featured article

Mapping the Nation's Physiography by Computer

Richard J. Pike
Gail P. Thelin

Recent advances in computer technology present opportunities for the machine visualization of topography. A new shaded-relief map of the conterminous United States is the first one-sheet graphic of U.S. landforms larger than Erwin Raisz's classic 1939 hand-drawn panorama. The 1:3,500,000-scale digital image (about 4.5' long), reproduced here at 1:10,000,000, has greater fidelity and detail than portrayals of this large area by artistic (manual) techniques. The new map also shows synoptic topography more clearly than contoured elevations, satellite images, or radar mosaics. We created the map by processing 12,000,000 elevations (digitized from 1:250,000-scale topographic sheets at a grid resolution of 0.8 km) on a VAX-11/780 computer, using proprietary software, a modified Lambert photometric function, 255 gray tones, and the method of Pinhas Yoeli as implemented by Raymond Batson and others.

PORTRAITS OF LANDSCAPE

Realistic portrayal and mapping of topographic form is a centuries-old problem: to trick the eye into perceiving a two-dimensional graphic as a three-dimensional landscape. All traditional solutions, including those partly implemented by machine, have been artistic (Horn, 1981). Among the cartographic devices invented by illustrators to supply the necessary visual depth cues are hachuring, hypsographic (elevation) tinting, contour density, parallel-profile density, pictorial relief, and shaded relief *(chiaroscuro)*. The latter two manual techniques have been particularly successful. Pictorial relief, which symbolizes topography by stylized morphologic types, was most fully developed by the 50 landform classes of Raisz (1931). Shaded relief, or hill shading, shows topography by the intensity of shadows cast by a light source (Imhof 1965). First drafted by pencil, pen, or brush, shaded relief also has been executed by airbrush, dark-plate, and photography of raised-relief models. However, topographic detail at, for example, a one-km resolution is much too complex to be mapped both accurately and economically over large areas by any of these means.

Fast computers, analytical software, digital data, and graphic input/output devices have converged over the last three decades to largely mechanize the craft of map making (for example, Burrough 1987, p. 4-6). This digital revolution has, among its many accomplishments, also solved the problem of mapping topographic form. Machine visualization now frees terrain portrayal from long-standing limitations (Kennie and McLaren 1988). Topography need no longer be mapped symbolically, by discrete hand-drawn morphologic types, or subjectively, by manual shading. Where the necessary information is available in digital format the computer can represent landforms as they actually are — given constraints imposed by data resolution — and portray terrain in the infinite variety of form that constitutes the true landscape. It is no longer entirely correct that maps of landforms are "drawn by men and not turned out automatically by machines" (Wright 1942).

We hasten to caution here that The Millenium has not arrived; it is just now within sight. The effectiveness of machine-mapped topography depends critically upon accuracy of the digital data and their astute manipulation. Wright's admonition that map makers are human beings, not machines, remains unchallenged in its most fundamental sense. Although design and production of landform maps will be increasingly automated and sophisticated, the conception of a map, even a highly computer-intensive graphic as that presented here, is essentially an

Richard J. Pike is a geologist at the U.S. Geological Survey, Branch of Western Regional Geology, 345 Middlefield Road, MS 975, Menlo Park, California 94025.

Gail P. Thelin is a research geographer with the U.S. Geological Survey at Ames Research Center, MS 242-4 Moffett Field, California 94035.

intellectual rather than a mechanical process. The descendants of this map, however technical in execution, will continue to remain the constructs of human vision and ingenuity.

MACHINE IMAGES OF TOPOGRAPHY

Digital image-processing and computer graphics have largely mechanized the art of landform representation by combining the two most effective traditional techniques, pictorial relief and hill shading. The resulting image is a shaded pictorial-relief (physiographic) panorama in vertical perspective. It is computed from an array of closely spaced terrain heights, usually in grid-cell (raster) format, called a digital elevation (or terrain) model (DEM/DTM). Although digital shaded-relief images can look deceptively like satellite pictures, they are not acquired directly by Earth-orbiting spacecraft, nor are the elevation data from which they are made. Currently, most data sources are conventional topographic maps.

Shaded relief is a complex derivative of terrain height (Figure 1). Digitally shaded maps of topography resemble cloud-free black-and-white aerial photographs taken at a low Sun angle, but actually they are large north-south/east-west arrays of minute gray squares (Yoeli 1965). Each square, or picture element (pixel), represents a theoretical reflected-light intensity (brightness value) computed from a mathematical relation between ground slope, Sun position, and location of the observer (ground slope is estimated from the corresponding point and its neighbors in a DEM). The lightest and darkest tones in the image show the steepest areas; intermediate gray tones represent gentle terrain. The most satisfactory image is obtained by experimenting with location of the simulated Sun (conventionally from the northwest at 45° above the horizon) and illumination intensity. For more information, see the appendix "Technical Details" below.

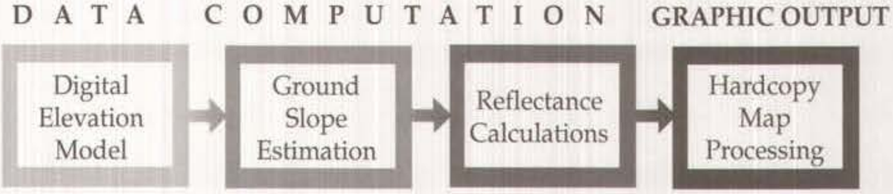

Figure 1: Basic steps in the generation of a shaded-relief map (modified from Brassel 1974 and Horn 1981).

Mechanization of the shaded-relief technique for DEMs, pioneered by Yoeli (1967), has been widely applied. Batson and others (1975) made the first synoptic shaded-relief images for parts of the western United States (at 1:500,000 scale), and Arvidson and others (1982) published the first image to include 48 states (albeit at 1:30,000,000). These were followed by small shaded-relief maps of Australia and South Africa, a larger one of Sweden, and the first shaded-relief map of the Earth (Heirtzler 1985). Among the latest synoptic images are those of several states in the American southwest at 1:1,000,000 scale by Kathleen Edwards and Raymond Batson (now available from the U.S. Geological Survey). Experimentation has further refined the technique, which has been equally effective in portraying gravity, aeromagnetic, geoid, and other geophysical data for interpretation (for example, Arvidson and others 1982).

As databases and output devices improve, we speculate that relief-shaded images, along with contour maps, eventually will be available on-demand and over-the-counter, from regional and local distributors.

The depiction of topography by digital relief shading is passing from an experimental technique to a method of map production. Although the many steps — from data formatting, editing and processing, through image generation and correction, to preparation of a reproducible master — still are time-consuming and can require much trial-and-error, this long chain of events can be much streamlined, if not wholly automated. Even now, a governmental, educational, or commercial mapping establishment that has the requisite hardware, software, data, and experience could conceivably implement relief shading in a production environment. As databases and output devices improve, we speculate that relief-shaded

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APPLICATIONS OF DIGITAL LANDFORM MAPS

Computer-generated maps offer several advantages for the visual study of topography. Above all, these images portray landforms accurately and disclose their true complexity (at a given resolution), two properties that often are lost in small-scale sketches, diagrams, or conventional maps. Perhaps equally important, surface features can be viewed in a broad regional context. Unlike aerial photographs, image extent is limited only by size of the DEM. Digital shaded-relief maps also lack the distortion inherent in photographs and radar images. They are free of the vegetation and cultural features that mask topographic form on images from Landsat, SPOT, and other satellites. Stereoscopic pairs in shaded relief can be created digitally (Batson and others 1975) and Sun position can be varied to obtain different views of the the same area. Finally, shaded-relief images can be generated much more rapidly from digital files than conventional relief maps can be prepared by a skilled artist from contour sheets or photographs of the same area.

Computer maps of elevation derivatives have many uses. Applications of relief shading include, but by no means are limited to, resource evaluation and the interpretation of regional and structural geology, global tectonics, and geomorphology. Surface features in shaded relief can be studied by conventional techniques, including aerial photointerpretation. Automated relief shading also provides an excellent cartographic base for mapping cultural and Earth-science information at any scale commensurate with resolution of the source DEM: local (Mark and Aitken 1990) to global (Simkin and others 1989). Shaded relief may be combined with such non-topographic information by machine registration with another digital file, for example, a computer-coded map of the United States highway network.

Relief shading is only one of several ways to map topography by computer. Other derivatives of elevation include slope angle and aspect, slope curvature, local relief, and ridge and stream spacing (Evans 1980). Maps of these measures can be combined statistically to characterize topography over large areas by means of numerical, nonverbal, fingerprints or signatures (Pike 1988). For example, the statistics of slope angle are contributing to the potential revision and elaboration of U.S. physiographic units (Pike and Thelin 1989). We expect that the regional geomorphology of the United States will be refined from these measures, as well as from the new shaded-relief image.

Finally, maps of slope and other derivatives of elevation can be combined digitally with maps of soils, vegetation, climate, and demography, using GIS technology (Burrough 1987), to address practical problems of environmental resource management and land use. Computer-intensive applications include mapping Earth-science hazards, hydrologic analysis, modeling air mass/terrain interactions for climatology and synoptic meteorology, and quantitative refinement of existing qualitative maps of United States ecoregions (Gallant and others 1989).

THE NEW UNITED STATES MAP

The full-sized version of the map reproduced here (Thelin and Pike, in press) is the largest single-sheet graphic of relief forms of the United States since the classic hand-drawn oblique map of the same area by Erwin Raisz (1939). In concept and execution it most closely resembles the vertical dark-plate map of United States shaded relief created for the Atlas of the United States by Richard Edes Harrison (Harrison 1969), but is intrinsically more detailed and accurate than either of the above works. The new map clearly shows the regional terrain textures on which physiographic divisions of the United States are largely based (Pike and Thelin 1989). It nicely complements Edwin Hammond's (1964) map depicting numerical classes of land-surface form, as well as various satellite-image color mosaics, which emphasize vegetation and hydrography. The Raisz map, which is still available[1] may be used to locate named surface features.

Greater detail is evident in the digital shaded-relief image than could practically be included in synoptic portrayals of the nation's terrain at this resolution by any manual technique. Much of the detail derives from the high density of the dataset (and the computer's ability to rapidly process so many terrain heights), but much of it simply reflects the map's large size, which is more than twice that of its closest predecessor, Harrison's U.S. Atlas plate (Harrison 1969). The 1:3,500,000 scale of the full-sized map also is the maximum consistent with visual merging of pixels into a continuous smooth surface. Map resolution — the length of a pixel edge — is 0.23 mm (0.8 km on the ground), slightly better than the 0.25 mm/pixel maximum value proposed by Yoeli (1965) for shaded-relief portrayal by computer.

The new map shows geomorphic and tectonic phenomena of the United States in unprecedented detail. These features, great and small, are so numerous (Thelin and Pike, in press, offer a sampling) that we mention only one here. In commenting that the map "may help redefine the mental images we have of the U.S. which to a great degree are the result of the maps to which we have been exposed," a reviewer gave an example: "the idea of the Great Plains as being featureless is shattered by this map." Indeed, this observation also was one of our first; there are many more. Treatises on regional geomorphology of the Country (referenced in Hammond 1964, Pike and Thelin 1989, or in a good introductory textbook on geography or geology), as well as other physical maps of the United States (for example, Raisz 1939, Hammond 1964), may be consulted for study of the landforms evident on the map.

FUTURE PROSPECTS

Our current shaded-relief image of the United States is not necessarily the ultimate digital portrait of the nation. Like any reconnaissance map, or for that matter a good scientific hypothesis, the map shown here is an ongoing experiment (Yoeli 1965). Because this map reflects a still-evolving technology, various improvements are possible. Foremost among these are restoration of digital elevations for southern Canada and northern Mexico (see following section entitled "Technical Details"; and Arvidson and others 1982), inclusion of Alaska and Hawaii, eliminating or reducing errors in the dataset through further editing and edge-matching of data blocks, and more hydrography. The visual perception of elevation could be enhanced through the use of color.

Changes in the shaded-relief calculation might address some remaining shortcomings of the map, particularly tonal imbalance between steep and gentle terrain. Detail in very mountainous areas is obscured because the steepest slopes are too dark or too light. We have found that the desired balance in tone can not be achieved simply by transforming all elevation or slope values to logarithms or square roots, and then computing brightnesses from the transformed values. The solution is likely to be more complex and may require incorporating special algorithms, called local operators, within the computer software to tailor reflectance values to specific conditions of elevation and slope (Brassel 1974).

Lastly, the information content of this map could be best improved

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[1] From Raisz Landform Maps, P.O. Box 2254, Jamaica Plain, MA 02130; (617) 522-3091

simply by increasing scale, data density, and image resolution. Such a map would provide the detail needed for a more effective relief portrait in many parts of the United States. An improved map of the entire country, probably at 1:1,000,000 scale and necessarily in several sheets, would require a cleaned-up file of all the original digitized elevations and an image resolution of about 0.1 mm/pixel (130 m on the ground). Multiple editions of this map at several Sun azimuth and elevation settings would further exploit the research potential of digital shaded-relief by accentuating terrain features that follow all the different trends in the country's landscape.

APPENDIX

TECHNICAL DETAILS

Image Processing and Hill Shading

Our map was made by digital image-processing, a technical specialty related to the broader fields of computer graphics and machine vision (Kennie and McLaren 1988). The technology includes the many spatially-based operations first developed for manipulating Ranger, Mariner, Landsat, and other images that are reassembled from spacecraft telemetry in a raster or scan-line arrangement of square-grid elements (Jensen 1986, Sheldon 1987). These computer procedures have been successfully transferred to landform analysis from remote-sensing applications by substituting terrain heights or sea-floor depths for the customary values of electromagnetic radiation obtained from satellites and stored in digital arrays of pixels (Batson and others 1975).

It is the 1 pixel = 1 elevation equivalence that enables image-processing technology to efficiently map elevation matrices and their derivatives over large areas. Recent examples are given by Arvidson and others (1982), and by Thelin and Pike (in press). Slope angle and other quantitative measures of surface form can be rapidly calculated, compared, and combined for display as shaded-relief and color images or stored as digital files for further study of topography and registration with nontopographic datasets (Batson and others 1975, Moore and Mark 1986, Pike and Thelin 1989).

The image-processing tool applied here — relief shading — is more formally termed analytical hill-shading. Although well known as an artistic and manual technique (Imhof 1965), it was impractical for large areas until Yoeli (1965) developed a modern analytical version for square-grid matrices of terrain elevations and then adapted it to the computer (Yoeli 1967). Analytical hill shading portrays topographic form through variations in mathematically determined intensity of reflected light (**I**) at each elevation/pixel located on the ground (Figure 2). This relation, known as the photometric function, has many variants (Brassel 1974, Batson and others 1975, Horn 1981). For the simplest case, the cosine law of Lambert,

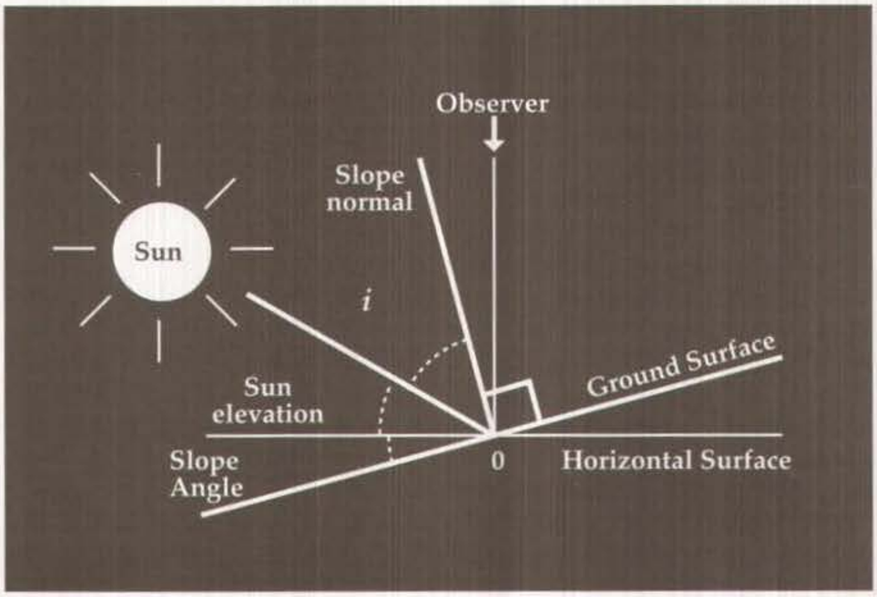

Figure 2: Geometric relation between ground slope and Sun position that is basic to reflected-intensity (brightness) calculations for shaded-relief mapping (modified from Batson and others 1975). See equations (1) and (2) in text. Point O is center terrain height in 5-point sample of digital elevation model (see Figure 3).

$$I = k_d \cos(i) \qquad (1)$$

where *i* is the angle between the incident light (the Sun) and a vector normal to the sloping ground and k_d is a coefficient describing reflectivity of the surface material (here, a perfect diffuser of incident light, Greenberg 1989). Position of the viewer is directly overhead. Ground slope may be estimated from a DEM in several ways, using 3 to 9 adjacent height values (Mark and Aitken 1990). Repetition of these calculations pixel-by-pixel over a large DEM yields a reflectance map, a continuous X,Y array of brightness values (Horn 1981).

Many refinements to the basic approach itself can improve relief shading without having to add data from other sources (such as Landsat). Besides direct illumination, reflectance maps generally include some ambient light, which strikes and reflects from a surface equally in all directions, to improve appearance of the final image (Greenberg 1989). Shadows cast by steep terrain also can be incorporated into the calculation, and even atmospheric effects can be simulated (Brassel 1974). Finally, advanced techniques of computer graphics used in some industries to digitally depict virtually any object with photorealistic quality (Whitted 1982, Greenberg 1989) conceivably could be adapted to take shaded-relief portrayal to even higher levels of realism (Kennie and McLaren 1988).

Source Data

The terrain heights from which our map was made were not remotely sensed by Landsat or other spacecraft. Rather, the data result from the machine sampling — initially by contour-tracing, later by drum- scanning — of available contour maps, some of which were first compiled as early as 1947. These measurements have a complex history that spans a quarter of a century, beginning with the Defense Mapping Agency Topographic Center's (DMATC) creation of a nationwide set of gridded elevations over the years 1964 to 1972.

DMATC digitized and labeled contour lines, and later spot heights and stream and ridge lines, on hundreds of 1:250,000 scale (1° by 2°) topographic sheets covering the United States and much of Canada and Mexico. Digitizing these maps by semi-automated methods at 0.01" (0.25 mm) resolution (3 arc- seconds or about 200' [63 m] on the ground) accounted for 1/6 of the elevations. The remaining 5/6 of the data were interpolated between digitized contours by computer. The entire DEM, containing more than 2 billion elevations arrayed in a square grid of 3 arc-second resolution, has been available since 1974 in over 900 1° by 1° blocks from the U.S. Geological Survey (USGS)[2].

The original DMATC data were later resampled (thinned) and averaged down (see Godson 1981 for some details) to the more manageable file used here and by Godson (1981) and by Arvidson and others (1982). The resulting 12 million elevations are spaced 30 arc-seconds apart, nominally 0.805 km on the ground, north-south and east-west[3]. The actual array (6046 x 3750) processed to make our map includes null (black) background values lying between the national boundary and the map border and thus is much larger. Although the initial DMATC data were read or interpo-

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[2] Contact the Earth Science Information Center, Room 1C107, 507 USGS National Center, Reston VA 22092; (800) 860-6045.

[3] The 30-arc-second DEM is available from the National Oceanic and Atmospheric Administration's National Geophysical Data Center, Code E/GC1, 325 Broadway, Boulder CO 80303; (303) 497-6128.

lated to the nearest foot, the elevations were later rounded to 10 m (map contour intervals were coarse: 100' or more). Accordingly, vertical accuracy of the data for this image may be no more than 30 m in smooth areas and 50 m in rough terrain.

Errors in both the 3-arc-second and the 30-arc-second datasets, in addition to those inherent in the source maps, account for visible flaws in the map, more evident in the full-sized version than that shown here. Most of these errors are systematic. Flattened hills and fine-scale rectilinear and stair-step textures on the map arise from round-off error and also from inaccurate interpolation between widely spaced contours, the result of too large a contour interval and a fast but suboptimal algorithm dictated by the slow computers available 25 years ago. Faint, widely spaced north-south and east-west lines mark defective splices between 1° data blocks.

Computation and Production

We created this map by processing all of the 30-arc-second height data through proprietary software, the Interactive Digital Image Manipulation System (IDIMS; Electromagnetic Systems Laboratory, Inc., 1983), installed on a DEC VAX 11/780 computer. After registering the location of each of the 12 million elevations to an Albers Equal-Area Conic projection (standard parallels at 29.5° N and 45.5° N; central meridian at 96.0° W, and latitude of projection's origin at 23.0° N), we produced a new grid of 0.805-km-resolution pixels from bilinear resampling. Topography beyond the national boundary, in two strips across southern Canada and northern Mexico, was excluded from the dataset by a 1:2,000,000-scale United States outline obtained from a USGS digital line graph.

The SUNSHADE routine within IDIMS computed strike and dip angles of terrain slope, by algebraic manipulation of the four elevations immediately north, south, east, and west of each sample point in the DEM (Figure 3), and from them assigned brightness values ranging from 0 (deeply shadowed areas) to 255 (fully illuminated surfaces) to all 12

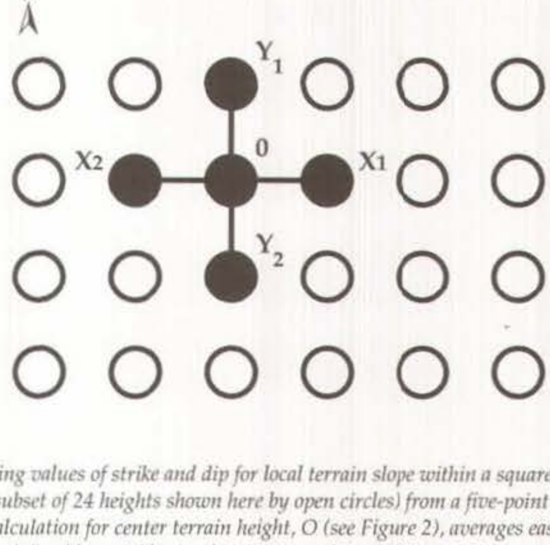

Figure 3: Obtaining values of strike and dip for local terrain slope within a square-grid digital elevation model (subset of 24 heights shown here by open circles) from a five-point sample design (filled circles). Calculation for center terrain height, O (see Figure 2), averages east-west and north-south slope values defined by neighboring heights X_1 and X_2 and Y_1 and Y_2, respectively (Electromagnetic Systems Laboratory, Inc. 1983). Sample point O is relocated at each height value throughout the DEM and the calculation repeated. Resulting values of strike and dip are used to compute the slope normal and then angle i (Figure 2) for text equations (1) and (2).

million pixels (these calculations took about 17 minutes of CPU time on the VAX 11/780). The algorithm (Electromagnetic Systems Laboratory, Inc., 1983) is built around a much-modified Lambertian photometric function (Horn 1981) that uses diffuse scattering to simulate the effects of solar illumination,

$$I = k_d[L\cos(i)] + A \qquad (2)$$

where L is a scaling factor for the intensity of illumination and A is an additive ambient light factor (the remaining terms are defined for equation 1, above). The calculation does not provide for cast shadows. Various parameters to the SUNSHADE routine control image contrast and thus final appearance of the shaded relief. We found that the following values gave the most crisp and visually appealing portrayal overall: vertical exaggeration, 2X; Sun azimuth, 300°; Sun elevation, 25°; scaling factor for the intensity transformation, 1.2 units; ambient-light factor, 0.7 units.

Errors in the DEM were located from both statistical analysis of the elevations (Pike and Thelin 1989) and visual identification of aberrant patterns in the image. We repaired some of the most visible artifacts by editing flawed portions of the DEM and changing elevations on a pixel-by-pixel basis, using a Hewlett-Packard 9000 Series-360 Turbo workstation. To retain maximum local detail in the map, we did not attempt to correct or change any of the erroneous elevations globally, by applying a digital filter to the entire DEM.

Preparation of the final image required several steps. To increase tonal contrast in smooth topography and diminish it in areas of high relief, we remapped the intensity values output from SUNSHADE, using a piecewise linear transformation, to new values based on breakpoints that we defined in the original shaded-relief image from a histogram of its brightnesses. Over 70 of the largest (over 20 mi^2 in area) natural lakes (20 shown here) were obtained from a vector file of hydrography, converted to raster format, and added to the shaded-relief file as a digital overlay. The image reproduced here was created from a digital file by making a photographic negative on an Optronics C-4500 color scanner and film recorder and enlarging the print to the desired size. The original print was then converted to a plate-ready negative by graphic arts photography through a 150 line per inch halftone screen.

Production of the full-sized map (Thelin and Pike in press) is more complex, requiring three separate reproducibles to achieve the desired tonal contrast and balance. The negative images, each of which emphasizes a different range of brightness, are made on the Scitex Response-300 computerized cartographic system. For each image the full range of 255 light intensities was computed for all 12 million pixels to generate a printing screen of 175 lines per inch on the Scitex system's laser drum plotter. The final map is to be printed from three metal plates made from these screens plus a fourth for the lettering. We expect the map to be distributed in mid-to-late 1991. Its availability will be announced here and in other journals.

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DISCLAIMER

Any use of trade, product, industry, or firm names in this article is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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La Construccion de un mapa fisiografico de los Estados Unidos por computadora

Extracto

Translation by Juan José Valdés
National Geographic Society

Recientes avances en la tecnología de computadoras presenta nuevas oportunidades para la formación de modelos topograficós. Un reciente mapa de relieve matizado de los Estados Unidos contérmino es el primer modelo gráfico de sola lamina que detalla la topografía Americana en un formato mas grande que el del clásico panorama de 1939 dibujado por Erwin Raisz. El imagen digital, a una escala de 1:3,5000,000 (mediendo aproximadamente 11.43 centimetros de largo), reproducido a una escala de 1:10,000,000, contiene mejor detalles y una veracidad superior sobre otras representaciónes producidas manualmente. La topografía sinóptica de este mapa es mas detallada que esas de elevaciónes contornas, imagenes satélicas, y mosaicos por radar. Este mapa fue producido procesando 12,000,000 puntos de elevaciónes (digitizados de laminas topografícas con una escala de 1:250,000, conteniendo una resolución triangular de 0.8 kilómetros) en una computadora VAX-11/780, usando software propietaria, una función fotómetrica modificada de la proyección Lambert, 255 tonos grises, y el método Pinhas Yoeli implementado por Raymond Baston y otros.