- DRAFT -
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MAPPING BY COMPUTER

AN INTRODUCTION

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- D R A F T -

Mapping By Computer

1 Maps and Cartography

Cartography is the blend of science and art used in making maps. A map is a representation (usually on a flat surface) of the whole or a part of an area. The area being represented is usually part of a curved, 3-dimensional surface, most often the surface of the earth.

The artistic aspect of making maps involves things like style and aesthetics, the selection of some options and the rejection of others, the collection of choices defining the content and form of the finished product. Art is involved in the choice of line types (solid, dashed, hashed...), thicknesses and colors. It includes the selection of media, map title and legend, ink, point symbols and area fill patterns or colors. The choice between emphasizing some features and not others is to some extent an artistic decision.

Though some differences exist in their implementation, these artistic decisions are common to both manual map-making and computer cartography, the process of making maps by computer. In manual map-making, art extends to the physical construction and implementation of these decisions, the transfer of mental images into the final or intermediate physical form of the map.

This part of the art of making maps has been largely converted to science in computer cartography. Most dramatic is the change in the tools used for production. Tools used in manual cartography include the hand-held pens and scribing tools, straight edges, compasses, french curves, erasers and opaquing brushes. In computer cartography, the tools include the computer, computer programs, monochrome (single color) and multi-color graphics terminals, manual and automatic digitizing tables, and line-drawing (vector) or dot (raster) plotters.

Science which is required in common by manual and computer cartography is the science used to gather or create the information to be portrayed on the map. Collection of map data may involve the use of computers as most scientific work does today, but at this gathering stage, the work is analytical science and not yet in the realm of the cartographer. At the time when the gathered information passes to the cartographer, original data in digital (computer) form may be far more advantageous to the computer cartographer than to the traditional cartographer.

In computer cartography the need for human comprehension of the processes of map construction and production remains. For the "high-tech" cartographer the knowledge required to operate the manual tools for map production is replaced by an even greater requirement for understanding of maps and the computer environment.

Arthur Robinson, in his Elements of Cartography (1984, 5th Ed., John Wiley & Sons, NY, p.4) refers to the map as an "instrument for recording, calculating, displaying, analyzing, and in general understanding the interrelation of things in their spatial relationship." In this it should be clear that the computer can perform or assist in performing the functions of recording, calculating, displaying and analyzing maps. The understanding function remains that of the people who are interested in the map.

It is also clear that the digital map (the computer representation of a map) enhances the above functions. While the digital map can always be used to (functionally) duplicate the original graphic form of the map, its digital form can also provide for endless extensions of calculation, forms of display and types of analysis. The digital map will also support functions never dreamed of with paper maps (see Advantages of Computer Cartography).

There is no restriction on the content of maps as defined above, but in practice there are three fundamental classes of maps (Robinson, p.7-10). These classes are general maps, thematic maps and charts. General maps are those which display the spatial relationships of a diverse set of geographical features such as roads, boundaries, hydrology and topographic (elevation) contours. Thematic maps usually display varying magnitudes of a single attribute (population, rainfall, temperature, income) with each unit area displaying a single, discrete value or range of values. Finally, charts are maps designed for navigation. Unlike other maps, charts are usually intended to be written upon.

All three classes of maps have been produced or approximated with computer cartography. Each has been done well by one computer cartography system or another. Unfortunately, no one system has been designed which can handle all aspects of producing all three classes of maps well.

Systems have been designed which can perform basic functions necessary for all kinds of mapping. A valuable system design characteristic is the flexibility to expand to meet the needs for additional mapping functions through addition of new programs rather than through rewriting of the entire system.

The past three decades have witnessed the conversion of cartography from a strictly manual operation into one highly dependent on the computer, computer programs and associated high-technology machinery. The infusion of digital technology was as predictable and inevitable in cartography as it was in virtually every other field. This was due to the promises of increased productivity, faster turnaround, greater flexibility and (perhaps) even lower cost in the long term.

From this infusion of technology grew a field which joined specialists from cartography, other geosciences, computer science and engineering. Much effort was required to design, build and improve the specialized hardware (machines) to perform the conversion of analog data such as printed or drafted maps, into computer form (digitizing, done on a digitizing table or digital scanner), graphic display of map data (representation of maps on a terminal screen), and plotting (the computer controlled transfer of processed digital map data back onto paper or other non-digital media via a digital plotter).

These hardware developments were necessary for production of maps by computer, and have found use in numerous other fields. By themselves, however, they were not sufficient for the development of computer cartography. The specialized hardware could perform nothing without the development of computer software (programs) to instruct the machines on how to process the data input. Due to variances in hardware, applications, resources, philosophies and other factors there emerged almost as many different systems (the sum total of the hardware, software, procedures and local data) for computer cartographic applications as there were people desiring them.

Because of the variables in the development process, many basic functions overlap among specialized computer cartographic systems. However, it is the nature of most computer systems that a significant price must be paid to transfer capabilities from one system to another. Thus, the extension of capabilities beyond existing in-house systems is frequently met through acquisition of an additional system with the desired specialized capabilities. Unfortunately this is usually accompanied by significant duplication of basic capabilities among systems.

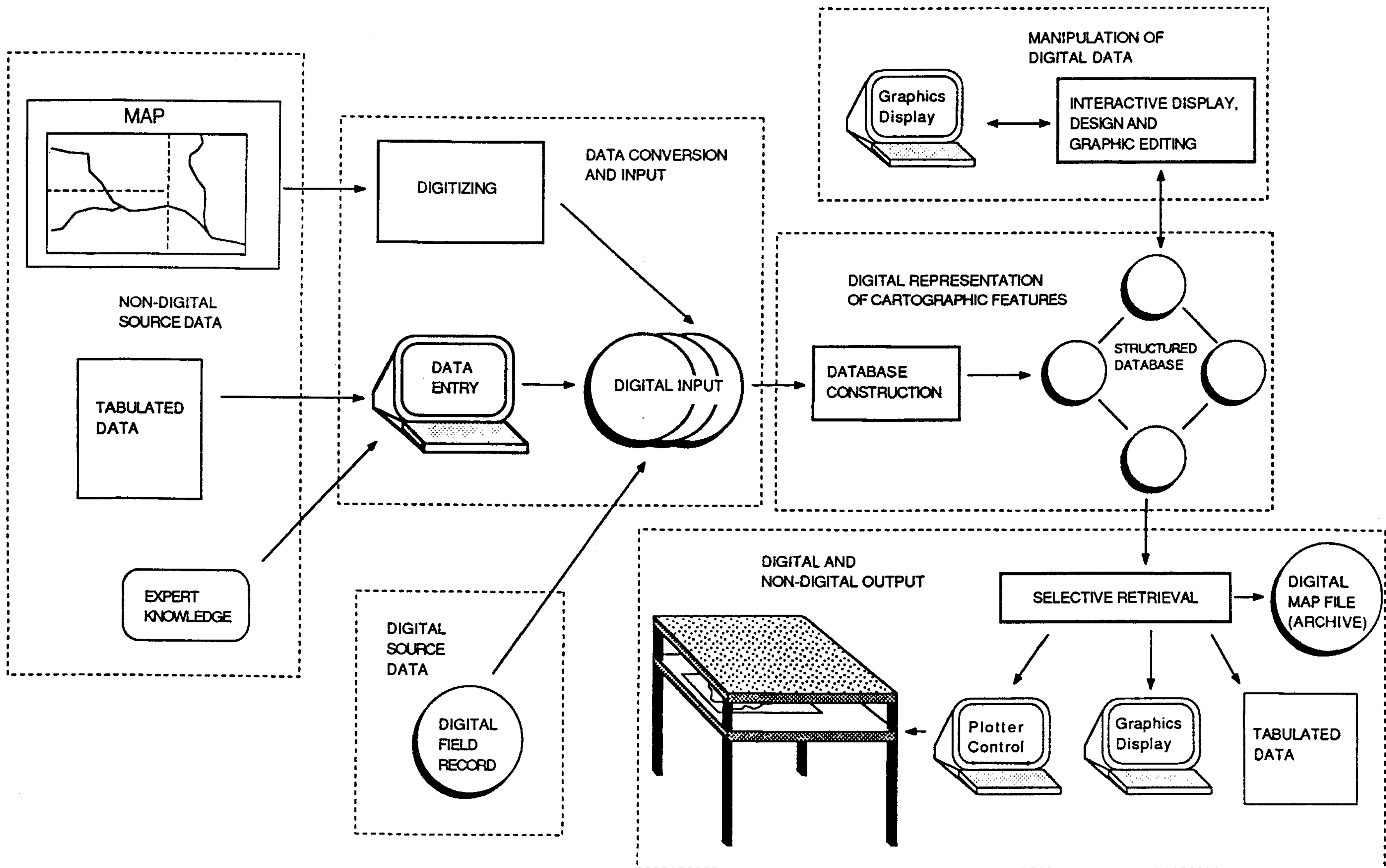
The geoscientists and computer scientists responsible for developing the software and operating procedures have referred to the new field by many different names. Included are automated cartography (popular and associated with the annual international AutoCarto conference in the field), computer cartography (to the point), computer-assisted cartography (more precisely correct), map data processing (perhaps from the image processing contributors), and geographic data processing (no doubt from the geographers). These terms are considered interchangeable, but computer cartography and computer-assisted cartography will be used here.

These names generally refer to the broad area which applies digital technology (computers, digitizing hardware, graphic display terminals and plotters) to the production of maps or other forms of display of spatially related data and to the preparation and analysis of that data.

Some generalized systems designed to handle multi-dimensional, or spatial, data have been referred to as spatial data management systems. They clearly provide functions distinct from those of traditional cartography or computer cartography systems. However, their cartographic functions may be insignificant or sub-standard. Systems which provide standard map-making functions as well as full data management capabilities (add, delete, edit, display, analyze, query...) on data describing attributes associated with spatial location are referred to as geographic information systems (GIS). Spatially referenced attribute data might include such information as depths of wells, magnitudes of earthquakes, diameters of pipelines, or soil type. Geographic information systems will be discussed briefly in the final section of this report.

A computer cartography system must include a basic, minimal set of capabilities. At the input stage is the capability to convert to computer form the information available from non-digital source documents. This may involve digitizing map features from source maps, entry of data from printed records, or entry of quantified expert knowledge. Once the data has been entered into the computer, it is necessary to create a coherent, internal digital representation of the input documents, a structured database. In this intermediate stage, the system must support addition, subtraction, display and modification of the digital map features. On the output or production end, the system must be able to retrieve data selected by area and content for new map products, with the ability to produce copies which are functionally, if not literally, identical to the original input document in one or more forms.

A BASIC COMPUTER CARTOGRAPHY SYSTEM



3 Types of Systems

There exist many variations in system design to support computer-assisted cartography. Within this variety of systems a dichotomy exists which is tied to alternative technologies for the capture and display of cartographic data. This technological factor divides the systems into two separate groups which are distinct in every aspect of the process from the initial philosophy of the map data structure to the hardware, software and procedures to perform the basic computer cartography functions.

In the vector approach to mapping, all map features are considered to be points and lines, where lines are defined by the sequence of points which approximate the original map line with as little error as possible. Areas are defined by their (closed) linear boundaries.

The vector approach employs hardware which allows the operator to follow lines and to digitize points along those lines, similar to the view of a draftsman or a manual cartographer. The technology of the output device, called a vector plotter, was developed originally to support automated drafting. Display devices were developed from the oscilloscope or cathode ray tube technology in which a beam of electrons is magnetically aimed to draw lines on a screen. The image is retained on the screen (tube) in this storage technology until the user requests a fresh view.

In the raster view of mapping, the map is defined as an ordered set of rows (rasters) of evenly spaced dots (called pixels, for picture elements), covering the area of the original map. The dots are coded to indicate the color of the map at the dot's location, or at least to show a black or white (feature or no feature) indication.

Hardware technology for raster processing was borrowed directly from that of the television in which scan lines of black and white or colored dots produce the TV image. It therefore required little time to perfect. Both the digitizing and plotting hardware for raster processing required considerably more development, but have become acceptable and even preferable for many applications. Raster digitizing involves a laser scan of color-separated overlays (which may cause some problems) and requires CPU-intensive post-scan editing which is expensive in time and money. Raster, color plotting devices come in many forms and range widely in performance and cost. Improved quality combined with cost reductions have effectively made newer color raster plotters more practical for many cartographic applications, especially where other kinds of color graphics applications may also be desired.

Considering the cost of hardware and software development, acquisition, and operation for raster-based systems, one may conclude that such technology might never have evolved had it not been for the ever-increasing use of satellite imagery for map-making. Satellite imagery was used in many ways prior to the Landsat (and other) images which have become so well-known today. Furthermore, raster processing might still be in its infancy were it not for the development of the discipline of image processing (the science of extracting, editing, analyzing and otherwise processing digital pictorial images by computer), which began long before mapping applications from satellite imagery.

Both the raster and vector approaches have advantages and disadvantages. One historic problem with the raster approach is the amount of computer memory space required to represent a map. The raster view of the map is one of a set of rows of dots covering the area of the map. In the raster view, dots which represent the absence of features must be maintained along with dots which do represent real map features. Thus, maps with sparsely located features require the same (large) storage space as those with very dense features.

There are also many advantages to the raster approach. One is that raster processing has (nearly) always supported a color display of map data. Such a display not only looks more pleasing and portrays map features more effectively, it greatly enhances areal editing functions and provides an in-house color-proofing capability (a "dress rehearsal" to check color compatibility).

Vector maps have traditionally provided clear, sharp images with excellent registration (matching of the separate overlays produced for the four-color printing process). The vector approach produces publication-quality maps by creating high-quality color separations for the traditional map printing process. Furthermore, maps represented in vector form store a virtual minimum of information compared to their raster counterparts. It is this output quality and data efficiency which have kept the vector approach going, along with lower cost and ready availability. Finally, the fact that the vector approach to the structure of map data can be easily compared to familiar manual drafting concepts and methods in a "common sense" or "natural" way lends to the continued preference of the vector method over the more complex raster approach.

There are some significant disadvantages to the vector system. Among them is the storage technology for display of the map data. In the storage technology, the map is displayed in whole or in part on the storage tube and does not change until requested by the user. At that time, the screen is erased completely and the entire map is redrawn. This can be very time consuming for complex maps.

In raster methods, a different display screen (based on the television) is used. On these raster or refresh screens all dots are individually and continually updated with current information. Individual map features may be updated as they are changed by the operator without erasing or redrawing any other features. This update procedure occurs continuously and is performed by the hardware of the display terminal, with update information coming from the computer and the software.

Another distinct difference between the two kinds of screens is that the raster terminal can (usually) display more than one color, as selected by the program and user. This means that different feature types may be represented as different colors and are thus easily distinguished. On the other hand, the vector terminal generally provides a single color for display of all features. Different map features must be distinguished by alternative line types (with resulting increases in display time and storage requirements), by masking out all but the desired features, or by some other technique in the software.

In both systems there are techniques which may be used to minimize the effects of some disadvantages, but many relative advantages and disadvantages still exist between the vector and raster approaches. What can be done in one system, probably can be done in the other. It may not be quite as good, or as fast, or as inexpensive ... at least not today.

With all the systems in use today and all the kinds of applications desired for computer cartography systems, it is clear that there exists no single system that can do all things. Cartography is art as well as science, and both art and science grow and change. Largely for this reason, any large computer cartography system must inevitably be a living system, requiring constant change, correction and improvement. As long as it is to be used in a robust environment by scientists and artists, the need for new and different mapping techniques will always be present.

As a natural result of the inflexibilities associated with the vector/raster dichotomy, there exists a small but increasing group which adheres to a third approach to computer cartography. This approach is the pragmatic one: take from the vector and raster approaches that which works best for you - build a hybrid system of components from both. A relatively common modification of otherwise totally vector systems is the addition of color raster display terminals and color plotters and associated data conversion software. Of course, for some the goal has become to make a system better than both. There is even a term for the data structure or map unit in one such system: the vaster, sort of a hybrid term for a vector-raster.

4 Introduction to Hardware

The hardware requirements for a computer-assisted cartography system will vary greatly depending on the applications involved. For example, there are some systems based on the microcomputer which can perform many cartographic functions. Given a modest plotter, such systems may produce their own plotted maps.

In a general sense, the hardware required for computer cartography is related to the basic functions which are inherent in such a system. These basic functions were discussed briefly at the conclusion of Section 2. Non-digital or analog data (base maps or overlays, tabulated data, or expert knowledge) critical to the desired end product must be converted to digital form and all digital map data entered into the system. Within the system, the data must be organized into a structured database which provides a logical digital representation of cartographic features. Once organized, the data may be displayed for interactive editing and map design. This function involves access of the structured database for analysis and modification of the map data. Finally, data must be retrieved, prepared and output to make maps. To support these four functions, there are four basic areas of hardware.

(1) In the first function of data conversion and entry, it is the conversion process which poses the significant hardware issues. Map data conversion is accomplished through the process of map digitization. The software and hardware necessary to accomplish this process constitute the digitizing system. In a vector system, this process occurs on an electronic digitizing table (or smaller tablet) containing an imbedded grid of closely-spaced wires. The user positions the crosshair of a digitizing cursor above the desired point. By pushing a button on the cursor, the user generates a magnetic field around the cursor. The magnetic field activates currents of differing strengths in the wires of the digitizing table (strongest at the cursor location). These currents are sampled and compared to determine the location of the cursor in (x,y) table coordinates. Data entry is accomplished when this location is sent to the computer.

Digitizing in raster mode requires a more complex and more automated system in which equally spaced positions of each row (raster) of the map are sampled to determine the presence or absence of map features. The most common device is a rotating drum on which the map overlay is placed. Normally only one feature type is done at a time since different colors confuse the system. As the drum rotates, a laser beam scans each row, recording or transmitting the sequence of digital bits which represent the on/off value found for each spot on the map. The transmitted sequence of values then represents the digitized map for the given overlay.

In both vector and raster digitizing, there is a terminal connected to (or in parallel to) the digitizing device for communications and to initiate operations. In vector digitizing, there may also be a graphics display terminal to show the progress of the operation. In some settings, this terminal may be used to perform interactive digitizing and corrective editing at the point of the digitizing process. Such a terminal may operate either in vector or raster mode.

(2) Organization of the data into a digital representations of the cartographic features is a function performed by the computer and the brains of the system designers and programmers. the most efficient database structure is dependent upon the specific computer operating system, the choice of vector or raster technologies for other functions, and the intended applications of the system.

(3) The display of the digital map is performed on a graphics display terminal. This display is used for many functions including modification or addition of map features and attributes, verification of color compatibility prior to publication, map design, editing color separations for publication, and examining the displayed "electronic" map for the same purposes as one examines a paper map. The functions themselves are carried out the computer hardware and software system and the operator, with the display terminal providing the communication link between computer and operator.

The display functions may be achieved through either a vector or raster graphics display terminal. The vector terminal draws from point to point, displaying only the map features on the storage tube. The vector terminal has no memory of the features it has drawn and can not reproduce the map image without repeated instructions from the computer. The image (usually) exists in a single color and individual features may not be updated without the entire image being redrawn by the computer. The line work of the storage tube is precise and fine.

The raster terminal displays full-color images of maps, displaying pixels (from "picture elements"). One pixel on the display screen corresponds to a single dot in the line or raster, and displays a single color. The technology for raster terminals comes directly from that of the television with its high frequency redrawing or refreshing of the screen. With the graphics display terminal the refreshing pattern or image comes from computer memory rather than a broadcast signal as in a TV. The pixels of the image on the screen are being updated continuously from this memory. Map features or individual pixels in the memory may be modified by the computer without requiring a complete image update.

Lines on the raster terminal may look jagged like a set of steps. Edges that serve as boundaries between different colored areas may be similarly affected. This unwanted effect, known as aliasing, is the result of the raster representation of straight lines, often with too few pixels of too large size. The number of pixels in a row and number of rows of pixels in the screen determines the resolution, which is a measure of the density of pixels in a unit area. The aliasing problem may be reduced through increased resolution and through special software techniques which attempt to reduce the distractive effect by altering the colors of the pixels involved.

Along with the graphics terminal, (assumed to include a keyboard), are two additional items of hardware which can greatly enhance the utility of the graphics terminal.

One item is a graphic input device, connected to the graphics terminal to allow the user to point to features and locations on the screen by positioning a screen-displayed crosshair cursor (a vertical and a horizontal line segment forming a "+" to identify a unique screen location). The position of the on-screen cursor is modified by movement of a physical input device. This input device may be a thumbwheel cursor (one vertical and one horizontal wheel), joystick (as in an airplane and now commonly associated with video games), digitizing tablet (a small digitizing table) , or mouse (a roller ball device also common with video games). Software may use the selected point to identify individual features of the map, or to create new ones.

The second device, a hardcopy unit, is used to make a direct, immediate paper copy of the image displayed on the graphics terminal screen. From the monochrome display of a vector terminal a black and white copy is usually produced. The color image of a raster screen may be copied in black and white or in color. In some cases the hardcopy colors will not be totally consistent with the screen colors.

The hardcopy is initiated by the push of a button or made under control of the software. In most instances the copy (typically page-sized) is not the desired final product, but may serve as an intermediate product. As such, it is useful for checking content completeness, color combinations, layout and accuracy. In some cases this copy may serve as a final product. Techniques used in the monochrome hardcopy units are fairly traditional. In the color hardcopy units, techniques are similar to those used in the color plotters described below.

(4). The output function is performed by a digital plotter. The plotter produces finished maps or intermediate separations for four-color publication. There are vector plotters of various kinds, including flatbed and drum plotters, which produce line drawings as instructed by the software. For line drawings, the plotter may use multiple pens or overlay plots (as created by the software) to produce different colors for different features and may vary the size of the pens for different line weights.

In vector plotting, different media may be used at varying cost to produce different effects. A two layer mylar (opaque on clear) called scribecoat is cut with jeweled pens as the first step in creating printing materials.

Area coloring may be approximated by using color shading lines, created by the software. Annotation, also generated through software, may be very high quality in vector plotting, as is the other line work.

Color, raster plotters have reached a level of development that has brought them into a useful range in many applications requiring high quality. Though they remain quite expensive (as do high quality vector plotters), their ability to directly plot solid areas of (user-defined) colors is highly desirable, and with increased resolution (which reduces aliasing and improves colors) the line quality has improved to acceptable levels. Raster color plotters are now fully capable of producing acceptable final products for many applications.

There are many technologies for producing color plots. In general, the paper is moved past a coloring head which has the ability to transfer or cause the transfer of a dot of colored ink at all selected dot locations (pixels) for a single line (raster) of the map at a time. As each new line approaches the head, new information describing the on/off pattern for the line is given to the head. The image is treated in this fashion for all the lines of the map image and for each of the primary colors, to produce the colors selected for the whole map.

Perhaps the best aspect of the modern color plotters and color graphics terminals is that while they do operate in raster mode, it is only an internal restriction. Both the terminals and the plotters now contain their own sizeable memories and processing capabilities, and both can convert a vector image into a raster image, usually in reasonable time. In both cases, there are some limits on the local memory and thus on the amount of map data which can be so handled. This restriction seems to be more severe in the graphics terminals than in the plotters, but where restrictions are not too severe, the gain in functional capabilities is significant and desirable.

The significant difference between vector and raster plotting hardware has been the trade-off between the direct color of the raster system and the publication-quality line work of the vector system. In vector plotting, any map that is to be published will be of very high quality, a level not yet obtainable in the raster world. As color plotter resolution has improved, the higher quality has brought more and more applications into the print-only-on-demand kind of operation. Now the vector world (through rapid image conversion) shares in all the improvements of the raster color plotters, while it retains the advantages of publication-quality vector plotters as well.

The functions of the computer all require the software and usually the intervention and decision-making ability of the operators. Included in the tasks of the computer/people/software "system" are the conversion, communication, construction, modification, addition, deletion, transformation, protection, correction, recovery, organization, selection, collation, reconstruction, annotation, analysis, enhancement and acquisition of map data.

Computing systems range widely from microcomputers to main frame computers. Microcomputers perform sophisticated operations and produce surprisingly acceptable cartographic products. Peripheral equipment like digitizers and plotters now exist in smaller sizes and at reasonably small cost to provide complete functionality (as defined above for the computer cartography system) within a microcomputer environment.

The mini- and super mini- computer systems provide much greater capabilities at much higher speeds to produce much better and more useful products - at much higher costs. Mainframe systems, costing more still, often rely on the same peripherals for digitizing, displaying and plotting as used on the smaller minicomputers. Thus, they provide a significant increase in speed and resources, and may result in much higher productivity for installations with greater throughput requirements, but generate products of no higher quality than can be obtained in a minicomputer environment for comparable costs.

There are some desired aspects for the computing system in a computer cartography environment when significant, sizeable cartographic products are to be produced, including the construction and maintenance of a large cartographic database (direct-access files referencing each other through the direct-access mechanism - the record number).

In these circumstances, the computing system should have a minimum memory size which can allow the computer cartography system to operate well in all extremes of the mix of computing that exists at the site. The processing speeds should be as fast as possible, and adequate secondary storage should be available for the proliferation of mapping files and cartographic databases which is bound to occur. Finally, the basic system should incorporate magnetic tape drives, a high-speed line printer and adequate terminals for all operations.

The computing system need not be a dedicated system for computer cartography operations only, but can be a general purpose system providing services to a multiple-user community, provided its basic resources are sufficient to maintain adequate speed for an interactive (computer operations requiring user input and decision-making) computing environment for its users.

5 Advantages of Computer Cartography

In comparison with the practices of manual cartography, cartography by computer has a number of distinct advantages. These advantages may be categorized by dividing computer cartography operations into "input" and "output" operations and an area in between for "internal" operations.

On the input side, the original art work of drawing or tracing or digitizing lines from a source map is similar in manual and computer cartography. However, the manual artist is generally working directly on the final output product at that point, while the digitizing operator is creating a temporary, intermediate product.

The manual artist may make repeated corrections to the map, which may cause some deterioration in the quality of the map. In the manual operation, this editing ends when the map is turned over for final production, but computer cartography editing may be repeated until complete satisfaction is obtained. Some errors made during manual compilation may require restarting the map from the beginning, but computer editing errors usually result in no more loss than the current edit session. There is no limit to the addition, deletion or modification of map data in the cartographic database.

A second advantage of computer cartography is that of accuracy in location of features. There are several ways in which a computer-assisted cartography system may be superior to manual techniques if all operations are performed properly. On the input side, the vector digitizing systems are very accurate, but can produce results no better than the quality of the work done by the people who operate them. Raster-based automatic digitizers may have high accuracy (depending upon system resolution) independent of the operator's abilities, but cannot be compared directly with manually controlled vector digitizers due to the considerable difference in the nature of their products.

Additional accuracy on the input side is provided to the vector digitizer by production of very accurate plots for comparison to the original documents, by further re-digitizing, and by interactive editing techniques. Importantly, once the map features are accurately represented in the digital map, they will remain that way indefinitely or until someone deliberately modifies them.

One other advantage on the input side is that there now exists a growing set of sources of digital cartographic data. Although the usefulness and quality of such data may be in question, it is certain these sources will become increasingly more valuable, but only to those with computer cartography systems.

There are advantages of computer cartography which are internal, somewhere between the clearly input and clearly output functions. Among these are the potential for spatial analyses of the map data by computer program, an option not available in manual cartography. Using a graphics display terminal, the digital map may become an "electronic map", useful for rapid inspection and analysis, and for production of variable displays of maps derived from the original map data by a user at the graphics terminal. Residing on secondary storage (such as disk) on the computing system, the map data is potentially accessible to a variety of users as copies of databases or directly through the cartographic databases themselves. And finally, the database itself is a new kind of cartographic product, valuable for all current and future mapping in its area.

With excellent fidelity of reproduction among them, the greatest advantages of computer cartography lie on the output side of the operations. Map data in a cartographic database is reusable without loss of quality. Reproductions of maps of equal quality to the original may be produced (plotted) in large quantity very quickly. Custom-made maps and maps derived from one or more cartographic databases may also be produced quickly. In manual methods, production of such maps may require as much effort as the original source map(s) did.

One of the best effects of computer cartography is that the map databases provide a source for an endless series of different maps which may be derived from the original map data by means of the software and with comparatively little effort. Available options include coverage boundaries, selection of feature content, map projection and scale, annotation and legend content and form, line and area color mixtures, and point or line symbolization types. All these may be altered at will, and new maps may be plotted within minutes or hours.

Computer cartography systems offer the possibility of map production virtually on-demand. In advanced systems, end-users may become directly involved in the production or (at least) the design and retrieval stages of production. Production of digital files from which the database may be easily reconstructed offer the potential for transfer of digital map data between sites and for archiving digital map data as well. Finally, maps produced from digital databases may serve as base maps of high accuracy and location control on which new map features may be drawn for digitization and eventual addition to the database.

The final item under advantages of computer cartography is the cost, not clearly an advantage per se. The cost of a computer cartography system including the special hardware for digitizing, displaying and plotting map data, and the cost of acquiring or developing software is very high in comparison to that of manual cartography. In addition, there is the consideration of the cost of maintaining a staff to operate the system, manage the database resources, design maps, organize the operations, and to extend or correct the software. Much of the data input and editing operation may be performed by relatively unskilled and low-paid staff. This advantage may be offset by higher-paid computer programmers needed to extend, document, and correct software, to recover from system errors, and to perform other technical system support functions.

On the face of it, cost cannot be considered an advantage for computer cartography over manual cartography. In fact, the cost is clearly higher in computer cartography. On the other hand, it must be noted that the two forms of cartography are not really comparable. Computer cartography offers many valuable capabilities which are not possible in manual cartography and it produces far more valuable assets, most importantly the digital cartographic databases.

Take, for example, the fact that a sophisticated computer cartography system may be used to produce a very large set of digital databases covering an extensive area of interest for an organization. Once established, these databases may be used by the system to produce a map of any area within their bounds, containing any combination of available map features in the area, annotated and symbolized as desired, and plotted in a selected projection system at nearly any scale. All in a matter of hours or days at most.

Providing such capability with manual methods, if it could be done at all, would probably require an extremely large staff of manual cartographers, each responsible for some small area. Even if it were possible, the final maps would probably be less accurate and more likely to contain errors and inconsistencies than the computer cartography maps.

6 Disadvantages of Computer Cartography

While there are many advantages to computer cartography over manual cartography, there are also a few disadvantages. The most prominent of these, as discussed above, is the expense of acquiring and operating the hardware and software which comprise the system. While there is clearly a cost in establishing and operating a manual cartography system, these costs are minuscule in comparison to that of just purchasing a digital plotter.

It can be argued that digital equipment is so well built today that its life expectancy probably approaches that of much of the manual cartography equipment. However, in truth digital equipment often becomes outmoded and replaced long before it ceases to function, thus widening the gap in expenses between manual and computer cartography.

As versatile and effective as computer cartography systems are, there are limits to the types and sizes of maps that they can produce. Often, the software or the hardware possess various limits in sizes which restrict the number of map elements or the physical size of the map. Digital plotters are limited in one or both dimensions, thus limiting the physical dimensions of the largest plot. Color display terminals may limit the number of features which can be displayed or the number of edges defining an area. These limits may be restrictive, but manual cartography methods have similar restrictions.

Smaller computing systems may have limitations on memory which prohibit the processing of large maps, and the low speed of operations in computers and graphics terminals may discourage or prevent computer mapping in some cases.

There are many such restrictions in the hardware and software of computer cartography systems which may cause limitations in the types and sizes of the maps which can be produced. However, in many cases, methods may often be found to achieve the desired results without concern for the limits. One example is the map which contains too many features for the system. Such a map may often be produced in spite of the limitations through physical and logical data segmentation (subdivision by area or class). In this technique the finished product is literally obtained by overlaying several intermediate (partial) products.

There are a number of other possibly less significant disadvantages which accompany the production of maps via the computer cartography approach. Another financial concern is the overhead of operating the computer cartography shop. In the computer cartography shop, a much greater use of paper and other materials is made to produce "intermediate" maps. These products are used for editing, completion testing, color and layout proofing, verification and interpretation of computer generated data, and many other applications. Such operations do cost. These intermediate steps may be avoided in manual cartography, either because they are not necessary or not feasible.

Finally, there is a set of issues , almost social in nature, which arise from the use of computers and associated digital hardware for making maps. These issues are common in the application of computers to many other fields as well, where they have rarely been addressed fully.

The use of sophisticated hardware as the basis for a cartography system creates a dependency on that hardware to achieve the map-making goal. When the hardware does not work, maps can not be made. If the hardware performs in error, the operator must detect and correct the error, a process which may be more difficult than in manual methods. In practice, hardware failures occur infrequently. Based on observations, hardware errors which are not grossly obvious either occur less often or simply go undetected.

Correction of (usually operator-created) errors in computer cartography is required at different stages, and always depends on timely detection of the error. Often, there are different operators involved in different stages of map production. The operator who made the error may not be the one to correct it.

Operators do not usually follow a computer-produced map from its beginning to its end as they might in manual cartography. Without this follow-through from beginning to end, operators may lose some of the sense of accomplishment and pride which might otherwise improve error detection and other quality factors in the production of the map. Ironically, when errors remain in the computer plotted map, manual cartographers may be called upon to correct them.

7 Geographic Information Systems

The term "geographic information system" is one which has been applied loosely and with little consistency over the past decade. This may be attributed in part to the rapidly developing field in which it applies, where truly remarkable progress has been made in a very short period of time. It may also result in part to the widely varying backgrounds of the researchers and the practitioners brought together for its development. Only recently, with the commercialization of some leading-edge systems does a more clear definition emerge.

As recently as 1980, nearly any computer-based system designed for mapping applications or analysis of geographically based information might be termed a geographical information system or GIS. The collection of some eighty systems presented as "full geographic information systems" in Calkins, H. and Marble, D. (Computer Software For Spatial Data Handling, v. 1, 1980, International Geographic Union, Commission on Geographic Data Sensing and Processing, for U.S. Department of the Interior, Geological Survey) includes many systems which could not qualify as geographic information systems by current standards. At that time, a GIS seemed to be any system in which spatial data was manipulated, and most computer cartography systems might well have qualified at that time.

The thrust of the modern GIS is to handle the complete geographic "entity" in a computer-based system. The geographic entity is multi-dimensional, with a location specification in two or three dimensions (on the map or the earth's surface). Other dimensions describe properties of "attributes" consisting of numerical or descriptive values associated with the entity. The location dimensions may also be considered as attributes of the entity and treated similarly. If desired, further complexity may be added by considering temporal changes in spatial dimensions or attributes.

Thus, both spatial and non-spatial information about geographic entities are to be built, edited, maintained, analyzed, retrieved and combined to produce maps and other significant forms of output to enhance the geographical (or geological) knowledge base.

Spatial information is simply the location of the entity. It may be in the form of latitude and longitude describing a unique position on the surface of the earth. It might also be in Cartesian coordinates (x,y) resulting from a map projection (such as UTM or Polyconic) of the earth's surface to the plane of a map. It may exist as state plane coordinates (a fixed form of map projection), or even as row and column numbers of a cell, raster pixel or grid node (perhaps from a satellite image).

In any case, spatial information is that which is necessary to locate objects for the production of a map or other graphic image (such as on a graphics terminal) in at least its most basic form. Beyond that, spatial information is necessary for determining spatial relationships and properties (distance from, area of...) which are in turn required for analytical operations on spatial properties and even more valuable analyses involving non-spatial attributes as well. Questions such as "What percentage of the surface area of Douglas county is covered by the Lawrence formation?" may be answered through such analyses.

Non-spatial attributes greatly outnumber spatial attributes, which are restricted to location. Rivers and lakes have names, highways have designations (US, Kansas...) and numbers, railroad lines are labelled by the name of the company (Santa Fe...), counties and states all have names. Both natural and artificial geographic features have many physical properties of interest, each of which may be an attribute in a GIS. Hydrologic features have depths, widths, surface area, elevation, measurements of flow and water quality, mineral content, temperatures and so on. And all at many different locations associated with a single geographical entity. All these properties may be used in conjunction with location to perform sophisticated analysis and retrieval for map production.

The GIS incorporates both spatial and non-spatial attributes to provide analysis and retrieval functions employing a combination of both types of attributes. This basic idea is very powerful and offers a high-level interface between the user and a vast store of geographic information through the tools of a computer-cartography system joined with a database management system for the (non-spatial) attribute information. An overriding system of software blends the two parts into an integrated whole called the geographic information system. This GIS accomplishes the desired goal of treating the geographic entity as a whole, with both the spatial and non-spatial aspects brought together for complete analysis and map production.

This report has focused on computer cartography systems in which only a minimal set of attributes is maintained. The emphasis in design of these systems has been on the spatial characteristics of the data and on map production. This emphasis is not always found in the commercial GIS, whose primary focus is often the combination of multiple data sets for an area and manipulation of attributes as described above. During the early stages of software development in this arena, preservation of high-quality and adherence to proven cartographic principles has often been secondary to the flash of new, unprecedented forms of graphics for geographic application. As the industry matures and standards develop, vendors will give increasing attention to quality of output.