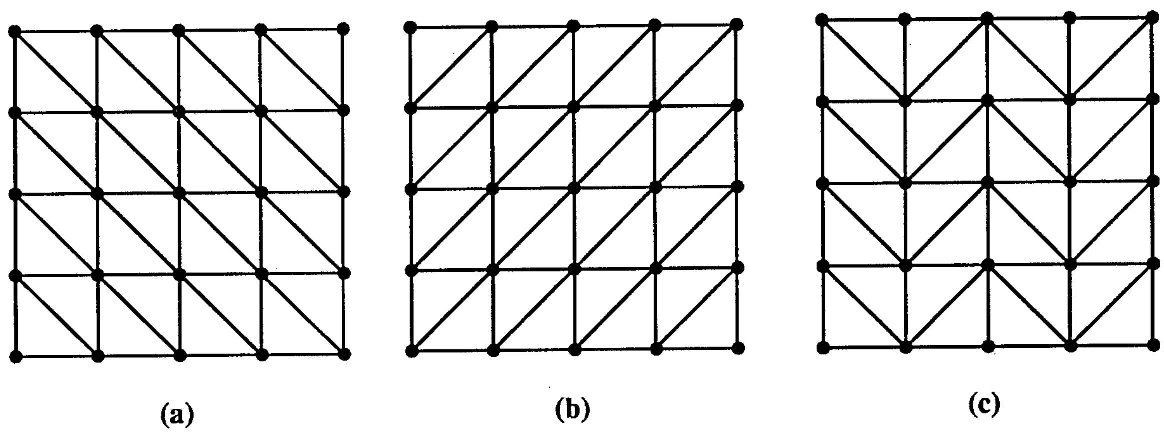

Figure 2. A Schematic Grid of Elevation Points. The points are represented as dots. The lines connecting the dots do not appear in the elevation data itself, but rather represent conventions for defining surface elements (here these are triangles) in terms of the elevations. Subfigures (a), (b), and (c) show some types of triangular subdivision.

The situation is symmetrical for triangular division along a line going from upper left to lower right or for a line going from upper right to lower left. A division line from upper left to lower right was chosen for this report. This is the case shown in Figure 2(a). Elementary surfaces can in turn be grouped to form composite surfaces. The composite surfaces, or *kernels*, that will be examined are shown in Figure 3. For convenience, call these the *lozenge* (a), the *house* (b), and the *quad* (c) kernels.

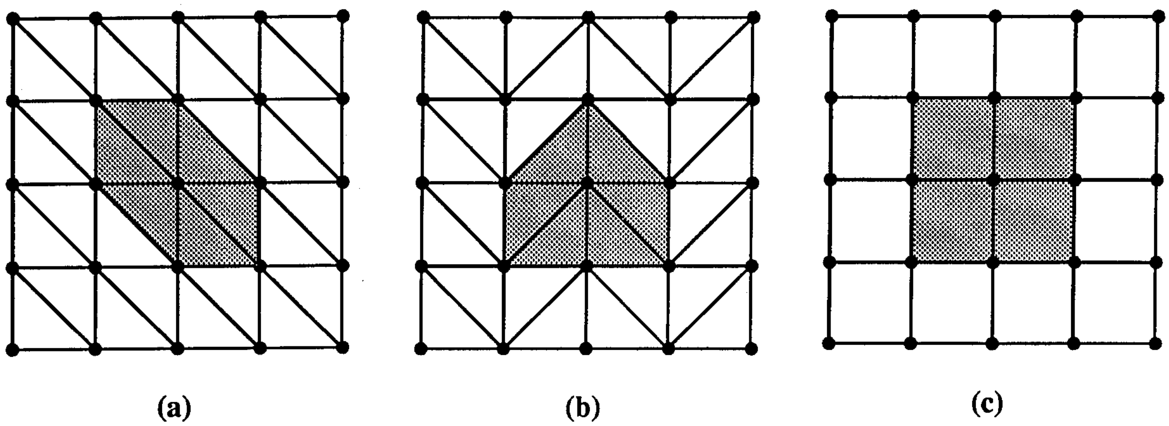

Figure 3. Kernels (Shaded Regions) Used in Calculating Vertex Normals. The elementary surfaces inside the kernels are used to calculate the vertex normal for the posting near the center of each kernel. The normal vectors of each of the elementary surfaces in a kernel are averaged to get the vertex normal. These elementary surfaces are triangles in cases (a) and (b) and quadrilaterals in case (c).

Once a surface slope has been determined, a physical model is generated mathematically that models the surface, an observer (your eye position), and a light source. This situation was shown in Figure 1.

Flat Shading

To assign a brightness to a surface, we need to know its 3-D slope. Slopes are determined from a grid of elevation postings by finding differences between a given posting and its neighbors. If these slopes are used directly to shade the geometric primitives defined by the elevation points, then a type of surface shading called *flat shading* is obtained.

Flat shading is the simplest and quickest shading method. The terrain is approximated by many small regions, and each region is uniformly shaded as if the terrain were flat in the region. Flat shading can give good results if the shaded areas are very small. However, for reasonable region sizes, the terrain looks faceted and is unrealistic.

Flat shading does not require much calculation and is therefore quick to compute and display. Figure 4 shows an example of flat shading of digital terrain elevation data.

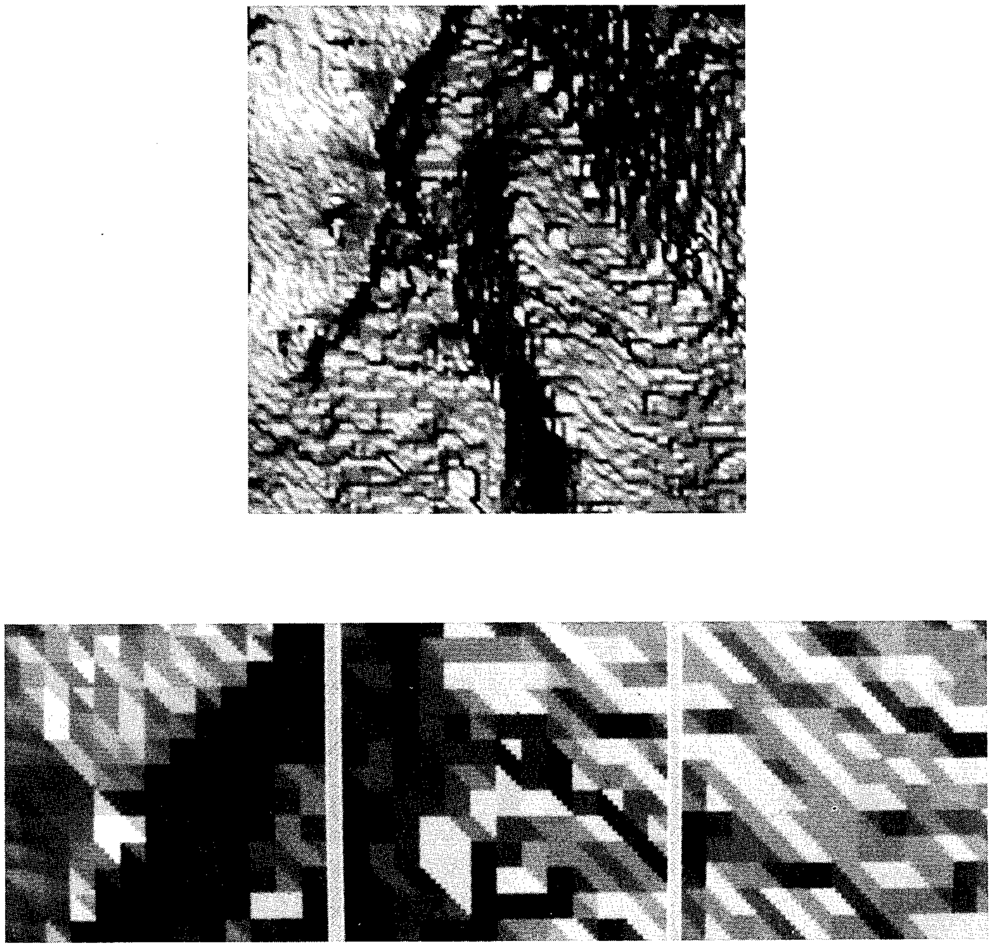

Figure 4. Flat Shading of Elevation Data. Elevation postings are set 5 pixels apart in both x and y directions, and a triangular grid is used to define the surface elements. The lower three squares show magnified portions of the upper image.

The three images at the bottom of Figure 4, which are chosen to reveal details of the shading, are magnifications of selected regions of the larger image. A similar display is presented for each of the examples that will be shown. As you can see, one can get a sense of the undulation of the terrain from flat shading, but the result is not very pleasing. Some significant details are also suppressed in a flat-shaded image. For example, there is an error in the elevation data, which shows as a narrow and deep canyon at a certain elevation level (along a contour). Although this "canyon" is difficult to see in Figure 4, it is easily visible in Figures 5, 7, and 8.

Two popular variations of physically modeled shading are Gouraud shading and Phong shading. Both of these methods produce the effect of curved terrain elements so the shaded terrain looks smooth and more realistic. Gouraud shading produces a matte surface without specular reflections, and Phong shading adds specular reflection to give the visual impression of shiny surfaces. Gouraud-shaded surfaces are used in this report because

Gouraud shading gives good results for terrain models and it is much less expensive computationally than Phong shading.

Gouraud Shading

A refinement over flat shading is Gouraud shading (see Figure 5). For Gouraud shading, smoothness is generated by interpolating between shading values for a single primitive surface. Interpolation between surfaces is not well defined; so to be able to do the interpolation, an intermediate result called a *vertex normal* is calculated. A vertex normal is the average of the surface normal vectors for the primitive surfaces surrounding a vertex. Call this group of primitive surfaces a *kernel.* The kernel contributing to the shading shown in Figure 4 is diagramed in Figure 3(a). Once the vertex normals have been determined, a shade is then calculated at each vertex using the vertex normals. Finally, these vertex shades are linearly interpolated over the regions between the vertices. As you can see in Figure 5, the results are superior to flat shading at the expense of some extra calculation.

Shading Kernels

Lozenge Kernel

We can now see that Gouraud shading is preferable to flat shading, but the necessity of defining a shading kernel means that the shape of this kernel is important in determining the quality of the result. Gouraud shading will be used to illustrate the effects of choosing different kernels to calculate vertex normals. Figure 5 uses the same triangular surface elements as we used for the flat shading shown in Figure 4.

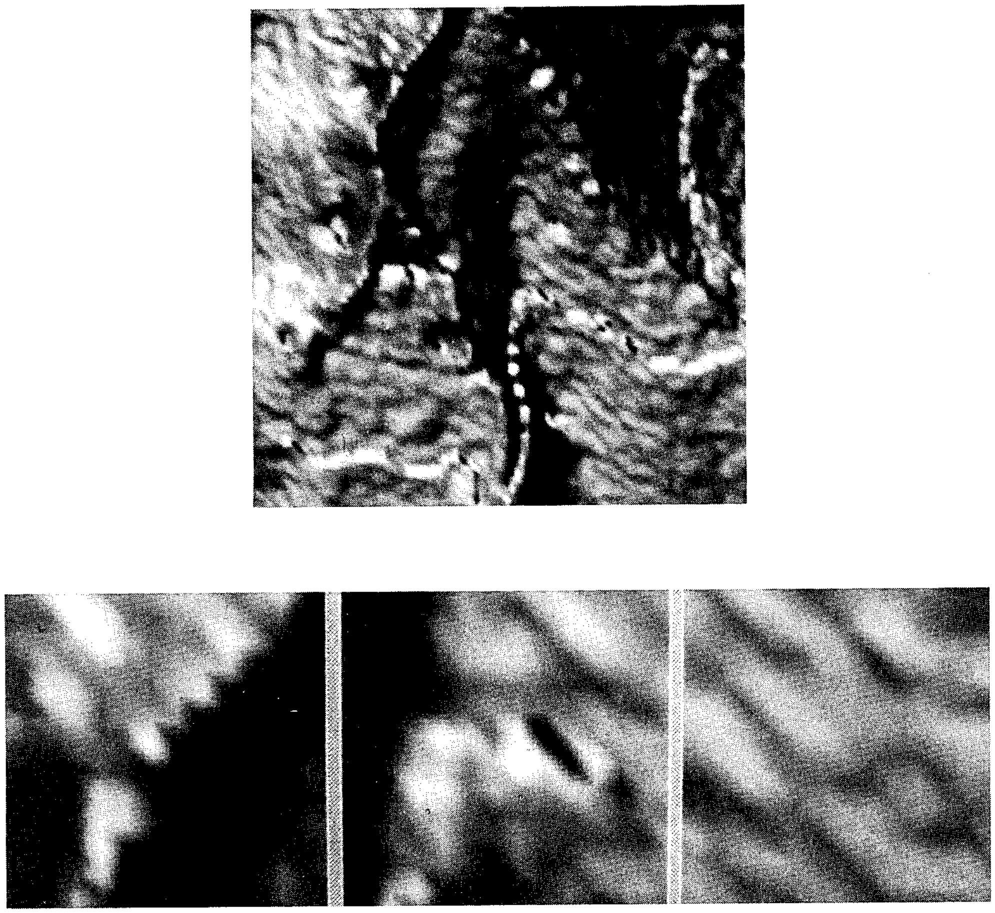

Figure 5. Lozenge kernel Gouraud shading.

Quad Kernel

We can also perform shading using quadrilaterals as the primitive kernel. Quadrilaterals are attractive because they do not have the asymmetries associated with triangles. A conceptual problem exists in using quadrilaterals, which is that a quadrilateral is generally not flat. If the elevation postings forming the corners of a quadrilateral are not coplanar, then the quadrilateral is not geometrically flat. The technique used to find an "average flat" quadrilateral is to define two vectors between the diagonal corners of the quadrilateral as shown in Figure 6. The cross product of these two vectors then defines an effective surface normal for the quadrilateral. The normal is always taken as pointing out of the surface.

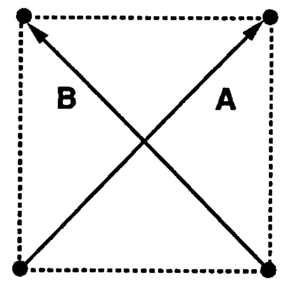

Figure 6. Cross Product Vectors Defined for Four Neighboring Postings. Forming vector product **A X B** defines an "effective" surface normal for the quadrilateral surface implicitly defined by the four postings and indicated by the dashed lines. The quadrilateral need not be a rectangle, or even a parallelogram.

Figure 7 shows the test region shaded using quadrilaterals (squares) as the kernel. This surface has fewer artifacts than the surface defined using the lozenge kernel (see Figure 5).

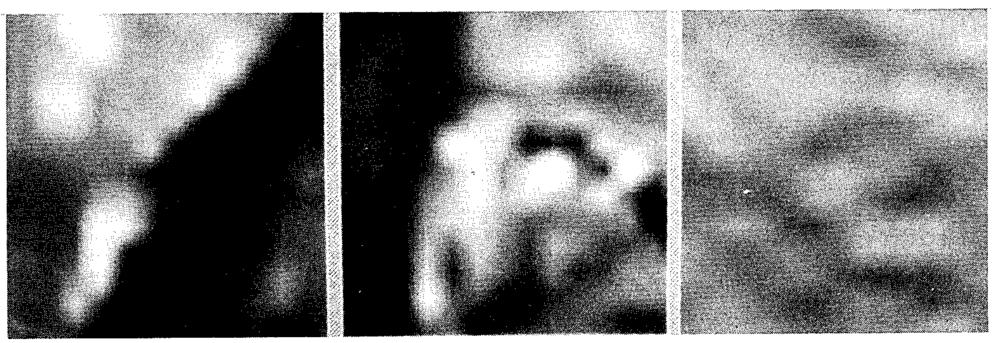

Figure 7. Quad Kernel Gouraud Shading. The magnified regions show that this shading creates no serious directional artifacts.

House Kernel

The biggest problem with triangulating a surface seemed to be asymmetry of the kernel. As Figure 3(a) shows, there is a ratio of 2:1 in orthogonal widths of the kernel used to define a vertex normal when triangles are used. For (square) quadrilaterals (see Figure 3(c)), the ratio of longest to shortest dimension is the square root of 2 or about 1.4:1. This asymmetry also lies at 45 degrees and not at 90 degrees as in the triangle case, so it is less annoying.

Treating triangles differently can allow us to synthesize still another kernel. The objective is to minimize the asymmetry of the region used to calculate a surface normal by dividing successive groups of postings along alternating diagonals as shown in Figure 3(b). The worst asymmetry of this figure along any two directions is only 1.06:1. The results of using this *house* kernel can be seen in Figure 8.

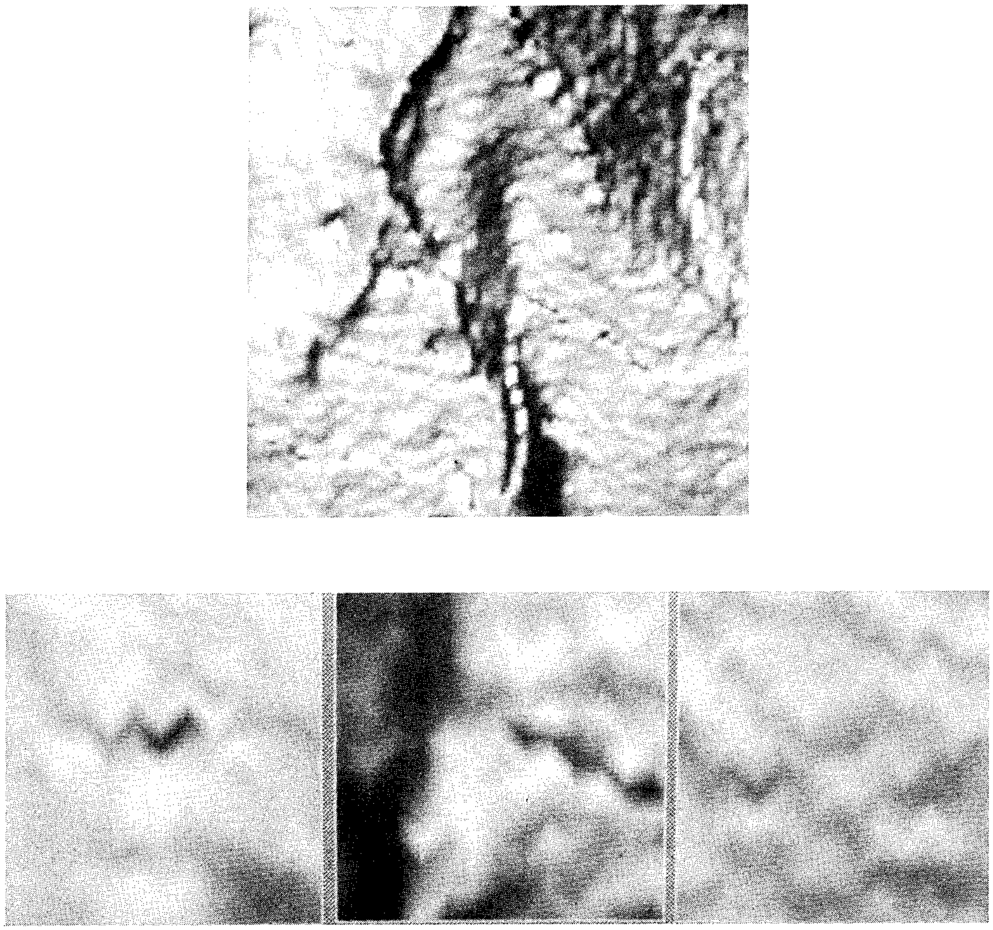

Figure 8. House Kernel Gouraud Shading. The magnified regions show strong artifacts despite the kernel's good symmetry.

For the house kernel, it seems that the gain of symmetry we get over the other kernels is more than offset by the fact that the region in between kernel positions is a narrow zigzag (see Figure 9). This causes zigzag artifacts in the resulting image. Related to this is the fact that the house kernel has two cases, point up and point down. For the lozenge and quad kernels there is only one kernel position, so this problem does not arise. The artifacts found in Figure 8 are at least as bad as those for the lozenge kernel. It is also more difficult to do the calculations required to find a vertex normal. It is reasonable to conclude that the shapes of the regions in between the kernels are as important as the shapes of the kernels themselves. This helps explain the superior quality of the shading using a quad kernel since the regions in between quad kernel positions are themselves quadrilaterals.

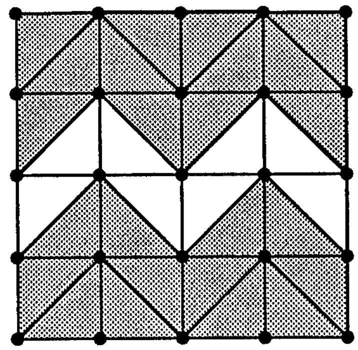

Figure 9. Zigzag Artifacts in the House Kernel, Gouraud Shading. This shows that the region in between house kernel positions can be a zigzag which creates bad artifacts in shading.

DISCUSSION

This investigation demonstrates that the quad kernel is more efficient and produces better visual results for Gouraud shading than the other kernels studied. Thus, quadrilaterals should be used for calculating shading from elevation postings. It is reasonable to expect that these results will hold true for irregularly spaced postings as well, since there is no need for quadrilaterals to be rectangles, but this case has not been tested.

Besides giving superior graphical results, quad kernels are also easier to compute. Here is a qualitative analysis of the number of computer operations necessary to find the shade of a single pixel for the three kernels considered. Finding the normal for a primitive surface is equally expensive for the lozenge and the house kernels since the primitives are triangles for each. The calculation for a surface normal of a quadrilateral is not appreciably different from that for a triangle since the expensive operation in all cases is a vector cross product that must be taken to get the surface normal. Averaging normals is also a fairly low cost operation by comparison, so the most important computational burden is the number of normals that must be computed per vertex. Since each region between postings is divided into two triangles for both the lozenge and the house kernels, but not for the quad kernel, the quad kernel is only half as computationally expensive as the other two kernels. The program to calculate the quad kernel is also simpler than those needed for the other kernels. The house kernel was particularly difficult to program since there is a flip of the orientation of the kernel around a vertex for every other vertex point (the house turns upside down), and these two cases have to be programmed differently.

REFERENCES

Imhof, Edward. *Cartographic Relief Presentation*, Walter de Gruyter 1982. See especially Chapter 9, *Shading and Shadows.*

Rogers, David F. *Procedural Elements for Computer Graphics*, McGraw-Hill 1985. See especially Chapter 5, *Rendering.*