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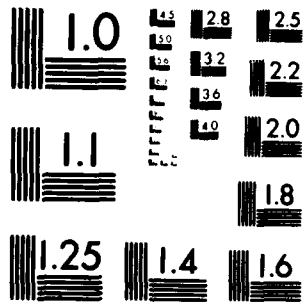
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SOME AUTOMATED CARTOGRAPHY DEVELOPMENTS AT
THE DEFENSE MAPPING AGENCY

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BIOGRAPHICAL SKETCH

Clifford A. Kottman received his formal training in the discipline of pure mathematics. He received a B.S. in 1964 at Loyola Marymount University, Los Angeles, and M.S. and Ph.D. degrees in 1966 and 1969 at the University of Iowa, Iowa City. His specialty is Functional Analysis, and he has published twelve research papers on this and related mathematical subjects. He has served on the faculties of Louisiana State University, Oregon State University, and Simpson College in their Mathematics Departments, holding rank of Assistant and Associate Professor. He joined the Defense Mapping Agency Hydrographic/Topographic Center in 1977 where he now serves in the Topography Department as Chief of the Techniques Office. His current interests include automated photogrammetric and cartogrammetric systems.

ABSTRACT

The first steps toward an automated cartographic capability at DMA were taken to relieve the burden of manual scribing and drafting. Thus, the focus was on the automatic plotting of grids and projections, and later, on the digitization and tagging of line work, its digital manipulation, and its automatic plotting or scribing in a symbolized format. The present capability includes many photogrammetric, graphic, and hybrid techniques to capture cartographic and topographic information in a digital format directly from aerial photography or existing topographic maps. The emphasis today is upon the processing of such data into large data bases of elevations, cultural and natural features, and place names. The developments which will demand careful attention in the next decade are twofold. First, the structure and scope of the data bases will expand so that they may fully support topographic mapping, hydrographic charting, and special activity graphics. Second, systems will be developed to quickly exploit these data bases for the generation of both special and general purpose products in both graphic and digital formats.

INTRODUCTION

The purpose of this paper is threefold: to sketch the evolutionary steps toward an automated cartographic capability within the Defense Mapping Agency (DMA), to support the thesis that essentially parallel steps must be taken by any mapping facility wishing to automate its production processes, and to communicate DMA's successes and false starts so that others may benefit from DMA's experience.

The scope of the discussion will be limited to topographic mapping at 1:50,000 and 1:250,000 scales, and related topographic and cartographic products. Also, the discussion will be limited to roughly the two decade interval from the late 1960's to the late 1980's.

The development of an automated cartographic capability at DMA can be organized logically and chronologically into three phases, which will be labeled in this paper as past, present, and future. Those activities labeled as "past" occurred at DMA prior to 1978. The developments of 1978 to 1983 constitute what will be labeled "present," and those planned for after 1983 are the "future."

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Before proceeding, it must be confessed that truly automated cartography is beyond the scope of this paper. The topic of discussion would be described more correctly as computer assisted cartography, or even digital cartography. It is certainly true that human intelligence and action are required for planning, feature extraction, production guidance, cartographic expression, and are deeply interwoven in all the production scenarios outlined in this paper. It is therefore appropriate to set forth a definition of "automated cartography" valid in this context.

DEFINITION

Automated Cartography has three salient features:

- (1) It is a production process whose final product is a traditional map.
- (2) All the data to be presented on the map are carried through the production process in a digital format (e.g. magnetic medium) from the moment they are extracted from the source material (e.g. aerial photograph or gazetteer) until they are scribed or engraved for mass reproduction as a finished product.
- (3) The production flow includes the manufacture of a digital data base of cartographic knowledge.

It should be pointed out that the definition offered above would not have fit DMA's vision of automated cartography in 1975, and it is probably doomed to major revision before 1990. The concept of a "data base" has been particularly dynamic. It has grown from a "room full of magnetic tapes containing cartographic data in a format suitable to drive a precision plotter" to today's "room full of computer compatible cartographic data possessing both positional and descriptive attributes" and surely will be subject to enormous refinements in the future. Nevertheless, the definition above accurately encompasses today's vision of automated cartography and comfortably fits the scope of this paper.

The motive for the introduction of automation is one or more of the following:

- (1) the economy and enhanced productivity of computer assisted production steps over wholly manual methods, (2) the promise of reduced future map revision costs or remapping (at perhaps a different scale) costs by exploiting the digital data base, (3) the increased accuracy afforded by computer assisted methods, (4) increased responsiveness, that is, a reduction in the time required to produce a map, or (5) the inherent value of a data base of cartographic knowledge, for which future uses will undoubtedly be found.

All of these motives are present at DMA. However there has been steadfast growth in emphasis upon the latter motives, and this pattern has promise to continue.

THE PAST

In the late 1960's and early 1970's, two major products of DMA were the standard line map and the plastic relief map. Preparation of line maps in the earlier years was a totally manual effort consisting of delineation of map features from aerial photography and the engraving of those features onto color separated negatives for press plate production. For plastic relief maps, contours were traced on a pantographic router creating a laminate step model which was moulded in plaster for carving into a terrain model. This section will trace DMA's early efforts to automate portions of these processes.

The automation began on several fronts almost simultaneously. Four significant developments will be examined here: (1) the introduction of analytical

stereoplotters to produce contours, (2) the introduction of systems for the digitization of contours and software to convert this data to a format suitable for an automatic routing machine, (3) programmable precision plotting and scribing instruments for grids and projections, and (4) systems which allowed the digitization of color separated manuscripts, software to allow manipulation of such data, and high speed proof plotters for validation before precision plotting. A process flow diagram which includes these systems is provided in Figure 1.

The analytical stereoplotters obtained by DMA were the Universal Automatic Map Compilation Equipment (UNAMACE) and the AS-11A. Originally, both allowed digital input of model, camera, and photograph parameters (obtained by way of a separate triangulation operation) for the automatic accomplishment of an absolutely oriented stereomodel. However, neither had the capability to create digital records of the topographic data they collected. The AS-11A provided operators with a binocular view of the stereomodel where a floating mark could be guided with hand and foot wheels while a slave coordinatograph produced plots at a selectable scale. It was used primarily for contour plots. The UNAMACE was more fully automated. It contained circuitry which measured the cross-correlation between video signals extracted from the stereo imagery by which local x-parallax was computed and removed. By simultaneously exposing film on output tables, two products were generated: a drop-line chart (from which contours could be traced), and an orthophotograph.

The orthophotograph was an extremely important product: it served as a control base for the placement of all remaining map features and thus eliminated the need for analog projection stereoplotters. However, the UNAMACE proved too unreliable for real-time orthophotograph production. Every correlation loss and operator error was permanently recorded on film. A solution was quickly conceived and implemented: the UNAMACE systems were modified to collect elevation data on magnetic tape. These data were subjected to error detection and correction software (CNTUR3), then used to control the Off-Line Orthophotograph System (OLOPS) or the Replacement of Photographic Imagery Equipment (RPIE) for the production of orthophotographs. This configuration has proven to be extremely flexible and reliable. The algorithm CNTUR3 also extracted contour plot data from UNAMACE produced elevation matrices. Unfortunately, the contours thus produced were seldom of map quality, and required manual correction to properly fit the drainage network and possess the easily interpreted expression of manually compiled contours.

The production of moulds for plastic relief maps was partially automated with a combination of hardware and software. A system called Digital Graphic Recorder (DGR) was introduced which allowed contour manuscripts to be manually traced while capturing a string of X- and Y-coordinates which defined their shape. Next came a software algorithm called PIPS which converted these digitized contours into a matrix of regularly spaced elevations covering the same area as the original manuscript. Finally, an automated routing machine milled a terrain model by carving away profile after profile while the thickness of the cut in each profile was controlled by the sequence of values in the corresponding column of the elevation matrix.

The manual scribing of grids and projections was identified early as an area offering economical automation. Precision flatbed Concord plotters were brought into DMA with sufficiently programmable control computers to perform these tasks. They were used primarily with photo scribing heads, and the grids and projection overlays they produced were entirely satisfactory.

An ambitious development carried on at DMA in the early to mid 1970's was the project known by the appropriate name Semi-Automated Cartographic System (SACARTS). This system was composed of a wide array of hardware and software

and it directly attacked the most difficult problems posed by automated cartography. The goals of SACARTS were (1) to allow the digitization of both the line work and symbolization codes from compilation manuscripts, (2) to provide software which accomplished validating, editing, merging, symbolizing, displacing, color separating, and other utilities for the purpose of obtaining symbolized map data fully adherent to the specifications of the map series being produced, (3) to allow both proof and precision plotting of symbolized map data as well as interactive reviews of the data by way of cathode ray tube (CRT) displays, and (4) to provide a means of automatically generating a reproduction quality symbols and names overlay for each required color.

The digitization goal was addressed with the procurement of Calma Graphic Digitizers. Later this capability was reinforced with two additional digitizing systems, the Digital Planimetric Compiler and the Comp-U-Grid. Although the newer digitizers provided additional capabilities, all of the SACARTS digitizers had shortcomings. Most serious among these was the meager feedback provided to the operator, and the limited editing (or interaction of any kind with the captured data) allowed on these systems. These shortcomings put additional burden upon the already overwrought SACARTS software.

The workhorse of SACARTS software was a collection of algorithms and utilities known as Graphic Improvement Software Transformation System (GISTS). This package allowed the transformation of cartographic data from the format of one hardware system to that of another, as well as from one coordinate system or projection to another. Also, GISTS provided merging, updating, and plotting utilities required for editing and verifying these data. More importantly, GISTS transformed line center (i.e. digitized) data into symbolized data (e.g., lines with specific weights, casings, hatchings and color groupings) using the symbolization code carried with the placement data. Added to this was an algorithm to automatically displace certain features (such as buildings) whose symbolization overlapped that of another feature (such as a road) in order to meet map specifications. In order to appreciate the accomplishments of GISTS, one must understand that all the algorithms within it were executed by batch submissions to a general purpose computer remote from the cartographers; real-time feedback and cartographer interaction with the symbolization process were not available. In spite of this handicap, GISTS was developed into a working system.

To provide the much-needed feedback to the cartographer exercising GISTS, a high speed four color Xynetics plotter was introduced to DMA. This plotter proved to be extremely well suited to the need. It was fast, reliable, and even accurate enough to scribe the open windows for vegetation, water, and other area fill symbols. An effort to provide even more efficient cartographer interaction with SACARTS data led to the development of the Digital Input/Output Display Equipment (DIODE). This system was to have featured a large format Lundy CRT for interactive editing of center line data, but it proved to be difficult to maintain and was never implemented fully into production.

The last subsystem of SACARTS for discussion here was the Symbols and Names Placement System (SNAPS). This was an effort to use computer assistance to avoid manual stickup of place names and point symbols. SNAPS consisted of a type composition station where names, their fonts, and symbol codes were keyed for input to a Photon printer where a film strip negative of place names and symbols in correct fonts was exposed and developed, a placement drum where position and orientation data were generated for each name and symbol, and a special attachment to the gantry of a Concord plotter which, using the position and orientation data, automatically flashed each name and symbol from the film strip onto its correct position on a film positive overlay.

The motivation for SACARTS was the desire to improve productivity at the color separation phase of mapping by the elimination of the costly manual scribing required in color separation. Although the SACARTS development encountered some difficulties and SACARTS production still required much manual intervention, the concept of Semi-Automated Cartography proved sound. In 1977, 250 topographic maps at 1:50,000 scale were produced using SACARTS saving 250 man hours per sheet over wholly manual methods.

Examples of the deficiencies and unresolved problems in SACARTS were: (1) road and road fill registrations were not fully automated, (2) intermittent stream nodes and endings did not meet specifications, (3) a comprehensive priority structure for automatic feature displacement was not accomplished, and (4) contours still required extensive manual reworking. None of these problems appeared particularly formidable, but work within DMA toward resolution of these problems halted in 1977. The reason was a change in DMA's product requirements.

THE PRESENT

Beginning in the late 1970's and continuing to the present time, DMA has experienced enormous growth in the volume and priority of its digital product requirements. To meet the pressing needs for improved accuracy, greater productivity, and strict adherence to digital product specifications, DMA has turned increasingly to automated and computer-assisted cartographic production techniques. This section will highlight four families of such developments: (1) systems to capture digital data from aerial photography, (2) systems to validate such data, (3) systems to transform graphic cartographic data to digital form, and (4) systems to organize cartographic data into standard formats. These systems will be examined relative to their roles in the production of two digital product types; Digital Terrain Elevation Data (DTED) and Digital Feature Analysis Data (DFAD). A generalized production flow diagram which shows the basic relationships between these systems is provided in Figure 2.

DTED is a generic name for a variety of products. Each product consists essentially of a matrix of elevation values. The matrix elements are in one-to-one correspondence with the intersections of regularly spaced projection grid lines on the Earth's surface; the value of the matrix element is the elevation of the Earth's surface at the corresponding grid intersection. A DTED product is specified by defining its particular projection grid, the number of and spacing between grid lines, sufficient data to identify the particular grid lines, and the accuracy with which the elevation data represents ground truth.

To capture DTED efficiently from aerial photography, DMA has recently upgraded and increased the number of its analytical stereoplotters: the UNAMACE and the AS-11A. The capability has been added to the AS-11A to allow it to produce digital records of elevation data from which DTED matrices can be interpolated. Both types of stereoplotters have been equipped with graphic CRTs and additional application software to allow feedback to the operator of the collected data and on-line editing of compilation errors. The UNAMACE has been fitted with additional hardware and software to allow the generation of a point-by-point Figure of Merit (FOM). The FOM is a computer word packed with fields in which are encoded such parameters as the power of the video signals being correlated, the height of the peak of the correlation curve, and the shape of the correlation curve. The FOM is being studied for its potential to assure accuracy by flagging data with suspicious combinations of these parameters for close inspection. Because certain DTED products are expected to convey a highly accurate sense of the shape of the terrain, special care is taken to capture ridges, drains, and other occasions of inflection in the Earth's surface for these products. This is done with the AS-11A instruments and the extracted data are called geomorphic data. It is merged with ordinary DTED to enhance its accuracy along critical lines.

All of the DTED discussed so far are organized according to stereo model. That is, each DTED block covers a patch of ground which is a subset of the region of overlap in the pair of aerial images from which it was extracted. Before proceeding to reorganize the data according to product specifications, DMA intends to validate this DTED with an instrument nearing completion of its development phase called Elevation Data Edit Terminal (EDET). The EDET will provide its operator with an absolutely oriented stereo view of the DTED source imagery with a simultaneous superimposed stereo view of the extracted DTED. The operator will have the ability to perceive and correct erroneous data with a variety of interactive software tools, or to reject some or all of the data and cause it to be regenerated on an analytical stereoplotter.

To quickly and efficiently gather the DTED required, DMA also has extracted DTED from the contour information on existing maps. To accomplish this, the contour color separate has been either digitized manually on the DGR (discussed in the previous section) or digitized automatically on a system called Automatic Graphic Digitizing System (AGDS). The AGDS is itself composed of three subsystems: the scanner, the vectorizers, and the edit/tag stations. The scanner subsystem, by measuring reflected or transmitted light from a moving spot on the contour manuscript, creates an array of one-bit values which indicate the presence or absence of a contour line. Naturally, the spot size must be considerably smaller than the contour line weight; therefore, the raster array is very large. The vectorizer subsystem consists of software resident in dedicated minicomputers which generates from this large array strings of ordered pairs of X- and Y-coordinates delineating the contour lines. The edit/tag stations allow operators to interact with the extracted contour lines by way of graphic CRT displays. At these stations, contours are labeled with their elevation value and any blunders committed by the scanning and vectorizing subsystems are corrected. Validated contours are fed to the PIPS software, and the resulting DTED are ready for the data basing functions.

It must be understood that the pieces of DTED collected in the variety of ways described above may be far from the DTED standard product matrices required. First of all, they may contain data within only a stereo model, whereas the product is required to contain data covering a standard geographic unit. Moreover, the raw collected DTED may be at a grid spacing or projection other than that of the required product. Further, overlapping pieces of DTED from different sources (e.g. from adjacent stereo models) in general do not agree in the overlap region, even if they share the same projection grids. The disagreement is due to random error in the collection process that should be consonant with the product accuracy specification. To create the final product, several processing steps must occur: (1) the DTED blocks covering a standard product matrix must be regridded (by an interpolation process) to the product projection grid, (2) the smaller blocks of data must be inserted into the product matrix elements in such a way that obvious seam lines are not apparent, and (3) the filled product matrix must be checked (and adjusted if necessary) to its neighbors (with which it shares a common edge or corner) to assure compatibility. These steps are called regridding, merging, and paneling and constitute the data basing functions for DTED. Currently, these functions are performed with batch software submissions to a general purpose computer. A considerable amount of graphic feedback to the cartographer is required especially in merging and paneling; this is provided with high-speed electrostatic raster plotters. This arrangement is not satisfactory, however, and a dedicated system with real-time interactive graphics capability is being procured to perform these functions. This is the Terrain Edit System/Elevation Matrix Processing System (TES/EMPS).

DFAD consists of digital files of feature records. Each file corresponds to a standard geographic unit of the Earth's surface. Three categories of feature records are collected: features which may be represented by a single point,

features represented as a sequence of connected line segments, and regions represented by a closed loop of connected line segments defining their boundary. These are called point, line, and areal features, respectively. Along with the positioning data, each feature in a DFAD file is tagged with descriptive data which encode such facts as the category of cultural or natural feature (e.g. building, tower, railroad bed, or shore line) and physical characteristics of the feature (e.g. height, orientation, surface material, or predominant vegetation category).

DTED and DFAD are important products because of their wide range of uses. They can be used for navigation and guidance, allow a variety of mission planning experiments, and are required for realistic flight simulation with either visual or radar scene simulators.

Three distinct technologies are being employed or developed for the capture of DFAD. They are the traditional method involving a manuscript and digitizing system, the Computer Assisted Photo-Interpretation device (CAPI), and the Extracted Feature Rectification and Processing System (EFRAPS). In the traditional method, a feature analyst searches aerial photography for features which meet product specifications using an analog stereoscope. When a feature is discovered, it is identified and its image is measured, if necessary, using a calibrated reticle. Using a programmable hand-held calculator and knowledge of the camera and photograph parameters, the physical dimensions of the feature are generated. In this way the descriptive data tag is created. These tags are recorded in a sequential data table which is merged with the positioning data later in the process. The positioning data itself is generated by the feature analyst who delineates the feature on a manuscript which is registered to a control base (which may be an orthophoto or a map, or a map intensified with a locally registered rectified aerial photograph reproduced at the map scale). When the manuscript is complete, the features portrayed on it are digitized sequentially using either manual or automated (AGDS) digitizing systems.

CAPI is essentially an analytical stereoplotter. On this system, the feature analyst is presented with an absolutely oriented view of stereo aerial imagery. When a feature is discovered, a floating mark is placed upon it by using hand controls, and the feature is traced to create a digital placement record. The descriptive data are entered at a keyboard before proceeding to the next feature. Throughout this process, the analyst is presented with a CRT view of the data collected, and thus perceives himself to be building a manuscript as in the traditional method, except that it is in softcopy (CRT) form. There are many advantages to the CAPI technology: it eliminates the digitization step, it allows the real-time marriage of positioning and descriptive data so that blunder checks and any error messages can be presented to the analyst immediately, and it is much more accurate. A disadvantage is that an analytical stereoplotter is an expensive tool for a process where 50% or more of the analyst's time is spent searching for features, a task which could have been done as effectively on a much less sophisticated stereoscope.

The EFRAPS technology is being developed to retain the advantages of the CAPI with a less expensive investment. With EFRAPS, feature discovery, identification, and image measurement are performed as in the traditional method; only the placement process is different. EFRAPS requires DTED covering the geographic area of work, a digitizing tablet, a graphic CRT, known camera and photograph parameters for aerial imagery covering the work area, and a computer. To perform the placement function, a cursor is traced over the feature on the aerial image which has been registered to the digitizing tablet. In this way, photograph coordinates are fed to the computer, where, using the photograph and camera parameters, lines of sight are generated in Earth coordinates which pierce both the feature on the ground and its image in its taking position. These lines of sight

are intersected with a terrain model generated from the DTED, thus, geographic positions are calculated. Feedback is provided to the analyst via the CRT, where he also may perform certain editing tasks such as assuring continuity within those features which are not wholly imaged in one photograph.

The same EDET which is being developed for the validation of DTED is expected to validate DFAD. Here, a stereo view of extracted feature data will be presented to the operator superimposed upon an absolutely oriented stereo model.

As in DTED production, the final step in DFAD production may be called data basing. This is the process of organizing the captured data into standard geographic regions, standard topology (e.g., loops to be listed counterclockwise with no self-intersections), standard bit structure formats, and into other product required structure. This family of operations has been done using batch oriented software modules which allow only limited operator interaction and are characterized by long calendar delays. To meet the requirement for enhanced computer assistance in this area, DMA is developing the Clustered-Carto Processing System (CPS). This is a collection of dedicated processors and interactive work stations at which operators can launch editing and processing algorithms and receive almost immediate feedback by way of graphic CRTs.

As an overview of the topics presented in this section, notice that DMA's current focus is not upon graphic products for human use, but rather on digital products. Great emphasis has been placed upon the efficient and accurate capture of DTED and DFAD and its efficient processing into standards of format, extent, topology, and accuracy so that machines and algorithms may process it reliably. This evolutionary step has been an important and necessary one; it leads directly to a new era in automated cartography.

THE FUTURE

The tasks remaining for DMA to achieve an automated cartographic capability fall into three categories. The first deals with those tasks associated with enhancing the scope and structure of DMA's cartographic data bases until they can fully support the automated extraction of traditional map feature data. The second encompasses the tasks involved in exploiting this data base and the actual computer assisted generation of a map product. The third involves rapid reproduction. This section will highlight some specific challenges in each of these areas. The list presented here has been chosen to be interesting and representative, but is certainly not exhaustive.

A cartographic data base must possess the information necessary to distinguish between positional data which are accurate to one specification from those which are accurate to another, as well as separating these data types from positional data which has been displaced for proper presentation on a particular map. Feature identification tags must be developed and used which are sufficiently specific to allow automatic symbolization for all map specifications supported by the data base. A means must be provided to assure the topological validity and consistency of the feature data. For example, link and node structures seem most appropriate for the storage of certain map features, while a raster organization seems best for others. Considerable development is required before one may enjoy automated assurance that these different structures encode map data which are self-consistent. Highly automated exploitation of map data will demand that nodes match perfectly, links not intersect, and many other logical constraints be imposed on the data which are not at all obvious.

Automated exploitation of cartographic data bases for the generation of traditional maps also holds many challenges. Algorithms for feature displacement to prevent overprinting are at present naive and unsatisfactory. Similarly, current

automatic names placement algorithms produce a product which requires much manual refinement. In many ways, these problems are to be expected. After all, a traditional map is in many ways an artistic device crafted in a way to communicate to the human reader the spatial relationship between certain physical features. This communication is more important than the precise positioning of feature symbols, and being an artistic human function, it is not surprising that full automation is difficult to achieve. Certainly, the computer assisted map finishing system of the future will be highly interactive and afford its cartographer operators the freedom to insert needed cartographic expression to the map product. Because this step may introduce unwanted delay in the creation of a map, new map specifications may evolve which would allow overprinting or the use of finer than ordinarily specified line weights in feature-dense areas. Softening specifications in these, and perhaps other, ways may be an acceptable compromise to achieve extremely rapid response in map production.

This raises the third area of future development: rapid reproduction. Traditional photo engraving of press plates from precision scribed reproduction masters is a lengthy process, and at least two technologies hold promise to greatly improve responsiveness in this area. One involves direct digital drive of a laser plate-engraver. The other involves large format color electrostatic printers driven by digital cartographic data. DMA will continue to follow both these technologies and adopt them as soon as feasible.

Figure 3 is a generalized production flow diagram depicting the principle components in DMA's future automated cartographic system.

CONCLUSION, AN OVERVIEW

At DMA, automated cartography began with activities which provided computer assistance to isolated work steps in the traditional cartographic production flow. The targets of these activities were labor intensive steps, especially those whose character allowed straightforward development of algorithms and were not too dependent upon uniquely human intelligence. These efforts were largely successful, and have demonstrated the rich potential for automated cartography.

In recent years, DMA has focused its attention on those steps involving the efficient and accurate capture of cartographic data, and its processing into validated data bases. This has been in response to customer requirements, but it was a necessary step in the evolution of automated cartography.

Automated cartographic developments in the future will be largely unconstrained by the traditional production flow. The future will see the development of a robust cartographic data base structure, and the introduction of interactive computer systems to exploit this data for the production of traditional maps. Because extremely fast (at least by traditional standards) response can be obtained in this scenario, and because of the costs associated with stockpiling large map inventories which may be unneeded in this scenario, one can expect continued growth and evolution in this direction.

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