Virtual Stereo Display Techniques for Three-Dimensional Geographic Data

Abstract
Techniques have been developed which allow display of volumetric geographic data in three-dimensional form using concepts of parallactic displacement. Image stereo pairs and synthetic stereo of digitized photographs, SPOT, Landsat TM, shaded relief, GIS layers, and DLG vector data are implemented. The synthetic stereo pair is generated from a single image through computation of a parallax shift proportional to the volumetric values at each location in the image. A volumetric dataset, such as elevation or population density, provides the single requirement for generation of the stereo image from an original digital dataset. To view the resulting stereo images, softcopy methods, including traditional anaglyph techniques requiring complementary colored lenses and an autostereoscopic procedure requiring no special viewing equipment, are used. Hardcopy methods include anaglyph displays of combined vector/raster datasets on large format electrostatic plotters. Stereo results for the Driftless area of Wisconsin, for northern Georgia, and for the Grand Canyon are presented.

Introduction
Extracting geographic information for topographic mapping from image sources has been traditionally accomplished using stereoscopic methods. However, the application of stereoscopy to support display and analysis of geographic phenomena in geographic information systems (GIS) has not been effective because of prohibitive costs, data processing limitations, and requirements for specialized equipment, including visual aids for the analyst. With current developments in computer graphics technology and an improved understanding of human vision, these impediments are being removed.

Cartographic and image processing researchers have developed synthetic stereo generation techniques for both continuous and discrete data distributions (Batson *et al.*, 1976; Jensen, 1980). The methods of display have required visual separation of the left and right images of a stereo pair to the left and right eyes, respectively (Wolf, 1983; Kraak, 1988). Separation of the left and right images has traditionally been accomplished passively in a simultaneous view time-parallel method with stereoscopes, polarized lenses, or anaglyph methods. Recently, new computer-based technologies offering alternating views for time-multiplexing stereo images have been introduced. These techniques provide separation on 120 hertz non-interlaced displays with liquid crystal shutters and radially polarized lenses or, alternatively, by active lenses which include the liquid crystal shutters and are synchronized with the display by an infrared transmitter (Beaton *et al.*, 1987; Moellering, 1989; Robinson, 1990; Hodges, 1992). While these technological innovations are likely to contribute to broader use of stereo images, new concepts of vision have established that this left/right separation is not necessary to establish a virtual three-dimensional image (Jules, 1971; Marr, 1982; Jones *et al.*, 1984).

Stereovision is not a reflex action but is in fact an intellectual activity in which one depth map, for example, the left image of a stereo pair, is received by the eye-brain combination and stored, and later merged with a second depth map, the right image of the stereo pair (Marr, 1982). This concept of vision opens new approaches to the display of three-dimensional geographic information and, with the use of current computer graphics technology, can be implemented at low-cost. Simultaneously, the development and distribution of large-format color hardcopy devices, such as electrostatic plotters, have provided opportunities to use traditional anaglyph image separation techniques to yield panoramic views of extensive geographic areas.

Current alternatives for achieving virtual three-dimensional displays include motion parallax systems based on single images, stereo and alternating pair systems using two images, and varifocal mirror and holographic systems using more than two images (Kraak, 1988; Hodges, 1992). Not all of these technologies are applicable to cartographic feature extraction and display of geographic phenomena, but the stereo and alternating pair methods hold particular promise for enhancing the productive capability of cartographic systems (Fornaro *et al.*, 1985).

It is the primary objective of this paper to present virtual three-dimensional images as a viable alternative for display, mensuration, and analysis of geographic phenomena. The thesis is that increased technological capability through digital and electronic media, and a better theoretical understanding of human visual processing of depth information, now permit virtual three-dimensional images to be used economically for simple display, mensuration, and analysis tasks. The approach is to provide the theoretical background of the methods and discuss implementation alternatives and resulting images.

To accomplish the objective, the application of angular and motion parallax from volumetric data to the display of both raster and vector geographic datasets is explored. Specifically, Landsat Thematic Mapper (TM) and SPOT stereo images and digitized photographic data in both real and synthetic stereo forms are used. Monoscopic raster images and U.S. Geological Survey (USGS) digital line graphs (DLGs) are modified using digital elevation models (DEMs) to create synthetic stereomates. The concepts of angular parallax and motion parallax are analyzed in the context of these datasets using anaglyph and VISIDEP™ realizations (Jones *et al.*, 1984). These concepts are implemented within current computer

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graphics capabilities embedded in GIS and image processing systems.

Background

Three-Dimensional Display of Geographic Data

The focus of this paper is display and measurement of geographic data in true three-dimensional form rather than as perspectives, contours, shaded relief, or other techniques which allow interpretation of volumetric information from a two-dimensional presentation. Two-dimensional presentation of three-dimensional geographic data is well-represented in the cartographic literature in standard textbooks and will not be examined here (Keates, 1982; Wolf, 1983; Robinson *et al.*, 1984). Kraak (1988) examines some aspects of three-dimensional displays but also includes two-dimensional presentations. Jensen (1978) reserves the term three-dimensional for only those displays resulting in a virtual image such as anaglyph stereo, holograms, and plastic relief models. This approach will be followed in this paper, such that any image termed three-dimensional will use three full dimensions for display, although the third dimension may be virtual as in an anaglyph display.

Any spatial dataset containing quantitative information over an area creates a surface and may be represented as a three-dimensional virtual image. Human visual perception requires two separate views of these surfaces to generate the virtual three-dimensional image, and methods to generate the second view by introduction of parallax based on the volumetric information have been termed synthetic stereo in the image processing community (Batson *et al.*, 1976). Jensen (1980)discusses methods of applying this concept to point, line, and area cartographic objects as well as raster-based digital images. For continuous data an equation of the form

$$p = h(K),$$

where p = parallactic displacement, h = height of point above a datum, and K = constant which determines extent of vertical exaggeration, will introduce parallax into a stereomate. For stepped surfaces or valued point symbols, the entire surface or symbol is displaced as a single entity.

Typical datasets to which the above equation may be applied include terrain surface representations such as DEMs or contour lines, population density, amount of rainfall, and others. GIS provide the capability to register many types of geographic data such as satellite images, land use/land cover, transportation, and hydrography to a DEM and, thus, a three-dimensional image can be generated. For vector-formatted data, such as transportation and hydrography from USGS DLGs, the stereomate is generated by determining for each vector point the corresponding elevation in the DEM and applying the equation above to shift the point in proportion to the height and the pixel size in the DEM. Several of these potential three-dimensional image products are examined below using anaglyph and VISIDEP^tm implementation techniques.

Depth Perception and Parallax

Human depth perception has been documented to rely on primary and secondary cues (Braunstein, 1976). The primary cues, sometimes called physiological (Okoshi, 1976), are accommodation and convergence associated with the muscular activity in the eye and binocular disparity. These are considered primary cues because they provide direct sensory data to be combined with the two-dimensional pictures on the retina, allowing interpretation as a three-dimensional scene. Secondary cues, sometimes called pictorial or psychological, are used to explain depth perception in photos and paintings. This group of cues include relative size, linear perspective, height of objects above the line of sight, shadow, relative brightness, and atmospheric attenuation. Motion parallax is the only cue which involves motion of either parts of the visual scene or the observer that has been considered by perceptual theorists.

Motion parallax is a monocular physiological cue which can be easily observed by scanning the objects in view. As the eye moves from one position to another, close objects move faster across the retina than far objects. This cue is consistently in use through motion of the body as a whole as in walking or through motion of the eyes themselves as they scan a scene and interpret phenomena.

Recent research indicates that human three-dimensional perception is not a reflex reaction to stimuli from two sources received by the two eyes independently (Marr, 1982; McLaurin *et al.*, 1986). Studies of persons with exceptional eidetic ability have demonstrated human capacity to fuse random dot stereograms and interpret the three-dimensional information when time separation of the images spans two or more days (Jules, 1971). This ability indicates a retention of the depth map in memory and later fusing that map with a new source also containing a depth map. Ogle (1963; 1967), Jules (1971), and others have demonstrated that this ability is not unique to eidetikers but is a part of normal human visual perception when the time delay is reduced to 100 milliseconds. Marr (1982) hypothesized that a depth map is actually stored in short term memory to be fused with a second depth map received after the time delay.

Jones *et al.* (1984) have used this concept to develop a three-dimensional imaging technique based on visual depth perception by parallax induction (VISIDEP^tm). This technique relies on the alternation of stereoscopic images to achieve the depth effect and does not require a left/right separation of images nor does it require the use of a visual aid such as glasses.

Central to the perception of depth using VISIDEP^tm is the concept of motion parallax. Motion parallax is conveyed to the user by the rapid alternation of the left and right images of the stereo pair. During alternation, the corresponding parts of the two images remain in the same position only if there is no parallactic displacement. Points in the image above the datum shift to the right and points below the datum shift to the left. Areas with high relief, and correspondingly large parallactic displacements, appear to move greater distances than those with less relief. The human eye-brain combination fuses the two images if the alternation frequency matches the depth map retention time. Current research indicates that alternation frequencies between 4 and 30 cycles per second are common with 10 being optimum for most people (Jones *et al.*, 1984).

One problem with alternating pair displays for geographic data is the apparent rocking motion of the virtual image which results from the switching of the images. This motion is not a problem with movies or video images with motion in the scene because the eye is attracted to the within-scene motion and mitigates the rocking sensation. With geographic phenomena, still images are used and the rocking motion is severe. Methods to reduce the rocking motion, such as retaining one image constantly displayed or imparting motion to the display through rotation or panning, are required. Research indicates that, if the left and right images are rotated 90 degrees counterclockwise creating vertical rather than horizontal parallax, depth perception is improved and the residual rocking motion is reduced (Jones *et al.*, 1984; Hodges and McAllister, 1985).

Little research has been conducted to examine the effects of motion parallax on three-dimensional cartographic presentations, primarily because of the static display requirements of paper maps (Kraak, 1988). The advent of softcopy mapping using automated cartography, image processing, and GIS provides an opportunity to evaluate motion parallax as an expedient to communicating three-dimensional geographic information.

Display Methods

Prior to display, the two images of a stereo pair are rectified to a common coordinate system. The rectification of natural stereo pairs requires a complete photogrammetric solution of interior and exterior orientation with exact modeling or can be approximated with polynomial equations for satellite and digitized images with insignificant loss of volumetric information (Welch and Usery, 1984). The development of the stereo pairs using synthetic methods requires that an image be rectified to a common coordinate system with a volumetric dataset such as a DEM. The parallax is then introduced into the stereomate using the equation detailed above and the image is resampled to redistribute the gray level or other attribute information to match the new image geometry.

With two images of the same object taken from different perspectives or generated synthetically, options for displaying a virtual three-dimensional model include left/right separation of the images projected to the left and right eyes, respectively, alternation of the two images, or both. Softcopy methods permit both techniques to be used while hardcopy requires the traditional left/right separation.

Softcopy

Fornaro *et al.* (1985) examined techniques of generating three-dimensional images for the purpose of quality control of DEMs and concluded that traditional stereo pairs and alternating pairs were superior to varifocal mirrors, holograms, and lenticular displays. Their conclusion was based partly on the availability of current technology to implement the stereo process but primarily on the ability of the display to provide an adequate depth image to permit detection and correction of errors in the surface representation. The stereo pair display methods require separation of two images, usually left and right based on horizontal parallax, while the alternating pair technique uses two images from different perspectives containing vertical parallax.

Anaglyph techniques with complementary colored images and filters are used to display stereo pairs of images containing horizontal parallax. This traditional display method is implemented on red, green, blue (RGB) displays by writing the left image in the red color memory and the right image in the green and blue color memories. For 24-bit displays, eight bits are used for each color. For displays supporting only eight bits per pixel, the bits are distributed to the three colors. For example, an acceptable display can be generated by writing the left image to the lower four bits for red and the right image to the upper four bits (two bits for green and two bits for blue).

The VISIDEP[tm] implementation is patterned after the work of McLaurin *et al.* (1986) and requires displaying left and right images alternately. Three implementations of this approach have been developed. Each of these implementations is optimized to particular types of softcopy devices based on spatial and color resolutions. The first implementation uses the concept of dual frame buffers in which each image of the alternating pair is stored in a separate buffer. The alternation of the images is achieved by changing the buffer being displayed. In the actual implementation, a single frame buffer is used with the two images stored in separate areas of the buffer memory (Usery, 1991). Switching between images is accomplished by changing the starting memory address of the display. This change occurs at frame rates so the image alternation timing is adjustable by the user from 1 to 30 frames per second. This implementation works best in 24-bit displays with high spatial resolution (e.g., 1024 by 1024 pixels) and supports both panchromatic and full color virtual stereo displays.

The second implementation alternates images by changing the lookup tables and requires that both images share the same position in display memory. This requires that the display memory be divided with one image in the upper portion of a memory location and the other image in the lower portion of the memory location. For example, on a display with eight bits per pixel, the left image occupies the lower four bits (bit positions 0 to 3) and the right image occupies the upper four bits (bit positions 4 to 7). This arrangement yields only 2^4, or 16, possible colors for each image. Note that values in the lookup table for the first image will be represented in the range 0 to 15 and values for the second image will be represented as even multiples of 16.

The color lookup tables are organized with values which only permit display of the lower or upper four bits but not both (Hodges and McAllister, 1985). To display the first image stored in the lower four bits, the lookup table values from 0 to 15 are used. To display the second image, a second lookup table is loaded with values which are multiples of 16. In this manner only the lower or upper four bits of the pixel value are displayed through the lookup table but never both. Examples of single memory location with two image pixels stored for alternating display and the associated lookup tables can be found in Hodges and McAllister (1985) and Podger (1991). The loading and switching of the lookup tables can also be performed at frame rates, permitting user control of the alternation frequency.

Lookup table switching with eight-bit displays permits virtual stereo of panchromatic images but is not sufficient to display a full color stereo image. Full color can be supported with this method on 24-bit color displays. In this instance, three color lookup tables – one each for red, green, and blue – are structured as described above, allowing 12 bits per pixel or 4096 colors for each image of the stereo pair.

The third method sacrifices spatial resolution but enhances color depth on eight-bit displays. In this method, each image of the alternating pair is written to the alternating scan lines of an interlaced display (Fornaro *et al.*, 1985). The highest bit is used to toggle between the display of the two images, leaving seven bits for image values. This method requires synchronization of color lookup table switching and the refresh cycle of the interlaced display. It provides 128 color levels for each image, but the spatial resolution is one-half that of the display memory because each image occupies only half of the scanlines of the video.

Several methods to reduce the apparent rocking motion of VISIDEP[tm] images have been developed such as retention of one image on the display while the second is cycled and creation of images with vertical rather than horizontal parallax (Jones *et al.*, 1984; McLaurin *et al.*, 1986). Although no theoretical justification exists, images with vertical parallax reduce the rocking motion without any apparent depth loss. The addition of motion to the display itself, such as rotation or panning reduces the apparent rocking motion, and can be implemented by a windowing function. For example, the left image is displayed on the full screen. The right image is displayed in a small window (5 cm by 5 cm). This window can be moved over the left image background with a mouse or other pointing device. The user-controlled motion of the window causes the motion resulting from image alternation to appear reduced.

The development of measurement capability using anaglyph techniques has been performed using simple floating mark concepts (Wolf, 1983). Essentially, a halfmark is displayed in the left image in a fixed position with respect to the virtual z-axis. The halfmark can be moved horizontally through the use of a mouse or other pointing device. A second halfmark is displayed in the right image, also moved horizontally by the mouse. This second mark can be moved along the z-axis in the virtual dimension by pressing the button on the mouse. Essentially, the mouse button controls the separation of the two halfmarks in the x direction. The two marks fuse visually in the virtual dimension of the image and operate identically to floating marks in conventional stereo plotters. Through this mechanism feature measurement, tracing, and extraction are possible.

Hardcopy

Hardcopy methods of generating virtual three-dimensional images require left/right image separation. This separation can be achieved using stereoscopes, polarizing films and filters, or complementary colors such as anaglyph techniques. The focus here is on anaglyph techniques and large format presentations. In this case, for both raster and vector data, electrostatic plotters provide an output device on which to generate the final image.

Raster

Images in raster form can be written to raster electrostatic devices by representation of single data pixels with multiple pixels on the device. Electrostatic plotters are essentially binary raster devices with multiple passes for the process colors — cyan, yellow, magenta, and black (CYMK). The spatial resolution of the plotter is usually sufficient to use multiple plotter pixels for a single data pixel, allowing increased color resolution in the resulting hardcopy image. For example, on a color electrostatic plotter with a resolution of 400 dots per inch (dpi), a 4 by 4, 8 by 8, or 16 by 16 matrix of plotter pixels can be used, yielding 16, 64, or 256 colors, respectively, for each data pixel. Representing a 30- by 30-m TM pixel with an 8 by 8 pixel matrix on the plotter yields an image at 1:59,055 scale. Specific scales for output images can be generated by appropriately resampling the input image data.

Mapping of the two images of a stereo pair is accomplished in the same manner as with anaglyph softcopy. The left image is displayed in red which is converted to cyan, and the right image is displayed in green and blue which are converted to magenta and yellow, respectively. The two images are printed to the same pixel locations in complementary colors and, when viewed with anaglyph glasses with the red lens over the left eye and the blue lens over the right eye, yield a virtual three-dimensional image.

Vector

Vector data in stereo are displayed similarly, with the left vector image of the stereo pair displayed in red and the right vector image in green and blue. The writing of vector data to the electrostatic plotter requires connecting the points of the vector line with a particular color. Red lines are written for the left image and green and blue lines are written for the right image. The width of the lines can be adjusted by the user to a minimum of single plotter pixels, for example, to 0.0025 in. on a 400 dpi plotter.

Integrated Raster and Vector

The integration of raster and vector data for hardcopy requires exact registration of the datasets and sequential plotting to the same media. The integration permits plotting at different resolutions for the two sources. For example, using a 4 by 4 matrix for a single raster image pixel, the corresponding vector may be threaded through this pixel and occupy only a single-pixel line width (Figure 1). Generating integrated virtual stereo images requires plotting four datasets: left raster image and left vector image in red, and right raster image and right vector image in green and blue.

Application of Virtual Stereo Images

Capabilities to create synthetic stereo images using both VISIDEP™ and anaglyph displays offer the potential to explore existing datasets in new visualizations. For example, DEM data can be used to generate a shaded relief image for which a corresponding stereomate can be generated. Viewing this type of display over a large area may show insight into the structure-forming processes of terrain. Using DEM and TM data together for virtual stereo displays allow TM data to be viewed as a three-dimensional image, and the inclusion of DLG data provides a more complete and realistic presentation of geographic phenomena than the corresponding two-dimensional representation. Similarly, generating VISIDEP™ displays of TM and DEM data may provide new visualizations of data for analysis purposes. In the following section, the results of applying these virtual three-dimensional display techniques in specified areas are discussed.

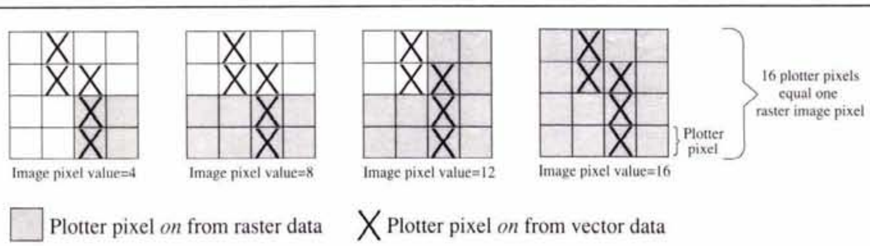


Figure 1. Using separate output resolutions for raster image data and vector line data requires threading the vector through the raster image cell. This example shows four plotter pixels used to represent one image data pixel with various values and one plotter pixel to represent the width of a vector line.

Results

The stereo display methods described have been implemented with datasets for Georgia, the Grand Canyon area, New Hampshire, and Wisconsin. Table 1 presents a summary of the data types and locations for which virtual stereo images are discussed. TM band 4 images of both natural stereo in the overlap area of two paths and synthetic stereo using a DEM were generated for Tiger, Georgia (Plate 1)*. These images were used in both softcopy anaglyph and VISIDEPtm small format (256 by 240 and 499 by 416 pixels) displays and provided the base for display technique development. These test data have revealed significant differences in natural versus synthetic stereo. For anaglyph methods, the differences are negligible with respect to the stereo effect; however, deficiencies of the synthetic generation algorithms, such as entire areas of terrain offset to a common elevation causing "hanging valleys," can be observed. The continuously changing elevations of the natural stereo do not contain these "hanging valleys." For the alternating pair display, this deficiency in the synthetic image causes large sections of the image to shift as one entity in the alternation process and increases the rocking motion. The natural stereo image has smoother transitions.

The VISIDEPtm method requires less separation of the images for best presentation of the depth information. While traditional stereo pairs require about six degrees of angular parallax, alternating pair images require between one and two degrees. This equates to 80 to 90 percent overlap in original acquisition of stereo photography rather than the 60 percent commonly used. To test VISIDEPtm with natural images, a stereo scene acquired on a space shuttle mission of the Large Format Camera (LFC) for Mount Washington, New Hampshire, was digitized and rectified for stereo viewing. This image with 80 percent overlap is ideal for alternating pair display. Rocking motion in the image is at a minimum with depth information at a maximum.

The results for the Wisconsin Driftless Area are primarily significant for the hardcopy display. An anaglyph synthetic stereo image was generated for the area covered by four 1:250,000-scale quadrangles — Madison, LaCrosse, Dubuque, and Rockford (Plate 2). The image was generated from USGS DEM data by creating a shaded relief image and offsetting each location according to its elevation to create a stereomate. Printed at 1:250,000 scale on a color electrostatic plotter with 400 dpi resolution and viewed with anaglyph glasses, the resulting virtual image provides insight into geomorphological processes. The combination of the relief shading and the parallactic displacement of the stereo images show significant features in this area of Wisconsin, including Military Ridge, Blue Mounds, the Baraboo Hills, and drumlin fields. The structural control evident in this large area image is not revealed by other display methods. Thus, the use of stereo displays and relief shading of large areas may provide new insight into the geomorphology of the region.

A virtual three-dimensional hardcopy image of the Grand Canyon area was generated from shaded-relief images of DEM data. This image covers an area of 12 1:250,000-scale quadrangles and provides an excellent view of the Canyon and the surrounding areas, including Death Valley, Lake Mead, and Marble Canyon. Again, the geomorphologic view is one unattainable by other methods.

One direct application of these images is for process and data validation and correction. Data errors apparent in the Grand Canyon synthetic stereo image include noise, for some of the 24 1- by 1-degree patches which were mosaicked, and mismatch of the elevations along patch boundaries (Plate 3). Occasional spikes and other singularities can be detected in the image. Process errors such as mismatch of the patches and an inability of the software to handle negative elevation values are also detectable using the anaglyph stereo displays.

Synthetic stereo images of vector data suffer from the mismatch of anaglyph lenses prepared for use with RGB displays and the use of pure colors in CYMK on electrostatic devices. Plate 4 shows an example of DLG data for the Las Vegas area offset with a DEM to create a stereo image. While the registration of the datasets is exact with appropriate parallactic shift, the blue/green lens of standard anaglyph glasses will not completely eliminate the blue/green lines created with process color. This difference has not been significant in other images because of the gradations of color rather than pure red and blue/green which appear with vector data.

Combination of vector and image data in stereo mitigates the problems of color mismatch for the vector data and provides a unique representation of the geographical area. This combination was performed for the Grand Canyon area, requiring significant processing to merge eight TM scenes and combine these data with 24 DEM files to create the stereo image (Plate 5) (Usery and Norton, 1991). Overlay of corresponding vector data required processing and merger of over 1,000 DLG files. Results of this process for the Las Vegas 1:250,000-scale quadrangle are shown in Plate 6.

VISIDEPtm techniques have been implemented on all test areas. The diversity of relief has allowed testing its effects on the perceived virtual image. The rocking motion increases with increasing relief as would be expected because perception of the depth is a direct function of the amount of mo-

* All anaglyph images included are displayed with the red image on the left and the blue/green image on the right requiring placement of the red lens over the left eye and the blue/green lens over the right eye for correct stereo viewing.

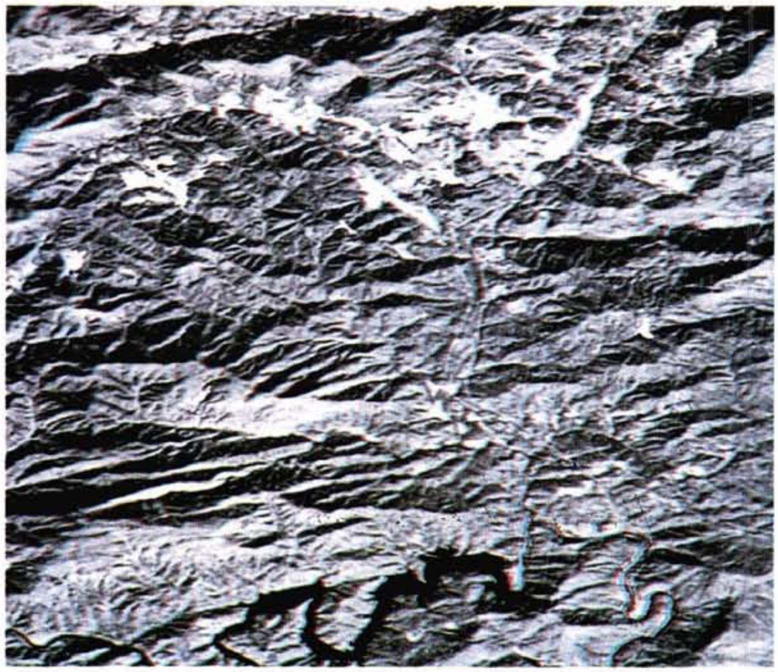
Table 1. Study Areas and Datasets for Virtual Stereo Images

Location	Area	Image Type	Scale/Resolution	Method*
Georgia-Tiger	7.5×7.5′	TM	30 m	A,V
Grand Canyon	8×3°	Shaded Relief	250,000	A,V,H
		TM	250,000	A,V,H
Las Vegas	2×1°	DLG	250,000	A,H
	2×1°	DLG/TM	250,000	A,H
New Hampshire	5×5′	LFC	50,000	V
Wisconsin Driftless	4×2°	Shaded Relief	250,000	A,V,H

* A = anaglyph, V = VISIDEP™, H = hardcopy

(a)

Plate 1. Softcopy screen display of TM band 4 data in (a) natural stereo and (b) synthetic stereo for the Tiger, Georgia area. Display size is 256 by 240 and 499 by 416 pixels, respectively. In this and all subsequent anaglyph images, the red image is on the left and the blue/green image is on the right, requiring placement of the red lens of the anaglyph glasses over the left eye and the blue/green lens over the right eye.



(b)

Plate 2. Hardcopy stereo image of part of the Driftless Area of Wisconsin. The original image was electrostatically printed in anaglyph format at a scale of 1:250,000.

tion. Synthetic stereo generation has allowed varying the amount of parallax, and again a direct correlation to the perceived motion is observed.

Conclusions

The advent of economical digital graphics technology has the potential to change the types of displays used for spatial analysis. This paper has attempted to portray one possible use of that technology to generate virtual three-dimensional images. The potential of these techniques appears significant, but only the display methodologies were detailed here with no attempt to quantify their benefits. Both anaglyph and alternating pair techniques can be implemented with standard GIS and image processing hardware. The utility of these

Plate 3. Hardcopy stereo image of part of the Grand Canyon area. The original image was electrostatically printed in anaglyph format at a scale of 1:250,000 in four panels and measures 3 m by 1.5 m.

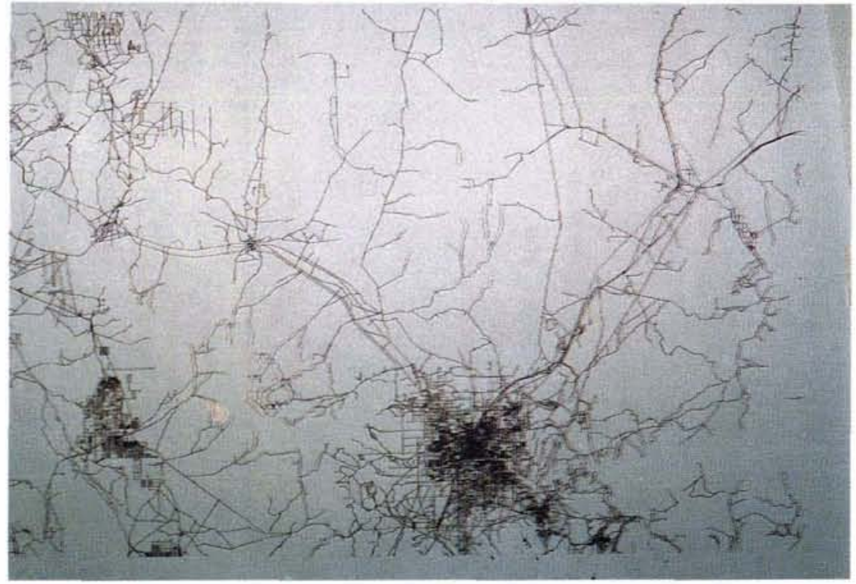


Plate 4. Hardcopy stereo image of DLG data for the Las Vegas area generated with anaglyph methods on an electrostatic plotter. Note that the red and blue-green colors produced in CYMK do not correspond to the red and blue-green of standard anaglyph glasses which are designed for RGB color.

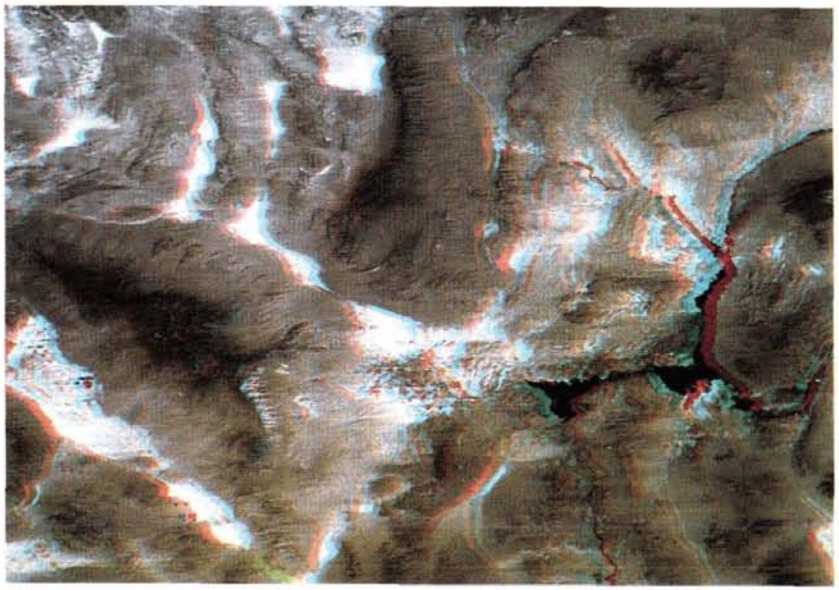


Plate 5. Softcopy anaglyph stereo image of TM band 3 data for a part of the Grand Canyon study area, photographed from the display screen. Compare this display of the Las Vegas area, reduced by a factor of two, to the photograph of the electrostatic hardcopy of part of the same area in Plate 6.

Plate 6. Hardcopy stereo image of the Las Vegas area in which TM band 3 and DLG data are combined. The original stereo data were generated by using the DEM to offset the TM and DLG, resulting in four images: left and right TM, and left and right DLG. These four images were combined as a single anaglyph image on an electrostatic plotter.

three-dimensional display techniques in constructive spatial analysis remains to be evaluated; however, it has been determined that large format anaglyph stereo and shaded relief displays are useful in geomorphology for assessing the underlying structural control.

The utility of these methods for data validation is established with organizations such as the USGS which routinely use anaglyph three-dimensional displays to detect and correct errors in DEM datasets. The use of large-format hardcopy displays to detect and correct software processing errors is also an area of potential use of virtual three-dimensional techniques.

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