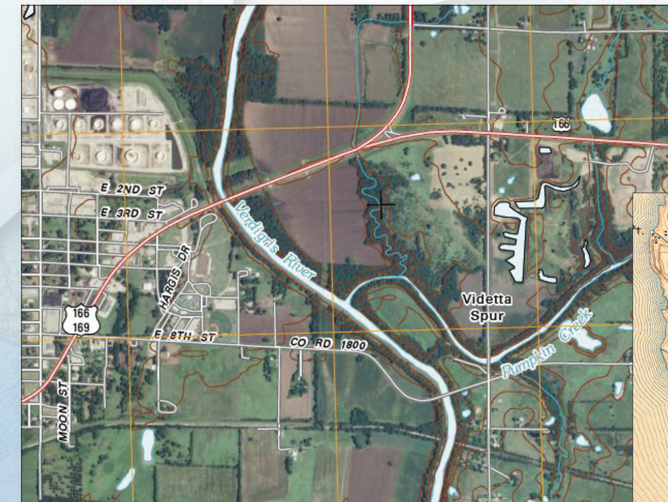
GIS Best Practices

125 Years of Topographic Mapping at USGS



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What Is GIS?

Making decisions based on geography is basic to human thinking. Where shall we go, what will it be like, and what shall we do when we get there are applied to the simple event of going to the store or to the major event of launching a bathysphere into the ocean's depths. By understanding geography and people's relationship to location, we can make informed decisions about the way we live on our planet. A geographic information system (GIS) is a technological tool for comprehending geography and making intelligent decisions.

GIS organizes geographic data so that a person reading a map can select data necessary for a specific project or task. A thematic map has a table of contents that allows the reader to add layers of information to a basemap of real-world locations. For example, a social analyst might use the basemap of Eugene, Oregon, and select datasets from the U.S. Census Bureau to add data layers to a map that shows residents' education levels, ages, and employment status. With an ability to combine a variety of datasets in an infinite number of ways, GIS is a useful tool for nearly every field of knowledge from archaeology to zoology.

A good GIS program is able to process geographic data from a variety of sources and integrate it into a map project. Many countries have an abundance of geographic data for analysis, and governments often make GIS datasets publicly available. Map file databases often come included with GIS packages; others can be obtained from both commercial vendors and government agencies. Some data is gathered in the field by global positioning units that attach a location coordinate (latitude and longitude) to a feature such as a pump station.

GIS maps are interactive. On the computer screen, map users can scan a GIS map in any direction, zoom in or out, and change the nature of the information contained in the map. They can choose whether to see the roads, how many roads to see, and how roads should be depicted. Then they can select what other items they wish to view alongside these roads such as storm drains, gas lines, rare plants, or hospitals. Some GIS programs are designed to perform sophisticated calculations for tracking storms or predicting erosion patterns. GIS applications can be embedded into common activities such as verifying an address.

From routinely performing work-related tasks to scientifically exploring the complexities of our world, GIS gives people the geographic advantage to become more productive, more aware, and more responsive citizens of planet Earth.

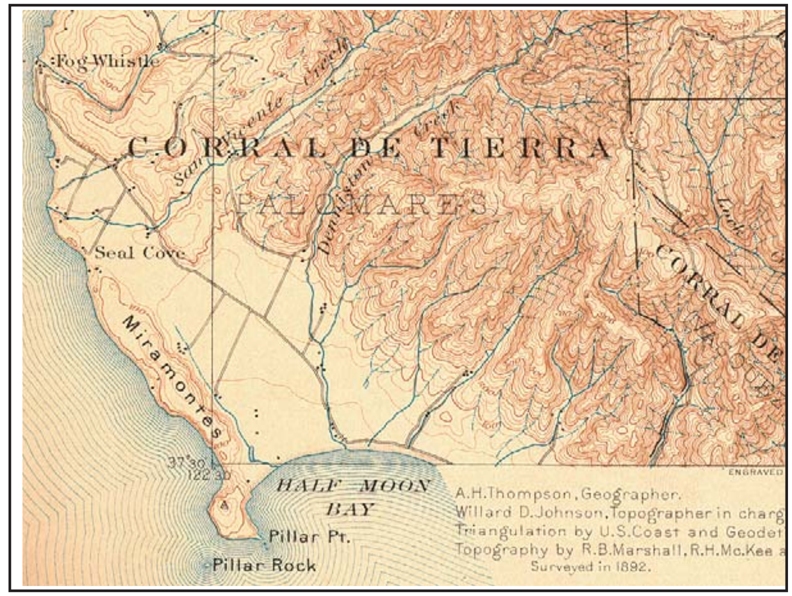
Introduction

The United States' largest water, earth, and biological science and civilian mapping agency, the U.S. Geological Survey (USGS), was organized in 1879 and recently celebrated the 125th anniversary of its national program for topographic maps (1884–2009). More than 55,000 7.5-minute, 1:24,000-scale topographic maps were compiled and published by USGS in the twentieth century, culminating in complete coverage of the contiguous 48 states in 1991. Together with the rise of the digital age and the explosion of Internet-based technologies, GIS technology has transformed topographic mapping science, enabling the electronic construct of the *National Map* of today. In offering the public an immense, authoritative resource for place-based analysis, diverse customization, and broad distribution of geographic information, the *National Map* has become the people's map.

USGS History, Part 1: 1884–1980

By E. Lynn Usery, Dalia Varanka, and Michael P. Finn, U.S. Geological Survey

On December 4–5, 1884, John Wesley Powell persuaded the U.S. Congress to authorize the U.S. Geological Survey (USGS) to begin systematic topographic mapping of the United States.



A portion of an early USGS topographic map surveyed in 1892, using contours for terrain and the water-lining method of representation for water bodies.

During the next 125 years, mapping techniques evolved from field surveys through photogrammetry to the computer-based methods currently used, and the scales and content of the topographic maps changed. It is the purpose of this two-part article to provide details of the USGS mapping processes through time and to help demonstrate that innovations by USGS employees and provision of public domain geospatial data helped spur the evolution and development of digital GIS and the commercial market for geospatial data and products of today. This first article describes topographic mapping developments prior to widespread use of GIS.

In the late 19th century, surveyors created topographic maps in the field. They measured a series of points in the field, using tape and compass traverses with elevations determined with an aneroid barometer and used in a process known as field sketching to draw a terrain representation using contours. The introduction of the plane table and alidade, which could measure vertical angles, point positions, and elevations much more rapidly, greatly increased the accuracy of data shown on topographic maps but still required the surveyor to field sketch the contours after control points had been identified. The aid of a visual three-dimensional model in the office to construct the surface representation awaited the development of photogrammetry.

During this time, USGS maps were created at scales of 1:250,000 for 1-degree areas and 1:125,000 for 30-minute areas. The scales were increased with time, and by 1894, most of the maps were created for 15-minute areas and produced at a scale of 1:62,500. Features shown on the maps included civil divisions of state, county, township, and city or village; public works, including railroads, tunnels, wagon roads, trails, bridges, ferries, fords, dams, canals, and acequias; hypsography with contours and floodplain representations; and miscellaneous features of forest, sand, and sand dunes.

The reproduction of maps from the original field sketches used a lithographic printing process based on copper plates. The image of the topographic features was engraved on the copper plates. A three-color process was used with civil divisions and public works in black, hydrography in blue, and hypsography and miscellaneous features in brown.

USGS cartographers commissioned for service in the Army Corps during World War I brought back knowledge of aerial photography. Throughout the 1920s, USGS experimented with photogrammetry, but it was not until the 1930s during the Great Depression, when the Tennessee Valley Authority needed complete topographic maps of the entire Tennessee Valley and was under time constraints for mapping, that USGS established a multiplex mapping office in Chattanooga, Tennessee.

The ability to view a three-dimensional terrain surface by doubly reflecting the overlap area, or stereomodel, of a pair of stereophotos in a multiplex stereoplotter effectively replaced the requirements of field sketching. An operator could fix a vertical floating mark at a preset elevation in the stereomodel and trace contours to represent the terrain. Similarly, tracing a road or other planimetric feature in the stereomodel, but allowing the mark to change elevation along the feature, provided recording of all required planimetric features for the topographic map.

After 1942, USGS used pen-and-ink drawings that were photographed to film separations, eliminating the need for copper plates. After a few years, the pen-and-ink process was replaced by engravers and scribe coat. The scribe coat replaced the film in the pen-and-ink process and could be used directly for photographic reproduction.

The 1:24,000-scale 7.5-minute mapping program resulted from demand for more detail on the topographic maps. With the larger scale, USGS included almost 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. The color separations were composited on a five-color lithographic press.

USGS widely adopted photogrammetry as part of the mapping process after World War II, and USGS employees developed innovations in the production workflow and instrumentation. Russell K. Bean of USGS 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 for USGS and was later manufactured and marketed by Bausch & Lomb as the Balplex stereoplotter. Also, during this period, the Kelsh stereoplotter, invented by Harry T. Kelsh of USGS, was widely adopted. A USGS innovation for the Kelsh and other optical projection stereoplotters was stereo image alternation (SIA), which operators often called the "squirrel cage" because of the rotating shutters inside a short metal tube; when viewed with the naked eye, SIA sequentially presented the left photo to the left eye and the right photo to the right eye to form the stereomodel.

Additional innovation and developments provided USGS with solutions for stereoplotting, aerotriangulation, point measurement, and other photogrammetric operations. The Kelsh stereoplotters were used in areas of moderate to high relief, but low-relief areas, such as along the coasts and large parts of the Great Plains, required the capabilities of the "heavy" stereoplotters that used projection by mechanical rods. These stereoplotters included the Wild A8 and B8; the Kern PG-2; and others of German, Swiss, and Italian manufacture. The Kelsh and the heavy plotters were used until completion of the 7.5-minute topographic map series in 1991; however, additional innovations led to the concept and technology for producing orthophotos in the 1960s.

The development by USGS of the orthophoto concept and building of a practical orthophotoscope by Bean, with a patent in 1959, led to the production of orthophotoquads—rectified aerial photos. Orthophotos became a standard product of USGS and later served as a base for the 7.5-minute topographic maps.

Many other innovations affected the mapping process, such as the measurement of angles in the field with instruments, including transits and theodolites. Distances were measured with electronic distance measuring units using microwave technology and, later, lasers.

The development of computers may represent the greatest technological innovation to change the mapping process, and USGS employees were quick to embrace this technology. In the 1960s, USGS developed the AutoPlot, a device that used stepping motors to move scribing engravers to create a scribe coat negative of the topographic map neat line (latitude and longitude lines that bound the quadrangles) and horizontal pass points.

After 1970, USGS embarked on three different tracks using digital technology. First, it initiated a massive program to manually digitize existing maps to create a product with an arc/node data model, known as a digital line graph (DLG). During the same time, USGS used advances in photogrammetric technology that generated an orthophotograph to simultaneously produce a digital elevation model (DEM). Both DLGs and DEMs were placed in the public domain.

A USGS topographer engraves topographic map information onto a copper plate for map reproduction.

The second track was the automation of the map production operation. The Digital Cartographic Software System development included retrofitting analog stereoplotters, such as the PG-2, with three-axis digitizers to collect and record the x,y coordinates and attributes of geographic features from the stereomodel to a magnetic tape. The tape later was used to drive a large-format automatic plotter, a Gerber 4477, to engrave the map data onto the scribe coat, or to drive a photohead device to expose a film negative. USGS also developed a cartographic interactive editing capability, referred to as the Graphic Map Production System. The scribe coats or film negatives from the final editing process became the color separations necessary for the five-color press to create the lithographic map.

The final track was the development of a land-cover data-generating program, Land Use Data Analysis. The program also developed software, the Geographic Information Retrieval and Analysis System, to support vector graphics and analysis from an arc/node data model. This data became the first complete land-cover dataset for the conterminous 48 states and, as with the DLG and DEM data, was provided in the public domain.

Throughout this period, USGS scientists were developing innovative computer-based data products and hardware/software systems that were made directly available to the public. A software example that persists today is the General Cartographic Transformation Package, written in the 1970s by Atef Elassal, a USGS employee. The computer code in FORTRAN IV (later converted to C and, in 2009, available in C++) can transform data to any of 21 different map projections. This software was the basis of map projection packages that became part of GIS software, which would have its commercial debut in the 1980s.

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USGS History, Part 2: From the Dawn of Digital to *The National Map*

By E. Lynn Usery, Dalia Varanka, and Michael P. Finn, U.S. Geological Survey

The new US Topo product includes hydrography, geographic names, elevation contours, and orthophotos.

The United States Geological Survey (USGS) entered the mainstream of developments in computer-assisted technology for mapping during the 1970s. The introduction by USGS of digital line graphs (DLGs), digital elevation models (DEMs), and land use data analysis (LUDA) nationwide land-cover data provided a base for the rapid expansion of the use of GIS in the 1980s. Whereas USGS had developed the topologically structured DLG data and the Geographic Information Retrieval and Analysis System (GIRAS) for land-cover data, the Map Overlay Statistical System (MOSS), a nontopologically structured GIS software package developed by Autometric, Inc., under contract to the U.S. Fish and Wildlife Service, dominated the use of GIS by federal agencies in the 1970s. Thus, USGS data was used in MOSS, but the topological structure, which later became a requirement for GIS vector datasets, was not used in early GIS applications. The introduction of ESRI's ARC/INFO in 1982 changed that, and by the end of the 1980s, topological structure for vector data was essential, and ARC/INFO was the dominant GIS software package used by federal agencies.

USGS production of the first map series designed specifically for the computer era began in the mid-1970s. USGS designed completely new symbology with solid continuous lines and colors suited for automatic scanning and reproduction with computer technology for the 1:100,000-scale topographic maps. The entire series, more than 1,800 maps, was completed in the 1970s and 1980s. In preparation for the 1990 Census, USGS converted transportation and hydrography from the 1:100,000-scale maps to DLG data.

The conversion process required photographic transfer of the transportation and hydrography line work from film negatives to special polyester film sheets. The polyester film sheets were then highlighted with specific colors in special inks to identify potential problems in the digital conversion process. The polyester film sheets were then scanned at 1,200 dots per inch on a raster drum scanner from Scitex. The scanned data was automatically processed to thin the raster lines to single pixel widths, convert them to vector lines, and build topological structure. During the vectorizing process, the Scitex editing software was set to automatically find the special inks used to mark potential trouble areas for the vectorizing algorithm. After the vectorizing and topological structure construction were complete, the data was transferred to the Census Bureau for additional attribution and entry as part of the Topologically Integrated Geographic Encoding and Referencing (TIGER) line files for the 1990 Census.

Production automation had begun in the 1970s with the development of the Digital Cartographic Software System (DCASS) for photogrammetric compilation and the Graphic Map Production System (GRAMPS) for cartographic editing, leading to the release of the first digitally produced map in a provisional format—of Birch Tree, Missouri—in 1983. During the 1980s, USGS continued its innovative role with developments in DEM and orthophoto production capabilities. From 1974 to 1983, USGS conducted research on 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. Data generated by the system included the laser returns to generate elevations and the video images. This system was a precursor to the lidar systems of today.

In 1987, USGS introduced the concept of the digital orthophoto quadrangle (DOQ), using digital scanning of photographic stereo pairs and processing software to create a digital image with correct map geometry. Following the introduction, USGS, in cooperation with the U.S. Department of Agriculture (USDA), generated digital orthophotos at one-meter resolution for the 48 contiguous states of the United States. The DOQ of USGS became the standard base image for many geographic information systems in the 1990s. USGS and other federal agencies continue to acquire new DOQ coverage of the United States every few years, building to complete repetitive coverage with the Imagery for the Nation (IFTN) program.

USGS began data model development for computer-assisted cartography and GIS in the 1970s with GIRAS, DLG, and DCASS. The development of the Federal Geographic Exchange Format (FGEF) in the late 1970s was the beginning of standardization of data models and formats for geographic information and led to the establishment of the Spatial Data Transfer Standard (SDTS), which was adopted by the International Organization for Standardization in the 1990s. SDTS libraries supporting import and export of data to and from SDTS were developed and made available to the public by USGS. Many GIS vendors incorporated these libraries into their code packages. Simultaneous to development of SDTS, USGS developed the digital line graph—enhanced (DLG-E), a feature-based GIS data model released in 1990. Further refinements of DLG-E led to DLG—feature (DLG-F) and, finally, to the feature-based data model currently used in the National Hydrography Dataset (NHD). Whereas the DLG-E and DLG-F models were not incorporated directly into software for GIS, during the next 15 years, the feature-based ideas pioneered by USGS became standard in the GIS industry.

In 1991, USGS completed the analog map coverage of the 48 contiguous states of the United States at 1:24,000 scale. The coverage includes more than 55,000 7.5-minute quadrangles. While completing the production of the 7.5-minute series of the National Mapping Program and continuing its revision, USGS also continued its developments of digital databases for cartography and GIS. After the completion of United States coverage with 7.5-minute, 1:24,000-scale topographic maps, USGS contracted to have the most recent editions of the maps converted to digital raster graphics (DRGs). The DRGs were geocoded and became a critical layer in GIS, useful for image rectification, feature extraction, and other applications.

In the 1990s, USGS moved from quadrangle areas, usually constructed from 7.5-minute, 15-minute, 30-minute, or 1-degree areas to seamless nationwide layer-based datasets. The first of these completed was the National Elevation Dataset (NED), a multiresolution, seamless, nationwide mosaic of elevations created from existing USGS databases of 7.5-minute tiles with 30-meter horizontal spacing, 7-meter root mean square error (RMSE), 1-degree tiles with 3-arc-second horizontal spacing, and a vertical 30-meter RMSE. USGS has continued to improve the NED with elevations on a 10-meter horizontal spacing that is now available for the conterminous 48 states and, most recently, with lidar data, generating elevations on a 3-meter horizontal spacing.

USGS also began to construct the National Hydrography Dataset (NHD) in the 1990s. The NHD incorporates the concept of geographic features in the form of reaches of streams and other geographic entities to represent surface water. In association with the Environmental Protection Agency (EPA) and many state organizations, USGS embarked on a new system of data maintenance and update with the NHD using a system of stewardship. This system is now becoming a model for other data maintenance agreements.

The National Land Cover Dataset was created as a seamless mosaic of 21 land-cover categories from Landsat Thematic Mapper (TM) images from 1991 to 1992. This 30-meter resolution dataset was released in 2001; a second coverage for the United States was released in 2008 from 2001 TM images. Seamless land cover for the United States provides a base for many scientific applications and is one of the most frequently downloaded of the USGS datasets.

In 2001, USGS released its vision for the topographic map of the 21st century: *The National Map*—a seamless, continuously maintained, nationally consistent set of base geographic data. A collaborative effort to improve and deliver topographic information for the nation, *The National Map* consists of eight data layers: transportation, hydrography, boundaries, structures, geographic names, land cover, elevation, and orthographic images. The goal of *The National Map i*s to become the nation's source for trusted, nationally consistent, integrated, and current topographic information available online for a broad range of uses. The seamless databases constructed in the 1990s and early 2000s became the base data for *The National Map,* with additional data from federal, state, local, and tribal sources being continually added.

In 2009, USGS defined the graphic output to be generated and distributed from *The National Map* as a GeoPDF of the eight data layers. The initial release, known as Digital Map—Beta, included an orthographic image based on photography from the National Agricultural Imagery Program (NAIP), transportation data of interstate and U.S. highways from the Census Bureau, geographic names from the Geographic Names Information System, a United States National Grid shown on 1,000-meter grid lines, and the metadata contained in the map border and collar information. Beginning in October 2009, contours and hydrography were added to the new map, which was renamed US Topo. The remaining layers of *The National Map* will be added to US Topo in 2011. The NAIP photography acquires complete coverage of the 48 contiguous states every three years; thus, USGS will generate new topographic maps every three years to follow the NAIP cycle.

In surveying, photogrammetry, and cartography, USGS innovations have led or enhanced developments in the broader fields of mapping and GIS. USGS developed agreements for local applications and provided data for land and science management needs. This history of accomplishment forms the basis for future innovations for growth of the industry.

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