MAPPING DEVELOPMENTS AND GIS IN THE USGS, 1884-2009

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Abstract

Introduction On December 4-5, 1884, John Wesley Powell, then Director of the U. S. Geological Survey (USGS), persuaded the United States Congress to approve systematic topographic mapping of the United States Thus, in December 2009, the USGS will celebrate the 125th anniversary of topographic mapping. This paper is a treatise on the history of topographic mapping and geographic information systems (GIS) in the USGS.

Objectives The objective is to illustrate innovations in mapping and GIS within the USGS and the approach and products, including public-domain data, which helped stimulate the current (2009) GIS industry. This paper traces the origins and chronological change of topographic mapping and GIS during the 125-year history of the USGS National Mapping Program, now referred to as the National Geospatial Program. This paper describes the expanding range of topographic mapping techniques from field sketching and the process of producing a three-color lithograph map from copper plates through techniques of advanced field completion, aerial photography, photogrammetry, scribing, and the five-color lithographic press that led to completion of the 1:24,000-scale, 7.5-minute coverage of the contiguous 48 states of the United States in 1991. This coverage resulted in more than 55,000 maps or more when multiple editions are considered.

Methodology The mapping process and USGS innovations in mapping and GIS, including developments in photogrammetry are detailed in this paper, including the invention of Kelsh and ER-55 stereo plotters in the 1950s, orthophotographs in the 1960s, digital cartography including Digital Line Graphs (DLGs), Digital Elevation Models (DEMs), the provision of public domain data for GIS and the Geographic Information Retrieval and Analysis (GIRAS) software in the 1970s, and digital orthophotoquads (DOQs) and Digital Raster Graphics

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(DRGs) in the 1980s and 1990s. The opinion that the development of arc-node based data, (such as DLGs), grid-based data, (such as DEMS), and software for map projection, (such as the General Cartographic Transformation Package; GCTP), along with the Unified Cartographic Line Graph Encoding System (UCGLES) and GIRAS, an arc-node based GIS processing system generating vector data with a companion raster product, Composite Theme Grid, for land-cover data in the 1970s, helped provide a base for the commercial expansion of GIS in the 1980s.

Results It has been argued that the debut of commercial GIS software in the 1980s based on a vector arc-node data model, with full capability for map projections, overlay, and other spatial processing and analysis relied on developments and data from the USGS and other Federal agencies, including the U.S. Census Bureau's Dual Independent Map Encoding (DIME) files in 1970 and 1980, and Topologically Integrated Geographic Encoding and Referencing (TIGER) line files in 1990; the Defense Mapping Agency (now the National Geospatial-Intelligence Agency) provision of the 3 arc-sec DEMs of the 1970s; and the Central Intelligence Agency's World Databank I and II in the 1970s, along with data products from other organizations. USGS developments and provision of DEMs, DOQs, and DRGs in the 1980s and 1990s catalyzed the commercial industry helping to build the United States leadership in these technologies and current Web-based and interactive GIS. With the development of *The National Map* of the United States in 2001 and other National Geospatial Program directives, the USGS continues to provide mapping, geospatial innovation, and data to the Nation and the world.

Conclusions The presentation in this paper is focused on key innovations of the USGS in topographic mapping and GIS and provides evidence that the provision of free nation-wide data and processing software to the public depended upon those innovations. In this way, the USGS helped lead the revolution of mapping to GIS and helped establish the United States as a leader in geographic information science.

Origin and Purpose

On December 4-5, 1884, John Wesley Powell, then Director of the United States Geological Survey (USGS), persuaded the United States Congress to approve systematic topographic mapping of the U.S. Powell stated:

> In planning the work for a topographic survey of the United States it has been necessary to consider that the area to be surveyed is very large—about 3,000,000 square miles, exclusive of Alaska, and with Alaska about 3,500,000 square miles. The survey of a region so vast must necessarily be at a great aggregate cost, and the economics relating thereto should be duly weighed.
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> The area and cost being great, the time for thé execution of such a survey must necessarily be long, that the cost may be distributed over many years ; but the needs for topographic maps are so many and so great that the time for its completion should be shortened as much as possible. (Powell, 1885, page 208)

The late 19th century surveyor, often referred to as a topographer, created topographic maps of the landscape. His craft often took him to hilltops with broad views of the surrounding area. With his instruments, first the tape, compass, and aneroid barometer, but later the planetable and alidade, he would make measurements of the terrain and use his field-sketching skills to create an accurate topographic representation, including natural and cultural features, as well as measured contours. The hilltop position might become a benchmark, a point of known location: latitude, longitude, and elevation, commonly marked with a metal disk with a shaft that is secured in the ground. The end product of the topographer's labors is the field sketch, a fair drawing of the topography using basic linework and symbols with labels for contour measurements and other features.

The field sketch was the starting point for creating the topographic map and continued into the 1980s. The production and reproduction of maps using copper plates included producing the original drawing, photographing it to a glass negative on a copy camera, correcting the negative as necessary, creating a contact print positive on a zinc plate, and creating a wax impression of the zinc plate on celluloid, which was then burnished onto three copper plates. The three copper plates included civil divisions and public works in black, hydrography in blue, and hypsography and miscellaneous features in brown. The inverse graphic image on the copper plate was transferred to a lithostone, which was used for final lithographic map creation. Lithostones were corrected or touched-up as needed for the final printing. Features shown on the maps included civil divisions of state, county, township, and cities or villages; public works including railroads, tunnels, wagon roads, trails, bridges, ferries, fords, dams, canals, and acequia; hypsography with contours and floodplain representations; and miscellaneous features of forest, sand, and sand dunes. USGS maps containing these features were created at scales of 1:250,000 for 1-degree areas and 1:125,000 for 30-minute areas. Demand for more topographic detail caused the USGS to increase map scales to an extent that by 1894, most of the maps were 15-minute areas and produced at a scale of 1:62,500.

The use of aerial photography and photogrammetry to mapping

The use of aerial photography in World War I led to its use for civilian mapping in the 1920s, but the intensive use of photos and photogrammetry began at the USGS in the 1930s. To respond to requirements of the Tennessee Valley Authority for maps, the USGS established the Multiplex Mapping Unit in Chattanooga, Tennessee. The Multiplex was a reflecting projector that used anaglyph techniques, red and blue/green glasses to separate the left and right images for stereo projection. The USGS photogrammetrists made many improvements and developed new stereoplotters to meet the topographic mapping requirements. Among these photogrammetrists were Russell K. Bean and Harry T. Kelsh. Bean invented the ""Ellipsoidal Reflector Projector"" (ER-55) for which he was awarded a patent in 1956. The ER-55 became a replacement for the Multiplex stereoplotter. Bean originated the concept of the orthophotograph and was awarded a patent in 1959 for his development of the orthophotoscope, an instrument for generating an orthophoto from a stereopair of photographs. The USGS deployed the commercial version of the orthophotoscope, the T-64. The USGS also developed and acquired several different types of Kelsh stereoplotters, invented by Harry T. Kelsh. These became the mainstay of photogrammetric mapping of areas of moderate to high relief throughout United States over the next three decades. Low relief areas, such as along the coasts and large parts of the Great Plains of North America, required the capabilities of the "heavy" stereoplotters, such as the Wild A8, B8, the Kern PG-2 shown in the photograph.

Photo-reproduction Cartography

World War II brought demands that affected the USGS mapping program. Among them was the demand for copper and the availability of high contrast films that could reproduce cartographic linework effectively. Thus, a pen-and-ink mapping process was initiated. The inked drawing was photographed to a film negative that was used in the reproduction process. Without the time-consuming process of copper engraving, topographic map production increased by a factor of 10. By 1955, the pen and ink process was replaced by the use of engravers and scribecoat. The scribecoat replaced the film in the pen and ink process and could be used directly for photographic reproduction.

Demand for greater detail of the topography led to the production of the 1:24,000-scale, 7.5 minute map series. These maps, each covering an area of 7.5 minutes of latitude and 7.5 minutes of longitude, were created using a five-color lithographic reproduction process. With the larger scale, the USGS included more than 200 features separated into color groups for the five color plates to be used in the film-based reproduction process. The five plates included cultural features, such as roads shown with casings, buildings, and much of the type used on the map on a black plate; road fills, urban tints, Public Land Survey lines, and other features on a red plate; woodland tint and other vegetation on a green plate; hydrographic features on a blue plate; and contours, depressions, and other hypsographic features on a brown plate. These color separations provided the analog for the development of thematic layers that could be combined for analysis in GIS.

Surveying

During the time when cartographic reproduction advanced from copper plates to film and scribecoat, photogrammetry advanced from the Multiplex to ER-55s, Kelshes, and heavy plotters, field instrumentation also advanced. The transit and alidade were replaced with theodolites, levels, and electronic distance measuring (EDM) units. The EDM units used microwaves to accurately measure distances for surveying and mapping. The USGS developed the Elevation Meter, a modified Chevrolet Suburban with a fifth wheel and electronics that recorded elevations as the vehicle traveled along roads. It was used to help establish ground control elevations along roads, and particularly at crossroads.

The transition to digital production

In the 1960s, the USGS developed the AutoPlot, a device that used stepping motors to move scribing engravers to create a scribecoat negative of the topographic map neat line (latitude and longitude lines that bound the quadrangles) and horizontal pass points. The USGS developed a prototype based on the Haag-Streit coordinatograph for producing base map graticules on scribecoat. The USGS modified the coordinatograph to hold “stepper motors” and a contemporary precision gearbox that would drive and position the plotting head at the speed of 0.7 inch per second with a precision of 0.0005 inch. Using the IBM System/360 for these tasks and for converting between geographic and plane coordinates, by 1968 the Autoplot system had replaced the manual plotting of base sheets (McHaffie, 2002).

The USGS rapidly embraced digital cartography in the 1970s. The first AutoCarto Symposium was held in 1974 at the USGS National Center in Reston, Virginia. The USGS organized the first AutoCarto Research Symposium and continues to be involved with this conference series with AutoCarto 2010, which will occur in Orlando, Florida, November 15-19, 2010.

In the 1970s, the USGS planned to create a digital cartographic base of binary files of line graphs of hypsography, hydrography, transportation, manmade features, and boundaries (Edson, 1975; Greenlee and Guptill, 1998; Chrisman, 2006). The Digital Line Graphs (DLGs) were digitized by line-following methods with Altek digitizing tables and processed with the Unified Cartographic Line Graph Encoding System (UCLGES), which was used to check the topology, alignments, and attributes of various geographic features for correctness and accuracy. These files were obtained from the 7.5-minute map series and created with complete topological structure of the line graph elements. The DLGs, placed in the public domain, also became an important input to GIS and later a base for the Digital Map Revision and Product Generation system, known as RevPG.

The goal of the land-cover mapping program was to produce a dependable set of land- use and land-cover information for the nation from remotely-sensed imagery (Anderson and others, 1976). Related maps of hydrologic units, political boundaries, census tracts, and Federal lands also were constructed. A GIS, the Geographic Information Retrieval and Analysis System (GIRAS), was developed to tabulate hectares of each type of land cover in a county or a hydrologic unit. The result was the Land Use Data Analysis (LUDA) Program that was soon after used to calibrate remotely-sensed land-cover characterizations. The vector-based polygons also were converted to a raster form called Composite Theme Grid. The vector and raster data were placed in the public domain.

Automated map production began with photogrammetric processing software, the Digital Cartographic Software System (DCASS), in 1980. The system consisted of analog stereoplotters, such as the Wild B8 and Kern PG-2, retrofitted with 3-axis digitizers, tape recording units, and a voice-entry system for attributes. The result of DCASS processing was compilation manuscript, photoplotted automatically on a Gerber 4477 photoplotter. The digital version of the compilation manuscript was then transferred to Intergraph interactive editing stations and processed with the Graphic Map Production System (GRAMPS), interactive cartographic editing software that allowed completion of the mapping process. In 1983, DCASS/GRAMPS began production with the release of Birch Tree, Missouri, 7.5-minute, 1:24,000-scale quadrangle.

Digital data were generated for land cover for the entire United States and maps produced at scales of 1:100,000 and 1:250,000. These data were generated in an arc-node vector format and processed with a package called the Geographic Information Retrieval and Analysis System (GIRAS). The GIRAS data were made freely available in the native arc/node format and in a raster format with 40-acre grid cells, known as Composite Theme Grid (CTG).

Digital elevation data for the 1:250,000-scale map areas were created by the Defense Mapping Agency (DMA) and the USGS from aerial photographs and contour maps (using interpolation). These data on a 3 arc-sec grid were made available to the public by the USGS. The USGS prepared DEMs on a 30-meter grid for 7.5 minute quadrangles as a by-product of the orthophoto generation process. DEMs also were generated with automatic correlation on the Gestalt PhotoMapper (GPM), a $1.5 million analytical photogrammetric instrument developed by Hobrough, Ltd, Canada for DMA. The GPM was used to generate more than 10,000 7.5-minute DEMs beginning in the mid-1970s. DEMs also were generated from interpolating digital contour lines. All DEM data were placed in the public domain.

Electronic instrumentation

From 1974 to 1983, the USGS researched the development of the Aerial Profiling of Terrain System (APTS) for measuring stream valley cross sections and profiles, older map reliability testing, and producing control for topographic maps. The system consisted of an inertial measuring unit (IMU), a laser tracker, a laser profiler, a video imaging system, supporting electronics, and a computer. This system was a precursor of the lidar systems of today.

Software and theory

USGS software was distributed freely and the General Cartographic Transformation Package (GCTP), which converted among 21 different projections, became the base for many government and commercial enterprises. John P. Snyder, who had developed the Space Oblique Mercator Projection for Landsat satellite data, published many books and papers on map projection, and in 1987 released his *Map Projections: A Working Manual*, which became the seminal volume and technical manual for cartography and GIS users of map projections. Snyder also had worked on the public domain version of GCTP, which is still distributed and widely used by the USGS.

Although geographic information systems (GIS) had been in use in government agencies in the 1960s and 1970s, the 1980s witnessed the debut of commercial GIS software. Environmental Systems Research Institute launched the Arc/Info product in 1982, and the USGS was among the first and largest users. Along with GIS, the Global Position System (GPS) became available and receivers as shown could receive accurate position locations from satellite triangulation. Photogrammetric stereoplotters evolved from analog solutions with optical projection and mechanical projection using control rods to mathematical projection with analytical instruments, such as the Traster used by the USGS. Modernization of map production became the focus of USGS mapping innovation in the 1980s with the MARK II project, primarily based on Intergraph hardware and software. Interactive map editing was accomplished on dual-monitor Intergraph workstations.

The USGS developed the concept and procedures for creation of Digital Orthophotographs (DOQs) in 1987. The USGS, in a cooperative effort with the U.S. Department of Agriculture, began creation of DOQs for the 48 contiguous states. A DOQ is a computer-generated image of an aerial photograph in which image displacement caused by terrain relief and camera tilt has been removed; thus a DOQ combines the image content characteristics of a photograph with the geometric qualities of a map. DOQs produced by the USGS are either gray-scale, natural-color, or color-infrared (CIR) images with 1-meter ground resolution. Each DOQ has between 50 and 300 meters of overedge image beyond the latitude and longitude corner crosses embedded in the image. The overedge allows seamless mosaicking of the individual image tiles to create the user-desired area of interest. The DOQ became a standard layer for control and registration for many GIS applications. DOQs also saw use in topographic mapping in the 1990s.

Geographic information systems began playing a larger role in topographic map production in the 1990s. The first all digital quadrangle produced from USGS DLG data and map modernization methods using GIS in a system known as Revision/Product Generation (RevPG) was Park Ridge, Illinois, in 1993. RevPG was a collection of Arc/Info Macro Language modules, C routines, shell scripts, and interface menus created by the USGS for revising DLG data and producing maps. DLG revision is performed using a Digital Orthophoto Quadrangle (DOQ). RevPG also provided display symbology and other support for the production of printed maps from DLGs corresponding to standard USGS topographic quadrangle specifications. It was available for download to use with various Windows and UNIX operating systems.

The need for digital cartographic data for the 1990 census led to the rapid scanning and conversion of the USGS 1:100,000-scale topographic maps. Transportation and hydrography were photographically transferred to special scanning Mylar sheets that were used in the Scitex scanners. Automatic conversion to vector representation and building of topological structure was developed. Hydrography and transportation from 1:100,000-scale topographic maps became TIGER files for the Census. TIGER strength and importance was because of its focus on the attributes of nodes, primarily the digitized node coordinates (Marx, 1986; Cooke, 1998)

USGS research focused on extending the DLG model with a feature-based approach, DLG-Enhanced (DLG-E). Continuing efforts in the area of data models and standards led to the development of DLG-Feature (DLG-F), the Spatial Data Transfer Standard (SDTS), and eventually to a production data model for the National Hydrography Dataset (NHD).

In the 1990s, the USGS began the development of "seamless" nationwide datasets. The National Elevation Dataset (NED) was created by merging the highest-resolution, best quality elevation data available across the United Statesinto a seamless raster format. NED is the result of the maturation of the USGS effort to provide DEM data for the conterminous United States based on the 7.5 minute quadrangle format and 15-minute format for Alaska. NED has a consistent projection, resolution, and elevation units, and is a living dataset that is updated bimonthly to incorporate the "best available" DEM data.

The USGS, in cooperation with the U.S. Environmental Protection Agency, has produced a land-cover dataset for the conterminous United States based on 1992 Landsat Thematic Mapper images and supplemental data. The seamless NLCD contains 21 categories of land-cover information suitable for a variety of state and regional applications, including landscape analysis, land management, and modeling nutrient and pesticide runoff.

The National Hydrography Dataset (NHD) is a comprehensive set of digital spatial data representing the surface water of the United States using common features such as lakes, ponds, streams, rivers, canals, and oceans. The seamless NHD adopted the feature-based concepts pioneered by the USGS with DLG-E and DLG-F, and initiated a new concept in stewardship and management of USGS data. These data are designed to be used in general mapping and in the analysis of surface-water systems using GIS. In mapping, the NHD is used with other data themes such as elevation, boundaries, and transportation to produce general reference maps.

A Digital Raster Graphic (DRG) is a scanned image of a USGS standard series topographic map, including all map collar information. The image inside the map neatline is georeferenced to the surface of the earth and fit to the Universal Transverse Mercator (UTM) coordinate system. The horizontal positional accuracy and datum of the DRG matches the accuracy and datum of the source map. The map is scanned at a minimum resolution of 250 dots per inch.

Distributed geospatial technology

Internet cartography came alive in the mid-1990s, creating changes in cartography, GIS, and non-spatial information expertise, and resulting in the fabrication of new virtual worlds to be mapped and analyzed (McEachren, 1998). The USGS embraced Internet cartography as it applied to topographic mapping by putting the National digital databases on line. The launching of *The National Map* followed soon after the Internet became widely available and used for mapping purposes.

The USGS vision for the 21st Century topographic map, *The National Map*, was released in 2001. *The National Map* is a collaborative effort among the USGS and other Federal, State, and local partners to improve and deliver topographic information for the Nation. It is accessible for display on the Web, as products and services, and as downloadable data. The geographic information available from *The National Map* includes DOQs, NED, NHD, NLCD, GNIS, boundaries, transportation, and structures. *The National Map* contributes to the NSDI and currently (2009) is being transformed to better serve the geospatial community by providing high quality, integrated geospatial data and improved products and services including new generation digital topographic maps.

The National Map includes eight data layers: transportation, structures, orthoimagery, hydrography, land cover, geographic names, boundaries, and elevation. The graphic product generated from *The National Map* is a "Digital Map" for a 1:24,000-scale printed product distributed as a GeoPDF. The first release of this map includes an orthophoto image, transportation, geographic names, and the U.S. National Grid. In 2010, contours and hydrography will be added to the graphic and by 2011 the GeoPDF will include all eight data layers of *The National Map*.

With the distribution of each new Digital Map, the USGS also will deliver high-resolution scanned images, geocoded to the U.S. National Grid, of all historical maps of the same area. In addition to the previous 7.5 minute editions, the Digital Map distribution includes maps of the area produced at smaller scales. The USGS is committed to providing the current topographic map user with the new Digital Map and all previous topographic maps of the area, including those generated with earlier technology in the late 1800s.

Conclusions

The USGS has an extensive history in topographic mapping and geographic information technology. Throughout this history, USGS employees have been dedicated to producing quality products for scientific and public use and creative in application of available technologies to mapping and geographic information. Requirements for the first topographic maps demanded the highest quality reproduction of the time, copper plates. The USGS used copper plates until better reproduction techniques were available in the form of scribecoat, film, and offset lithography on a five-color press. Developments in the areas of field surveying, photogrammetry, cartography, and map reproduction, some developed by the USGS and others by the industry in general, have been adopted to help the USGS achieve its mission of providing topographic maps and geospatial information in the public domain.

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