STATE-OF-THE-ART AND FUTURE NEEDS FOR DEVELOPMENT OF DIGITAL TERRAIN MODELS

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ABSTRACT

The state-of-the-art of production of digital terrain models has progressed from simple digitization of contour sheets with subsequent digital interpolation to analytical stereo compilation with full photogrammetric control. Furthermore, current developmental efforts include digital terrain models produced by automatic digital stereo image correlation, analysis of multispectral responses influenced by terrain modulation, and compilation from stereo synthetic aperture radar imagery. In addition, theoretical studies are addressing geomorphological quality and accuracy estimation of digital terrain models, empirical studies are addressing model differences as a function of production equipment/ methodology, and experimental analyses are developing techniques for digital terrain model anomaly detection and removal.

INTRODUCTION

The task of compiling a comprehensive paper on the state-of-the-art of digital terrain models is indeed a complex issue. This is due primarily because of the ever-increasing demand to represent terrain in a digital format for exploitation by analysts using modern computers for a variety of applications, including resource exploration, land use and mission planning, computerized guidance systems, aircraft and land vehicle simulators, and automated chart production. Because of the wide variation of source data, including various types of sensor data, different scales and resolution of input sources, and magnitude of required terrain coverage, coupled with the variation of photogrammetric exploitation equipment and computer resources, digital terrain model producers have developed a wide variety of state-of-the-art techniques to optimize production based on individual production requirements, source information, and exploitation equipment combinations.

To further enhance the complexity of the issue, similar individual scenarios have resulted in variations in digital terrain model data structure, storage, and representation. The one common thread in the various production and representation methodologies for digital terrain models is the requirement to mathematically measure the accuracy and quality of the models, and to develop techniques to remove or minimize errors and anomalies in the models. This common concern leads to a variety of analytical and empirical approaches that are bound together by basic mathematical and physical properties, and a common desire to develop new production scenarios for digital terrain that better define the surfaces being modelled.

A major problem in the discussion of digital terrain models is the definition of what is meant by the terminology used in the description of the model and associated accuracy statements. For purposes of this paper, a Digital Terrain Model (DTM) is defined as any numerical representation of a landform, not to be confused with a Digital Elevation Model (DEM), which only describes digital terrain elevations at regular or irregular intervals. Note that a DEM is one version of the general class of DTM's. Furthermore, this paper will concentrate on production of DTM's over large landmass areas (one degree cells and larger) because many significant problems arise that are not important in small area production.

CLASSES OF DIGITAL TERRAIN MODELS

There are many ways in which DTM's may be classified; however, DTM's may be logically discussed by classifying them in terms of type of source data used for DTM generation, the data collected in DTM compilation, and the method of representation of the DTM as a product. Each of these classifications are important, because each class defines the requirements for the compilation equipment, the mathematics used in compilation, and the methodology for evaluation and usage of the DTM.

Sources of DTM Information

DTM's may be produced from two basic sources, physical measurement of the surface or mathematical derivation from remotely sensed images of the surface. This paper will constrain its discussion of physical measurement of the surface to cartographic DTM's, those produced from digitized contour sheets produced by conventional surface mapping. All DTM's mathematically derived from remotely sensed imagery will be designated as photogrammetric, consistent with a similar definition appearing in the Fourth Edition of the Manual of Photogrammetry.

Cartographically produced DTM's require digitization of contour sheets either manually with the aid of a digitizer, or by automatic methods using a raster scanner with subsequent vectorization or by using a line following scanner. If a grid of elevations are required, then some interpolation algorithm must be used to generate points from the contour information.

Optically photographed stereo pairs of imagery are the most commonly used photogrammetric source for DTM's. Optical photogrammetric techniques have developed since the second half of the 19th century, and the Fourth Edition of the Manual of Photogrammetry is probably the best reference on this topic. Without going into further detail about optical photogrammetry as a source of DTM's, it should be emphasized that most if not all of the modern day analytical stereoplotters collect either elevation point or profile data in an electro-optical environment based upon rigorous geometrical and mathematical principles. Digital correlation and production of DTM's will be discussed later.

Stereo side-looking and synthetic aperture radar (SAR) may also be a viable source for DTM's. Leberl et. al. (1982) and Domik et. al. (1983) provide good mathematical developments for radargrammetry, and Elachi et. al. (1982) provide a good discussion on SAR techniques. Crude DTM's have been produced using SEASAT-SAR, and the recent support given to new research efforts should produce SAR based DTM's in the near future. An interesting proposal has been made by Breshears et. al. (1982) to use interferometric SAR to produce contour information, and a preliminary experiment was conducted.

The use of non-stereo imagery sensed with multi-spectral bands by Landsat as a source for DTM's has been presented by Haralick (see Wang, et. al.) in a variety of papers. Basically, the concept is to automatically cluster similar reflectance classes and then subcluster the image into a reflectance image using multi-spectral ratios and a topographic modulation image from which a DTM is produced using an elevation growing technique.

Data Collected in DTM Compilation

The purpose of producing a DTM is to obtain a numerical representation of a landform. As previously mentioned, commonly collected information includes contour or iso-elevation data, spot elevations, and elevation profiles. Alternative information that might be collected include slope, curvature, ridge and drainage patterns, fractals, power spectrum, and surface polynomial descriptors. The non-stereo Landsat approach mentioned collects reflectance information which is a function of the slope information. It is important not to confuse the method of representation of the DTM with the data collected, as the quality of the DTM is highly dependent upon the information inherent in the model, as well as to data degradation resultant from the method of representation.

DTM Representation

Once DTM information has been collected, it may be represented in a variety of compressed or non-compressed formats. The terms format, representation, and structure are used interchangeably here. Keep in mind that most DTM production systems today collect only elevation information, either as discrete spot heights or line profiles. DTM's, however, may be represented by elevations, contours, tessellated polygons, surface polynomials, fractal numbers, slope maps, power spectra, convolved displays, etc. Each representation is some approximation to the data collected, and is done to satisfy the storage and input requirements of the DTM user.

ACCURACY CONSIDERATIONS

The term accuracy related to DTM's means many things to different people. It would be appropriate to define accuracy in terms of geomorphological quality, precision of information, positional accuracy, data commonality, data compatibility, and compression (representation).

Geomorphological Quality

The geomorphological quality of a DTM is the degree to which the DTM represents the actual landform. This concept is extremely difficult to define quantitatively. It considers all of the statistically measurable quantities of the DTM as well as the visually apparent anomalies, texture, and fit to the actual landform. Forstner (1983) presents a good discussion on sampling interval and form of data collected on the quality of a DTM. He presents evidence that demonstrates that slope and curvature information are extremely important in the quality of a DTM. Note however that most DTM production systems do not collect this information.

Faintich et. al. (1982) demonstrate that variations in production such as different types of equipment, source scale and type, etc., produce a variety of textures and anomalies in DTM's when the pieces are assembled over large cells of data. Although such DTM's may meet numerical accuracy requirements, the overall quality of the DTM is affected by the non-uniform appearance.

Precision of Information

The precision of the data described by a DTM is a statistical representation of the primarily random error or noise in the model. Precision is generally determined by statistical comparison of repeated measurements and relates to the quality of the production process.

Positional Accuracy

Positional accuracy of a DTM is a measure of all errors with respect to a fixed (absolute) or relative (local) coordinate system. Such errors include horizontal and vertical displacement, rotation of axes, and non-linear differential scaling/warpage in any direction. Systematic errors can be described by a seven parameter non-linear error function:

$$\varepsilon\ (X, Y, Z, \omega, \phi, \kappa, S);$$

where: X, Y, Z are translational errors;

ω, ϕ, κ are rotational errors;

S is the non-linear scaling error.

It is not always a simple matter to determine for a single point in a DTM which of the seven parameters is contributing to a positional error, but there may be global solutions for the entire DTM.

Data Commonality

Data commonality is the degree of congruence between different DTM's; i.e., the degree to which two DTM's have the same parameter values for the same geographical location.

Data Compatibility

Data compatibility is the degree of agreement between different DTM's; i.e., the degree to which two DTM's have parameter values within the precision tolerances of each other for the same geographical location.

Compression (Representation) Error

Once DTM information is compiled, further processing may add additional errors into the DTM when it is compressed or reformatted. A variety of compression algorithms have been developed. Additionally, various structure transformations have been used for user specific requirements. Jancaitis (1977) developed a methodology for the transformation of uniformally gridded digital elevation values into coefficients for polynomial surface patches. Jacobi and Kubik (1982) and Frederiksen et. al. (1983), address the problem of using fractals to describe terrain roughness. Several researchers have investigated Fourier transformation of DTM's (see Frederiksen, 1980). Faintich et. al. (1982) consider DTM's convolved with a variety of filters. Various aircraft simulation scenarios tessellate DTM's into best-fit triangular patches. (See Bunker, 1974.) At best, these transformations are zero error in nature; i.e., the original data can be reconstructed without any loss of information. Simpson (1979) investigated a variety of compression techniques and found that for large areas (one degree square cells) zero error compression was at least 4:1 and as large as 10:1 in certain regions. The 4:1 zero error compression ratio seems to be a common finding among other investigators. Many of the above mentioned transformations, however, are certainly not zero error in nature, and ~~the~~ loss of information can be statistically described, usually by maximum and standard deviation or by bit significance lost.

Cartographic Versus Photogrammetric DTM's

A further consideration must be the source of DTM information and the resultant impact upon geomorphological quality and numerical accuracy.

Cartographically produced DTM's all suffer from the same problem. Inherent in all cartographic DTM's is the fact that there is not any information collected between contour lines except for the knowledge that the terrain does not vary enough to produce another contour line. If the contour line data is to be used for other than automated chart purposes of contour line regeneration, then additional data points are usually required. Independent of all horizontal and vertical accuracy considerations, the production of terrain information between contour lines requires a model or interpolation algorithm to be supplied to the process. Although several advanced techniques have been developed (e.g., Clarke et. al. 1982, and Davis et. al., 1982), they all suffer from the same paradox: the proper model to use for interpolation is the same one the algorithm is trying to produce, i.e., the actual terrain model, and any other model only approximates the actual model and will produce either inaccuracies or anomalies, or both. This should not lead to the conclusion that cartographic DTM's are not useful. It does point out, however, that DTM data should be collected using parameters and representations that match usage requirements as closely as possible in order to minimize interpolation between collected data points.

The advantage of photogrammetric DTM's over cartographic DTM's is clear. The former relies upon rigorous mathematical computation based upon the geometry of the sensor and the surface, whereas the latter relies upon an approximation model of the surface. Photogrammetric DTM's, however, suffer from additional instrument and processing errors, but are better mathematically modeled and controlled. The non-stereo approach using LANDSAT has mixed considerations.

Another significant problem in the photogrammetric production of DTM's is the "Bald Earth" problem. The DTM should be representative of the land surface after removal of natural landscape and manmade cultural features. In any manual or automatic photogrammetric DTM collection system, vegetation, such as trees, and buildings, etc., do not always allow the elevation of the ground to be measured. For example, an elevation profiling scenario in an analytical stereoplotter may well pass through an isolated tree, but will probably lose its ability to "see" the ground in a dense forest area, and the resultant DTM will probably have a portion of the tree height combined with the ground elevation. In a very dense urban area, a nearly vertical view is required, otherwise the street level may not be visible between buildings. The inability to see the "Bald Earth" needs to be considered in all DTM accuracy estimates.

DTM ANALYSIS

A number of investigators have developed methods for DTM accuracy assessment. Although not written for cartographic application, Ripley (1981) presents a good collection of generic techniques for the analysis of two dimensional numerical data, including sampling, smoothing, interpolation, and analysis. Faintich (1983) presents information on interactive analysis of DTM's, and newer results are presented in this paper.

The Defense Mapping Agency (DMA) produces digital data bases that describe the physical appearance of the surface of the earth. These data bases include, but are not limited to, terrain elevation, culture including landscape characteristics, and vertical features. This data is collected from digitized source maps, from optically or digitally correlated stereopairs of photographic imagery, and from digital multispectral sensor data. A dramatic impact has been made in the ability to analyze these digital data bases by applying state-of-the-art digital image technology processing and display concepts. These include a variety of color and/or black and white displays of not only intensity/color coded matrix data, but also image processed data using specialized convolution filters, texture discrimination, and special color representation techniques. In addition, computer generated imagery from these data bases serves as a final analysis tool.

For purposes of quality control and data base applicability investigations, DMA has developed the Sensor Image Simulator (SIS), a very high speed data base edit station and static scene simulator that allows for interactive query and manipulation of individual features in the data base displays and/or simulated sensor scenes to determine the corresponding data base elements responsible for the simulated features (see Figure 1). The SIS was installed at DMA in 1981, and plays a key role in determining the applicability of prototype data bases for use in advanced training simulators, as well as to ensure the quality of, and coherence between the various digital data bases prior to new data insertion into the master cartographic data base files.

SIS Concept

The natural evolution of sensor simulation at DMA led to the design and fabrication of the Sensor Image Simulator (SIS), a dedicated mini-computer-based image processing system capable of performing simulations in an interactive mode.

The Sensor Image Simulator performs five major functions:

1. Digital Data Base File Input and Output.

2. Off-Line to On-Line Data Base Transformation.

3. Sensor Simulation.

4. Interactive Data Base Editing.

5. Software Development and Maintenance.

The SIS brings together, in a self-contained integrated hardware/software facility, a significant capability to evaluate the digital data bases. All operations are conducted under interactive control. Both the software structure and operations sequence reflect a top-down implementation philosophy wherein principal control functions are resident at the top of the hierarchy and functions concerned with processing individual data elements are the lowest. The system is implemented in such a fashion that future changes in processing can be accomplished at the highest level of system software support.

Technologies and Results

In order to perform interactive analysis of the digital files, digital terrain elevation data may be used to generate color coded contour plots and line profile displays (see Figures 2 and 3). An alternative is to color code the matrix terrain data directly (Figure 4). While analysis of these matrix image displays is superior to trying to perform analysis by visual inspection of the data in printed numerical matrix format, they only provide for a low spatial resolution analysis capability. Shaded relief display with variable illumination adds additional information for analysis of all types of matrix data (see Figure 5) and is particularly meaningful for cartographic data because of the relationship to the physical world. Higher spatial resolution analysis of the shaded relief display may be gained by applying photogrammetric models to generate pseudo-stereo-pairs of images in which spike points are apparent under stereoscopic analysis. These techniques, used singly or in combination, allow for data base analysis far superior to techniques of a decade ago, but they are not enough.

In order to perform high resolution anomaly analysis of data bases for the purpose of either quality control or information gathering, advanced techniques are required. These techniques include convolution filtering, specialized color representation, digital fourier analysis, and computer generated sensor simulation.

Convolution filters have been used very effectively to enhance matrix data to show processing anomalies as well as where data has been merged from different production equipment, different stereo models, different production methods, variable requirement specifications, and even from different analysts. These types of filters are used extensively by the image processing community to detect edge differences, and then to reapply the differences to sharpen the original image. They also have been shown to be a powerful tool for the analysis of cartographic data bases (see Figures 6 and 7).

For the purpose of determining compatibility between data types, such as between digital terrain and culture data, simple color coding and overlay in Red-Green-Blue (RGB) space may not be sufficient. A more powerful technique employs coding each data type along an Intensity-Hue-Saturation (IHS) axis and then converting from the IHS space to RGB space prior to display. Since the visual perception process can distinguish variation between IHS, the data types can be overlayed without a merging of colors, and therefore, without an information loss. Various cultural thematic displays may be overlayed on variably illuminated terrain displays (see Figure 8).

The DMA is beginning to explore the potential of using digital fourier analysis for filtering of the terrain data. The capability of digital generation and interactive display of two-dimensional fourier transformations of the terrain data in conventional frequency vs azimuth as well as profile displays are shown in Figures 9 and 10. A variety of digital pairs and rejection filters such as shown in Figure 11 have been applied to these transforms for anomaly removal.

Finally, and probably unique to cartographic data bases, is the technique of computer generating landform scenes as seen by various visual and electro-optical sensors. This allows for a final quality control analysis of information content, and also has been very valuable in the definition of data base requirement specification (see Figures 12 and 13). The impact of this interactive system development to data base display and analysis has been enormous. Not only has there been a greatly increased capability for the degree and sophistication of quality control, but there is an associated cost savings in both the quality control review process, and in the resultant expense of using cartographic data bases containing anomalies.

In the realm of automatic analysis, DMA has investigated seven parameter adjustments for mosaicing small DTM's into large area DTM's. This is accomplished by identifying common or compatible points in different models and making interactive least squares adjustments between the models. The parameters that are influenced most in the adjustments are a function of the particular production scenario used in the generation of each model.

FUTURE NEEDS FOR DTM DEVELOPMENT

As we progress into the world of more sophisticated remote sensing platforms, the variety of sources for DTM production will grow. Surely the development of algorithms to exploit these sensors will be accomplished. Perhaps the integration of data from various sensors will provide some capability to solve the "Bald Earth" problem. One factor is almost certain; that is, the processing of these multi-spectral remotely sensed images will be done in a digital environment, using advanced digital correlation and exploitation algorithms. Along with the analysis of these images in the digital world comes the potential for extraction of not only elevation information, but also slope, curvature, and surface function information to yield a much higher quality DTM from a geomorphological viewpoint.

Still the task remains to define what is meant by quality and accuracy of DTM's. We must strive for international definitions and standards of measurement. Until this is done, individual researchers will develop analysis and measurement techniques against different baselines. A clear objective is required for concentrated development of automatic accuracy measurement, anomaly detection, error removal, and model adjustments.

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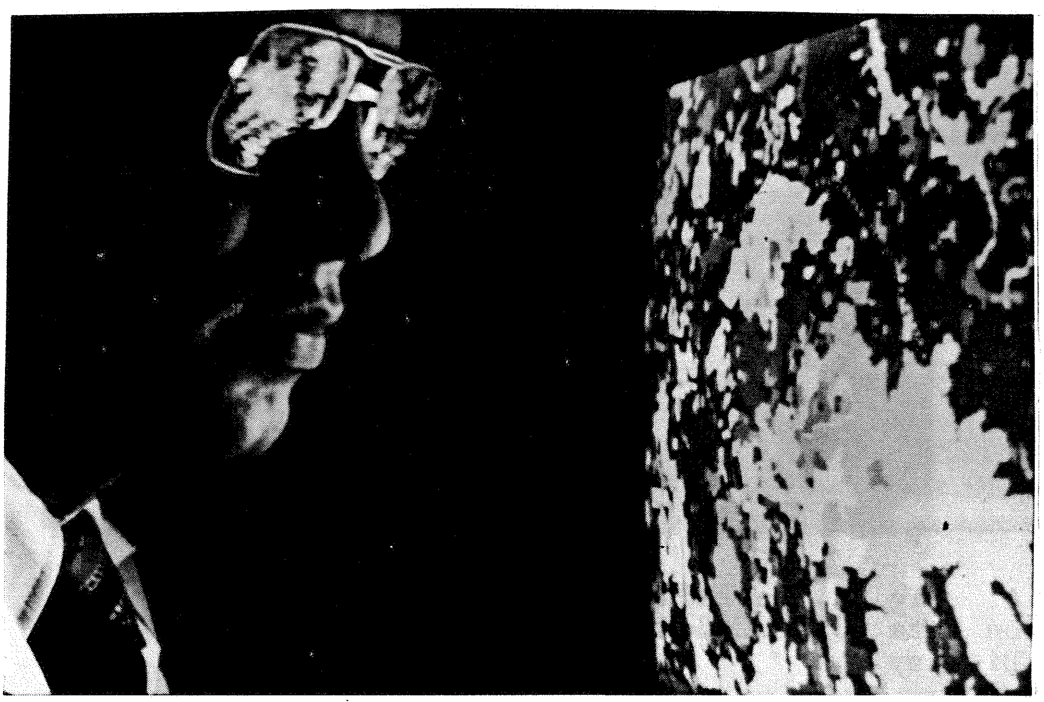

FIGURE 1. Sensor Image Simulator Work Station

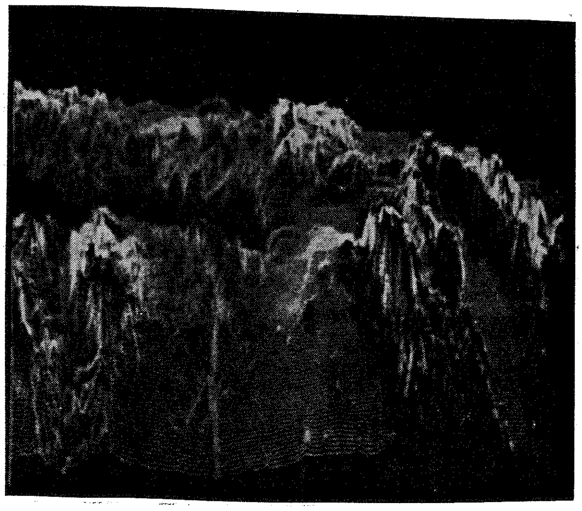

FIGURE 2. Digital Terrain Elevation Data Profile Display

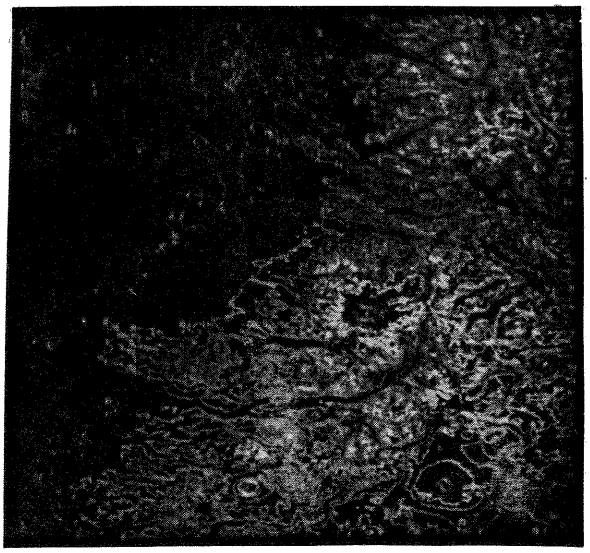

FIGURE 3. Digital Terrain Elevation Data Contour Display

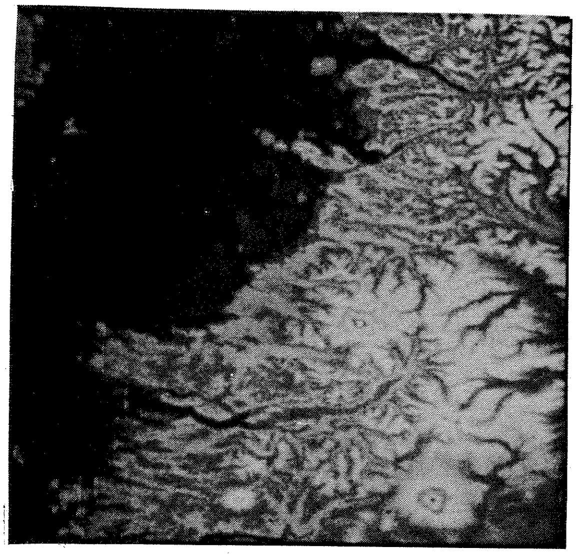

FIGURE 4. Digital Terrain Elevation Data Color Coded Matrix Display

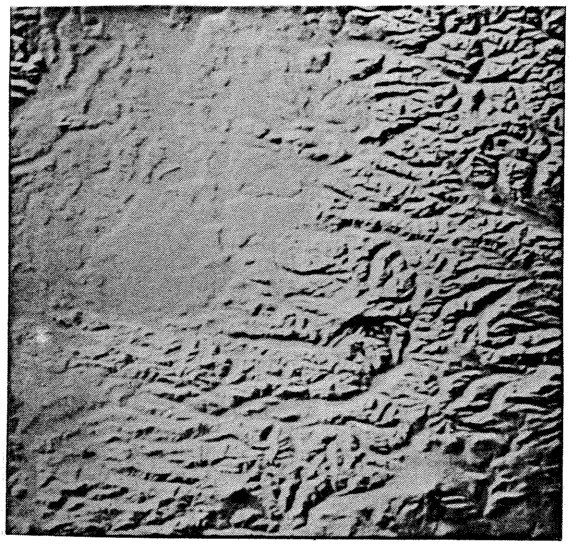

FIGURE 5. Digital Terrain Elevation Data Shaded Relief Display

FIGURE 6. Digital Terrain Elevation Data Gradient Magnitude Display

FIGURE 7. Digital Terrain Elevation Data 5 x 5 Edge Filter Showing Inserted Data Patch Anomaly

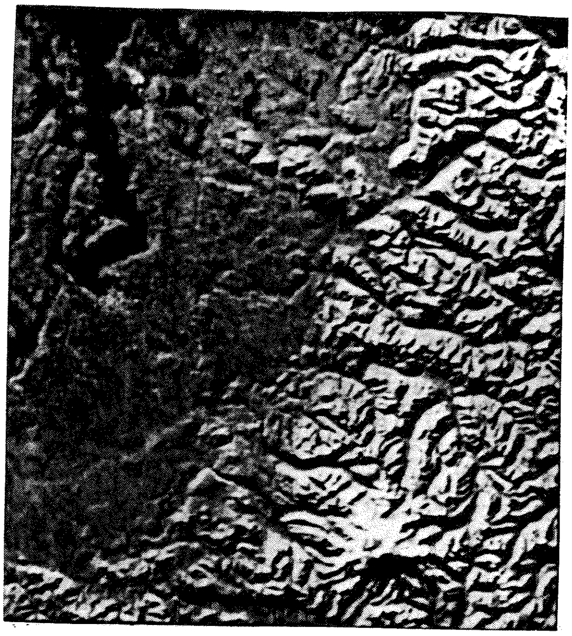

FIGURE 8. Intensity-Hue-Saturation Display Showing Terrain Data with Cultural Thematic Overlay

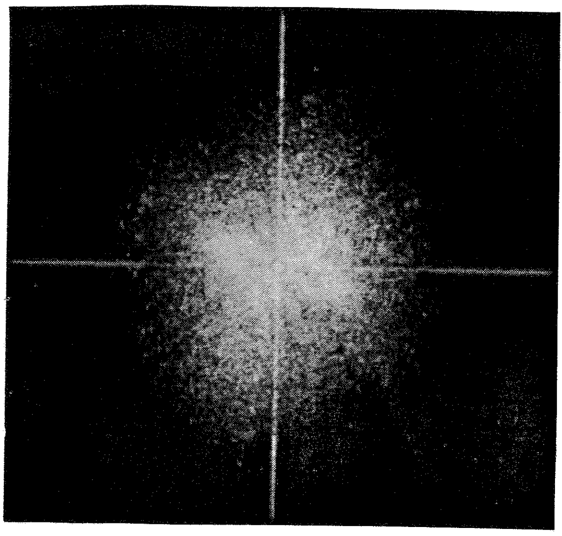

FIGURE 9. Digital Terrain Elevation Data Fourier Transform Display

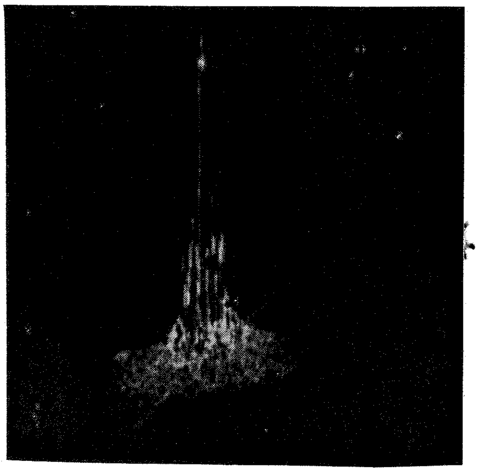

FIGURE 10. Digital Terrain Elevation Data Fourier Transform Profile Display

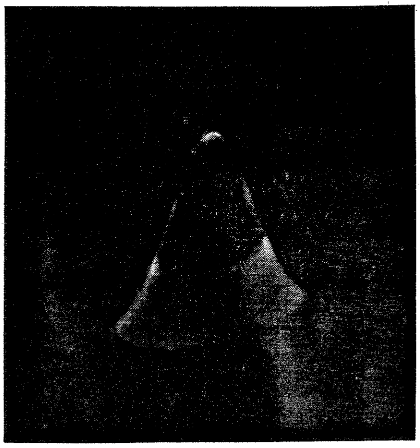

FIGURE 11. Digital Exponential Pass/Rejection Filter

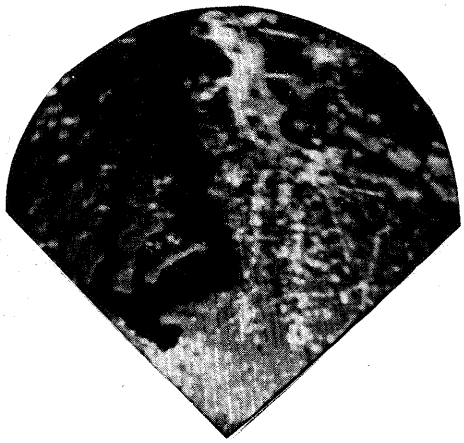

FIGURE 12. Computer Generated Radar Scene from Digital Terrain and Culture

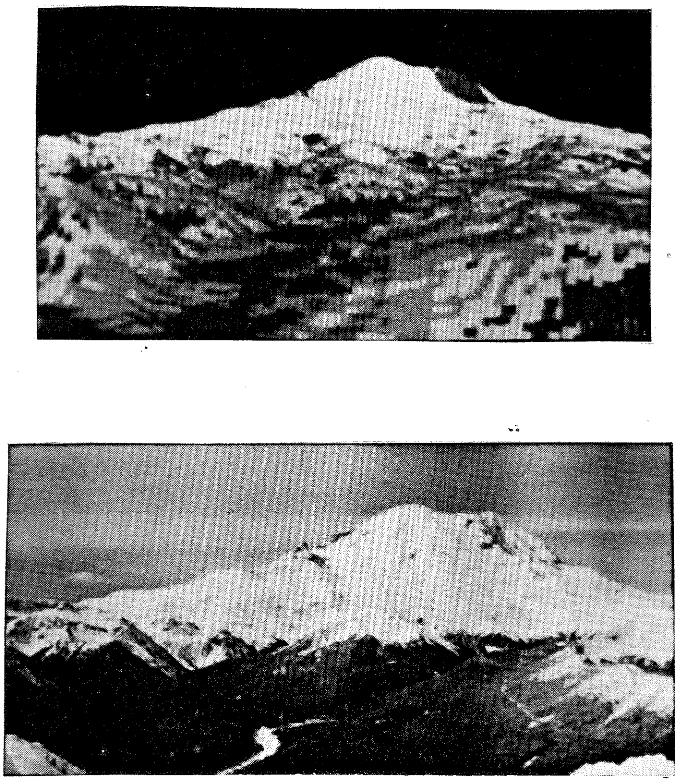

FIGURE 13. Computer Generated Visual Scene (top) Compared With Actual Photograph (bottom)