G

Gannett, Henry. Henry Gannett was an American geographer who is celebrated primarily for establishing new institutions within the federal government to collect and present information depicting aspects of the nation's physical and human geographies. In doing this, he transformed the existing fragmentary approaches into a set of interrelated federal institutions that established a framework for the creation of integrated geographic information systems in the late twentieth century.

Gannett was born in Bath, Maine, 24 August 1846. He proved to be an academically gifted student, and after graduating from high school in 1864 went to sea until entering Harvard's Lawrence Scientific School in the fall of 1866. After graduation in 1869 he participated in a summer field class led by J. D. Whitney, William Henry Brewer, and C. F. Hoffmann, all from the California Geological Survey, and Raphael Pumpelly, just returned from geological exploration in China. The class ranged from the Lake Superior mining region to Colorado. Gannett spent the subsequent academic year at Harvard obtaining a mining engineering degree, and upon graduating in spring 1870 took his first professional position as assistant to Joseph Winlock at the Harvard College Observatory. During the next two years, he compiled maps, prepared calculations to precisely measure the observatory's longitude, and photographed the sun's corona during the famous Mediterranean eclipse in Jerez, Spain.

In the spring of 1872 Gannett joined the U.S. Geological and Geographical Survey of the Territories, led by F. V. Hayden, as its first astronomer-topographer-geographer. He introduced scientific topographic mapping to its existing geological and biological research programs. During seven years with the Hayden survey, Gannett led topographic mapping parties during summer field seasons in the Yellowstone National Park area, Colorado, and Wyoming, and prepared reports and maps during winter office seasons in Washington, D.C.

In 1879, when the federally sponsored scientific expeditions directed by Hayden, Clarence King, and John Wesley Powell were folded into the newly formed U.S. Geological Survey (USGS), the federal government was preparing to conduct its decennial census of population. At the request of the superintendent of the census, Francis Amasa Walker, Gannett joined the tenth U.S. census (1880) in the newly created position of geographer. As the census's first geographer, he established geographic operations to collect information with a door-to-door enumeration of households; to compile that information; and then to present it in substantive reports with maps, charts, and text. These programs included the creation of enumeration districts that were based on the nation's physical and human geographies for the first time and dramatically improved the quality of census information. Gannett served as geographer–assistant director of three U.S. censuses and four censuses overseas—Cuba (twice), Puerto Rico, and the Philippines (North 1915, 10–11).

When the tenth U.S. census concluded in 1882, Gannett joined the USGS, headed by Powell. As its chief geographer, Gannett created the nation's topographic mapping program. Once this program was established as an ongoing operation, he created several additional programs that demonstrated the utility of topographically mapped geographic information for water issues and for the delineation and inventorying of timber stands. In so doing, he geographically defined the nation's initial 110,000 square miles of national forests.

Gannett also chaired the federal government's Board on Geographic Names for twenty years and served on numerous interagency commissions to coordinate federal mapping and other scientific programs. In 1908–9, he directed the research program of President Theodore Roosevelt's National Conservation Commission, which inventoried and projected future demand for the nation's natural resources for the first time.

During his long and productive career, Gannett developed major new institutions not only within the federal government but in the private realm as well. He worked with others to found and manage the National Geographic Society, Association of American Geographers, Cosmos Club, and Geological Society of Washington. He served as secretary of the 1904 Eighth International Geographical Congress (IGC), the first to be conducted in the United States. In conjunction with the IGC, he formulated the standards that guided preparation of the International Map of the World (IMW) at the scale of 1:1,000,000. During his career, he published two hundred scientific and popular articles on human geography, cartography, and process geomorphology topics; edited journals; published academic textbooks; and served on a wide range of committees outside the federal government.

Many of Gannett's programs continued remarkably intact up until the revolutionary transformation that resulted from the introduction of electronic computing at the close of the twentieth century. Elected a fellow of most of the major scientific organizations of his day, Gannett was additionally honored by foreign societies and governments; by Bowdoin College with an honorary doctorate; and most fitting of all perhaps, by the naming of a physical feature for him. When the crest of Wyoming's Wind River Range was measured to produce its first topographic map sheets in 1906, the highest point, still unnamed, was designated Gannett Peak.

When Gannett died 5 November 1914, Washington, D.C., mourned the passing of this unassuming but remarkably productive individual with a memorial service at the National Geographic Society's Hubbard Memorial Hall. Gannett was described then as the father of American mapmaking. Although a definitive biography of Gannett has yet to appear, several accounts provide useful introductions to his career (North 1915; Block 1984; Meyer 1999).

DONALD C. DAHMANN

SEE ALSO: Board on Geographic Names (U.S.); Geographic Names: Applied Toponymy; U.S. Census Bureau; U.S. Geological Survey

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Gazetteer. See Geographic Names: Gazetteer

General Bathymetric Chart of the Oceans (GEBCO).

Bathymetric charts represent submarine relief. They are constructed with isobaths, which are contour lines connecting points of equal depth, and they often include shading between selected isobaths to indicate increasing depth. This type of thematic map became widespread only after the mid-nineteenth century due to technical, scientific, and economic factors: positioning at sea, equipment, and methods for sounding all improved; marine sciences developed; and greater knowledge of seabed relief was needed to lay submarine cables.

Oceanographic expeditions continued to improve this knowledge during the last quarter of the nineteenth century. But simultaneously, nomenclature (the choice of names given to specific submerged features of relief) and terminology (terms describing forms of underwater relief) became anarchic. The Seventh International Geographical Congress in Berlin (1899) addressed this issue (Carpine-Lancre 2005), and it adopted a resolution "nominat[ing] an international committee on the nomenclature of sub-oceanic relief, charged with instigating the preparation and publication of a bathymetrical map of the oceans before the time of the meeting of the next Congress" (International Geographical Congress 1901, 1:314).

The Commission on Sub-Oceanic Nomenclature, composed of nine oceanographers and geographers, convened in Wiesbaden 15–16 April 1903, with Prince Albert I of Monaco as chair. For the design of the map they adopted most of the proposals submitted by French professor Julien Thoulet: sixteen sheets on the Mercator's projection between 72°N and 72°S on the scale of 1:10,000,000; four sheets for each polar cap on the gnomonic projection; the use of the meter as the unit of measure; and Greenwich for the prime meridian (Thoulet 1904). The offer of Prince Albert I of Monaco to assume all expenses was gratefully adopted.

The twenty-four map sheets, the title sheet, and the assembly diagram for the *Carte générale bathymétrique des océans* were printed in Paris in 1905 (fig. 280). Emmanuel de Margerie sternly criticized the errors and shortcomings of this edition, which he felt was too speedily produced. Preparation of a new edition was entrusted to the newly constituted Prince's Cabinet scientifique, and a second commission that met in Monaco in 1910 decided to add terrestrial contour lines. The second edition was printed from 1912 to 1931. This long printing interval, partly due to World War I, made the chart obsolete before the last sheets were printed, and neither the Cabinet scientifique nor the Musée Océanographique de Monaco could afford the technical and financial burden of a new edition insofar as the use of sonic and ultrasonic devices had greatly increased the available data.

The International Hydrographic Bureau (IHB) agreed to keep the General Bathymetric Chart of the Oceans (GEBCO) up to date. The first step was an international inquiry about the usefulness of the chart and desired improvements. Eight revised sheets were printed from 1935 to 1942. After World War II, in spite of the help given by the French Institut géographique national, the IHB was unable to bring the third edition to a successful conclusion (the last three sheets appeared in 1968, and three sheets were never printed). A fourth edition was started in 1958, its preparation shared between eighteen hydrographic services, however only six sheets were printed (up to 1971).

Additional problems needed to be solved. During the Cold War, bathymetric data acquired immense strategic value for submarine navigation. Most of the new information was classified, leading the Lamont Geological Observatory to create a different type of bathymetric chart: the physiographic diagram. However, marine scientists felt more than ever that GEBCO was still necessary, but that it must be produced with greater cooperation of scientists with cartographers for interpretation of the data. The international organizations related to oceanography, including the International Association of Physical Oceanography, the Scientific Committee on Oceanic Research, and the Intergovernmental Oceanographic Commission of UNESCO (United Nations Educational, Scientific and Cultural Organization), brought increasing attention to the endeavor, and their efforts were successful. The fifth edition was published in 1982 by the Canadian Hydrographic Service, with the eighteen sheets receiving different numbering and boundary limits than previous editions (fig. 281).

The permanent problem of updating the chart led to the digitization of the data by the British Oceanographic Data Centre. A digital atlas was published on CD-ROM in 1994 and revised in 1997. A centenary edition was prepared and distributed on the occasion of the meeting held in Monaco in 2003 (British Oceanographic Data Centre 2003; Scott 2003). The latest development is the 1-minute Global Bathymetric Grid (2006).

JACQUELINE CARPINE-LANCRE

SEE ALSO: Digital Worldwide Mapping Projects; Geographic Names: (1) Applied Toponymy, (2) Gazetteer; International Hydrographic Organization (Monaco); Law of the Sea; Marine Chart; Marine Charting

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Genetics and Cartography.

Perhaps the first attempt to represent genetic data on a geographic map can be attributed to J. B. S. Haldane, considered one of the founders of population genetics. This branch of genetics focuses on gene and DNA variants, in particular on their frequency, distribution, and change under the influence of the four evolutionary forces: natural selection, genetic drift, mutation, and gene flow. To interpret the results, population geneticists take into account population subdivisions and population differences in space, termed "genetic structures" because, in genetics, "cartography" refers exclusively to the mapping of genes on chromosomes.

In 1940 Haldane plotted the blood-group frequencies of European peoples as mathematically computed contour maps. Following in the steps of physical anthropologists, he sought to infer the past of European populations, up to Neolithic times, from present-day genetic variability. For almost forty years after Haldane, the only genetic markers offering a satisfactory worldwide geographic coverage of human populations were still constituted by blood phenotypes, as demonstrated by the research (through 1976) of A. E. Mourant and his colleagues, who similarly displayed their results as contour maps with isolines threaded manually—"by eye"—rather than estimated mathematically. The main preoccupation at the time was the identification of new markers and DNA variants as well as their localization on chromosomes. This is why the effort of population geneticists to represent their data geographically was minimal.

The ability to use DNA variation to reconstruct the demographic history of populations increased through the 1970s and exploded in the last decade of the twentieth century with the advent of PCR (polymerase chain reaction), a method to replicate DNA sequences. New markers became available and human populations were typed intensively. While the use of several markers promoted more reliable studies by minimizing stochastic errors, a new approach to geographic mapping of the results was needed because thematic maps describing the variability of a single marker were no longer efficient. A solution suggested by Alberto Piazza involved using principal components analysis (PCA) to reduce a large number of markers to the first components (often the first, second, and third) and plotting each of them on a separate three-dimensional map. On each map individual samples were represented by (x, y, z) points, where x and y were the longitude and latitude coordinates and z was the component score. Adopted in 1994 in a reference book about the history and geography of human

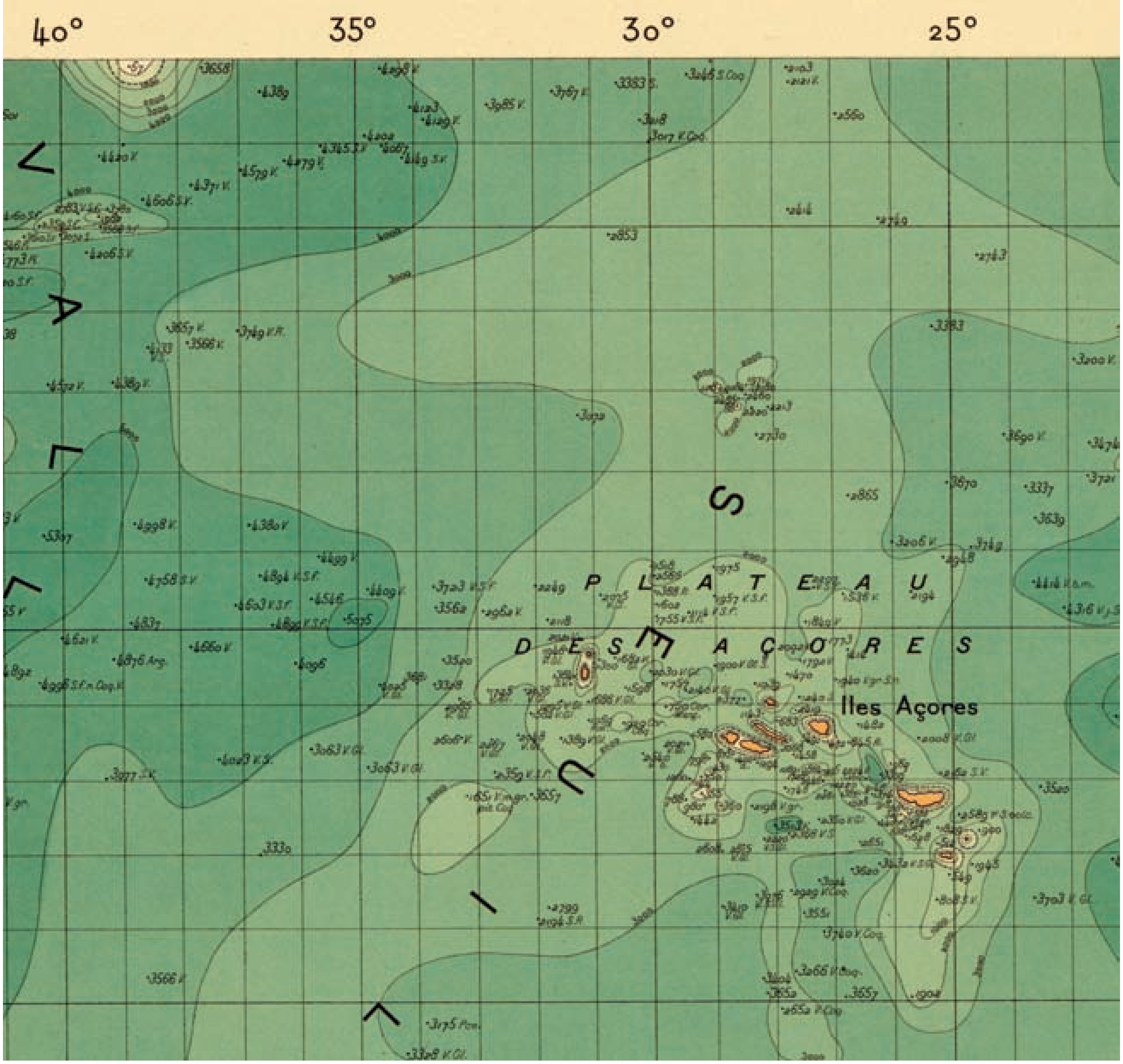

FIG. 280. DETAIL OF THE AZORES, *CARTE GÉNÉRALE BATHYMÉTRIQUE DES OCÉANS*, FIRST EDITION, 1905. Paris: Impr. Erhard, twenty-four sheets at a scale of 1:10,000,000. This part of sheet A1 shows an area extensively studied by Prince Albert I of Monaco, during his oceanographic cruises.

Size of the detail: ca. 20 × 21 cm. Image courtesy of the American Geographical Society Library, University of Wisconsin–Milwaukee Libraries.

genetic variability (fig. 282), this technique caught the attention of scholars outside the discipline (notably archaeologists and historical linguists) as well as a broader public.

However intriguing, these maps conveyed a false sense of precision insofar as the interpolation process used to fit contour lines to point data strongly influenced the mapped pattern. To provide more reliable maps of genetic differences, Guido Barbujani and Robert R. Sokal (1990) adopted the Wombling procedure (Womble 1951) to identify the zones of abrupt genetic change. Later, Barbujani et al. (1996) introduced in genetics the maximum difference algorithm developed by Mark Monmonier (1973). This method proved well suited for identifying, without resort to interpolation, those samples highly different from their neighbors.

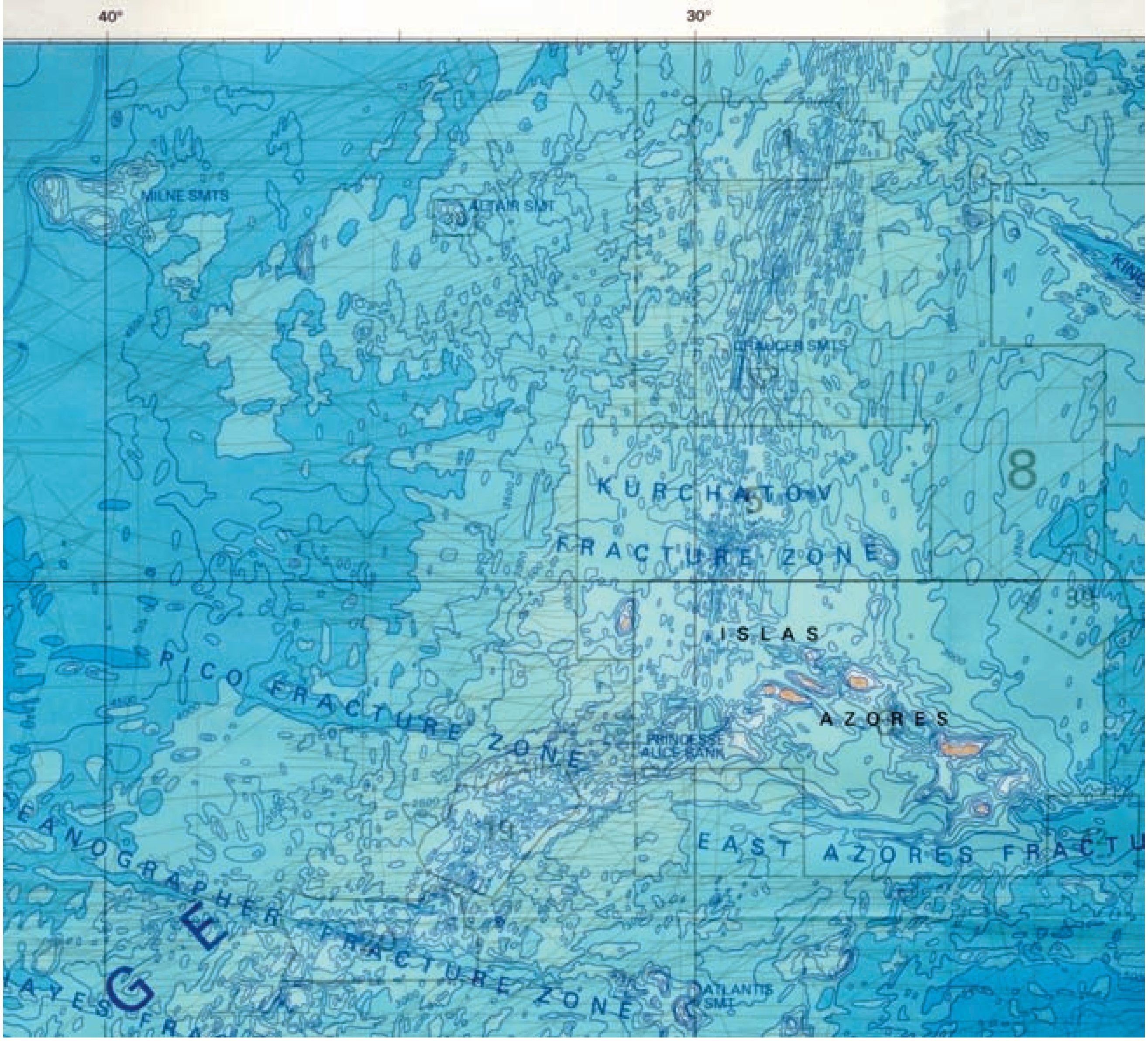

FIG. 281. DETAIL OF THE AZORES, *GENERAL BATHYMETRIC CHART OF THE OCEANS/CARTE GÉNÉRALE BATHYMÉTRIQUE DES OCÉANS*, FIFTH EDITION, 1982. Canadian Hydrographic Service, eighteen sheets, at various sizes and scales. This part of sheet 5-08 illustrates the changes between the first and the fifth editions of the chart. Ottawa: Canadian Government Publishing Centre.

Size of the detail: ca. 19.9 × 21.6 cm. Reproduced with the permission of the Canadian Hydrographic Service, Ottawa. In a standard disclaimer, the publisher advises that the chart is "not to be used for navigation."

Boundary methods epitomize the geneticist's interest in the difference between populations rather than in their homogeneity. This is understandable insofar as only 15 percent of the variance of the human genome is explained by differences between groups of populations, in contrast to individual differences within a population, which account for 85 percent of the total variance—the reason why the scientific definition of race does not apply to humans.

In the 1980s, work by population geneticists promoted the study of the geographical distribution of genealogical lineages, termed "phylogeography" (Avise 1998; Hewitt 2001). Such studies proved to be effective in reconstructing refugia (areas that fostered relict species by escaping wider ecological changes), postglacial colonization routes, and the speciation processes of different organisms. These studies also helped geneticists

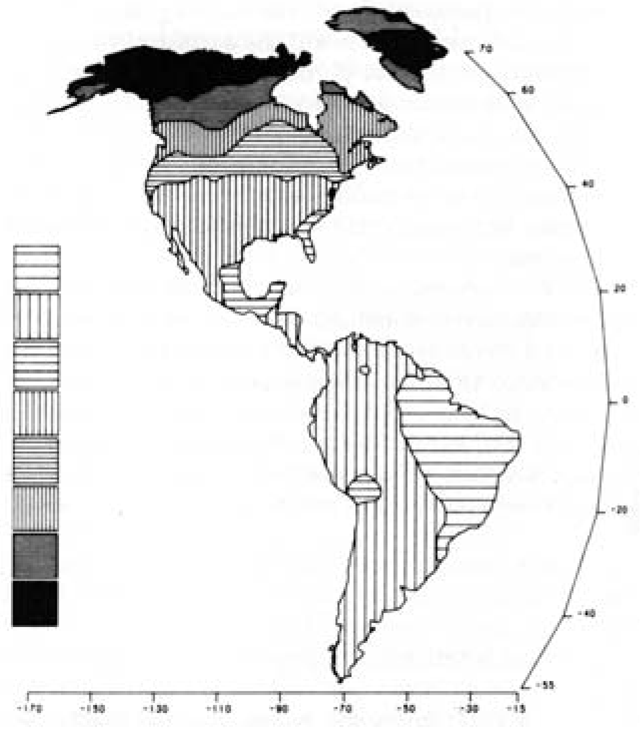

FIG. 282. SYNTHETIC MAP OF THE AMERICAS USING THE FIRST PRINCIPAL COMPONENT. Example of Alberto Piazza's strategy for mapping separately principal components (PCs) extracted from a multivariate set of marker data. This synthetic map displays the first of the seven PCs that were computed. It accounts for the variation of seventy-two genes and explains 32.6 percent of the total variance. The map shows a north-south gradient in North and Central America with the greatest slope in Canada, thus emphasizing the distinction between the Eskimos + Na-Dene group and Amerind populations closer to Eskimos on the one side, and the rest of America on the other. In South America there is differentiation between east and west. For easy visual recognition, Piazza used eight classes of PC values, but his choice of the increasing or decreasing density of shading is totally arbitrary; it could be reversed without any loss of information. Intermediate classes are close to the average, whereas extreme classes indicate populations that globally differ most from each other for the particular PC under study. Populations and regions with similar shading do not need to be similar, for they may be very different for another PC. In such synthetic maps, Piazza preferred not to display the location of samples.
Size of the original: 9.5 × 8.3 cm. From Cavalli-Sforza, Menozzi, and Piazza 1994, 338 (fig. 6.13.1). © 1994 Princeton University Press. Reprinted by permission of Princeton University Press.

define appropriate policies for preserving endangered species (or populations), avoiding excessive levels of consanguinity in living stocks, and reintroducing animals with a genetic makeup similar to that of an extinct or displaced species. Such tasks required a straightforward and effective evaluation of the habitat based on a refined level of geographic detail and on the use of geographic information systems.

Although geographic cartography used in genetics in the latter half of the twentieth century might appear simplistic, new challenges seem likely as a result of efforts by Gustave Malécot (1948) and other theorists to mathematically model the relations existing between the genetic distance between pairs of populations and the corresponding geographic distance. An appropriate representation of this model may inspire the next step in the geographic portrayal of genetic differences.

FRANZ MANNI

SEE ALSO: Biogeography and Cartography; Ethnographic Map; Linguistic Map; Statistics and Cartography

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Geocoding. In the 1960s and 1970s the term "geocoding" referred to a broad array of activities associated with systems of referencing data spatially (Dueker 1974). Geocoding was a central element of methods for computer processing of geographic data. Waldo R. Tobler (1972) defined geocoding broadly as place naming, with two types of place-names. The first are nominal or ordinal names or codes that require a map to infer location. The second are coordinate-based, which make geographical relationships explicit. Early geocoding systems dealt with the first type of place-names, processing codes for places that were not geometrically defined (Shumacker 1972). Over time, geocoding systems moved from the first type of place-names to a more explicit encoding of spatial location and geographical relationships. Currently, geocoding is thought of more strictly as the process of assigning geographic coordinates expressed in latitude-longitude or *x, y* form to map features and associated data records referenced by a street address. Geocoding has been closely tied to geographic information systems (GIS) and is now commonly thought of as the process of finding the location of an address with a GIS (Arctur and Zeiler 2004). Street addresses are the most commonly used means by which users can enter their location of interest to GIS. These addresses are geocoded to geographic coordinates or geographic unit codes employed in GIS. With the advent of Global Positioning System (GPS) technology in the 1980s, reverse geocoding was developed for the assignment of GPS-derived latitude and longitude values to streets and intersections, as well as to nearby points of interest such as an address of a business.

Geocoding relies on directories or databases to convert addresses or place-names to geographic area codes or coordinates. This requires complete street address information and an accurate geocoding database of place codes and coordinates. Early geocoding efforts in the United States focused on standardizing place codes used by various state and federal agencies. Standardization of state, county, and city codes was needed to collect sharable data. However, efforts to standardize geocoding below the city and county level floundered due to the lack of a common small geographic area, such as a city block, that served a broad community of users (Werner 1974, 312). National-level geocoding in the United States had to await two developments: extension of urban-style addresses to rural areas to support emergency dispatch and the development of a nationwide geographic base file, TIGER Line (Topologically Integrated Geographic Encoding and Referencing), by the U.S. Bureau of the Census, which was first used in 1990, replacing Dual Independent Map Encoding (DIME), which was limited to metropolitan areas.

Urban area geocoding efforts emerged independently in several locations but developed largely in conjunction with planning and implementation of the 1970 U.S. Census of Population and Housing (Dueker 1974). The U.S. Bureau of the Census developed address coding guides (ACG) for metropolitan areas to automate enumeration using mail-out and mail-back questionnaires. The ACG consisted of a table of ranges of street addresses within each census block (Fay 1966). Figure 283 illustrates the dual encoding of a line network consisting of street segments with adjacent blocks. Table 14 illustrates the conceptual format of the ACG that assigns a street address to census block, tract, and county codes for subsequent tabulation for streets in figure 283. Field testing showed compilation of an ACG was error prone since it was easy to transpose right and left codes and difficult to detect these errors. Nevertheless, the computerized data access and use procedures developed for the 1970 census were responsible for creating the current demographic analysis industry (Cooke 1998).

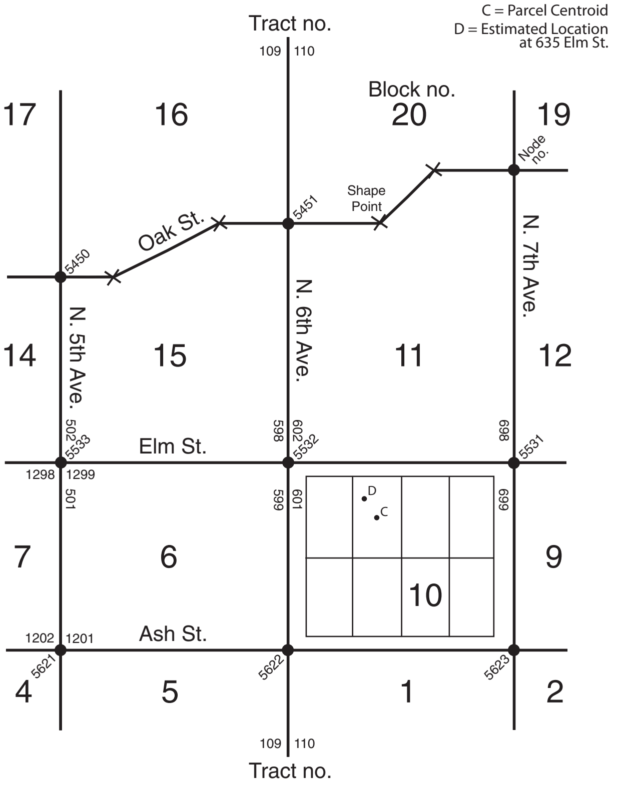

FIG. 283. DUAL ENCODING OF STREET SEGMENTS AND BLOCKS.

To remedy deficiencies of the ACG the Census Bureau developed the DIME mapping process that was based on applying mathematics of graph theory and topology to the urban street system (Corbett 1979). When combined with the address coding guide, it was called ACG/DIME. By 1980, ACG/DIME had been renamed Geographic Base File DIME (GBF/DIME).

The 1966 New Haven Census Use Study provided a test bed for DIME file design and implementation (Cooke and Maxfield 1967). The street system was encoded as a graph with nodes representing intersections (and bends in roads and ends of dead-end streets), and lines representing street segments (and railroads, political boundaries, and water features) that make up areas representing census blocks. The mathematical dual is a boundary network consisting of blocks with bounding streets. Chaining boundary streets around blocks is done to verify that streets are encoded correctly. This editing ensured the integrity of the GBF/DIME.

Geocoding involves a spatial lookup of an address against a geographic database that spatially encloses any possible address and whose address style is of the same type as the addresses being geocoded. The spa-

Table 14. Address coding guide: the table look-up approach

Odd/even	Low address	High address	Street prefix	Street name	Street type	Street suffix	Block number	Tract number
E	502	598		Ash	St		6	109
O	501	599		Ash	St		5	109
E	502	598		Elm	St		15	109
O	501	599		Elm	St		6	109
E	1202	1298	N	5	Av		7	109
O	1201	1299	N	5	Av		6	109
E	1202	1298	N	6	Av		6	109
O	1201	1299	N	6	Av		10	110

tial look-up process depends on efficient parsing of addresses to standardize abbreviations and to separate component parts—number, street prefix, street name, and street type—as well as on efficient spatial indexing of address ranges by state, city, and/or ZIP code. The geocoding process then searches for matches between the input address and the geographic database. The procedure may find a number of possible matches; users may be asked to choose from a list of candidates, or the procedure may assign probabilities for selection of the correct street segment when doing bulk geocoding.

The U.S. Bureau of the Census (1971) led in the development of ADMATCH geocoding software as the address matching system for DIME files used in the 1970 Census. ADMATCH operated by linking a data file containing street addresses or address ranges and a geographic reference file containing street addresses and corresponding geocodes. A matcher program analyzed the street addresses in the data file according to syntax and keywords specified by the user and created a standard version of each address called a match key. Each match key was then compared with the geographic reference records with the same street name and the best match was selected according to a weighting scheme defined by the user.

The GBF/DIME file system was followed by the development of TIGER, the seamless nationwide digital map file system. TIGER was implemented by U.S. Census Bureau geographer Robert W. Marx and his team for the 1990 Census (Cooke 1998, 54–55; Marx 1986). The main differences between DIME and TIGER files were better cartography and extended coverage from metropolitan areas to nationwide in the TIGER system. Legacy TIGER Line files and the redesigned master address files (MAF/TIGER) have become the database basis for modern address geocoding systems (Galdi 2005).

Vendors commercializing geocoding for business GIS use have played an important role in extending geocoding content and performance. In the 1970s Urban Data Processing Inc. used street address matching software with Census ACG/DIME files to provide geocoding services for 85 of the 100 largest banks in the United States. This was the first major commercialization of geocoding. Both Geographic Data Technology (GDT) and Etak purchased Census GBF/DIME and TIGER files in the 1980s, improved their accuracy and currentness, and sold the improved databases and geographic services both to businesses and a growing vehicle navigation market. Etak and GDT wrote and commercialized batch and interactive address matching programs for geocoding with their databases.

By century's end geocoding was commonplace. Business information systems often start by asking for a person's ZIP code, and the system responds with addresses of their stores within the ZIP code or in nearby ZIP codes (Wombold and Ting 2006). This capability is based on a database of adjacent or nearby ZIP codes. This is a coarse geocoding based on geographic areas rather than coordinates. More precise geocoding converts a unique street address to a unique coordinate location, which enables business information systems to distance order their stores from the street address, using either straight line or on-street distance. Current database products provide addresses accurate to individual buildings. Addresses are represented as discrete points rather than approximations interpolated from address ranges for street segments.

Vehicle navigation systems, using Navteq street centerline databases and Internet map services like MapQuest, calculate routes from geocoded origins and destinations and provide driving instructions and a map with highlighted street route segments. Using Google Maps to zoom to a specific location below the city level involves geocoding an address from an underlying Navteq street centerline database. Then one can zoom in or out and drape imagery on the map.

Table 15. Geocoding accuracy and method

Positional Accuracy (low to high)	Geocoding Method	Example
+/−10,000 m	County name to centroid table	Relate vital statistics to population data
1000 m	Street address to census tract table	Relate individual health data to areas of high poverty
1000 m	ZIP code to centroid file	Find nearby businesses
100 m	Interpolate addresses along street segments	Find approximate locations
10 m	Street address to land parcel table	Find parcel boundary/centroid
10 m	Street address to building footprint table	Find building boundary/centroid
1 m	GPS	Find precise location directly

Assigning a geocode involves conversion of place-names and street addresses that are familiar to positionally accurate coordinates that can be used for computing distances and assignment to areas by means of a point-in-polygon routine. Table 15 illustrates the positional accuracy of various geocoding methods.

The more commonly known geographic place-names for cities, counties, and states do not yield very precise locations. Street addresses can yield greater positional accuracy if investments are made in look-up tables based on accurate positions of streets, parcels, or buildings. While geocoding in the United States relies heavily on street address conversion, other countries with more centralized land records rely on land and property data to construct street addresses used in land parcel look-up tables to improve geocoding accuracy (Morad 2002).

Some geocoding systems rely on look-up tables to directly relate addresses to school attendance areas, emergency service zones, and other service areas. This is not recommended, however, as a change in service area boundaries requires extensive and error-prone updating of the look-up tables. Representation of service areas as polygons and addresses as coordinate points leads to fewer geocoding errors.

The need for positional accuracy depends on the application. For example, environmental health applications may need to geocode the locations of patient homes relative to toxic waste plumes. Geocoding accuracy of plumes, whether aerial, surface, or subsurface, is also an issue. Similarly, accurate assignment of welfare cases to statistical areas is needed to assess causes of poverty.

The six character postal codes in Canada fully implemented in 1974, alphanumeric post codes in Britain introduced over a fifteen-year period from 1959 to 1974, and five-digit ZIP codes begun in the United States in 1963 are useful because people know them and they are easy to relate to a point location. But they do not relate to unambiguous areas. Postal codes can denote a specific single address or range of addresses, which can correspond to an entire small town, a significant part of a medium-sized town, a single side of a city block in larger cities, a single large building or a portion of a very large one, a single (large) institution such as a university or a hospital, a business that receives large volumes of mail on a regular basis, postal facilities, or a rural route. A postal code can be wholly contained in another. In 1970, the U.S. Bureau of the Census provided approximated ZIP code tabulations (three-digit ZIP codes outside of Standard Metropolitan Statistical Areas [SMSAs] and five-digit ZIP codes inside SMSAs), for 1980 as a special tabulation, in 1990 based on an equivalency file relating commercial census blocks to ZIP codes, and in 2000 and 2010 by ZIP Code Tabulation Areas (ZCTA) based on groupings of census blocks.

The development of reference data that were strengthened by applying principles of topology to the encoding of map information advanced rapidly during the latter half of the twentieth century, as computing power increased. Until the advent of robust GIS software in the 1980s, homegrown software tools were developed for aggregating discrete data to small area data for map display and analysis. The process of assigning a small area code to data with a street address as the location identifier became known as geocoding. Building reference databases for geocoding was a major issue from the mid-1960s to the late 1980s when TIGER became stable and GIS software tools to use it became widely available. The U.S. Bureau of the Census was largely responsible for standardizing and developing reference materials needed for geocoding in the United States. Although their motive was to convert to a mail-out, mail-back decennial census of population and housing, the reference materials have served many uses and have become building blocks for many GIS databases throughout the world, as TIGER-like databases have developed elsewhere. Other countries developed similar databases, though the lack of systematic street addressing posed a major problem, especially in developing countries.

Geocoding has become commonplace as it is the first step in converting street addresses to geographic coordinates for a wide range of GIS applications. Meanwhile, GPS is emerging as a means of direct entry of locations into a GIS and may reduce the need for geocoding.

KENNETH J. DUEKER

SEE ALSO: Canada Geographic Information System; Census Mapping; Electronic Cartography: Data Structures and the Storage and Retrieval of Spatial Data; Geographic Information System (GIS): (1) Computational Geography as a New Modality, (2) GIS as a Tool for Map Analysis and Spatial Modeling; Software: Geographic Information System (GIS) Software

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Geodesy.

GEODETIC TRIANGULATION
GEODETIC TRILATERATION
GRAVIMETRIC SURVEYS
SATELLITE GEODESY
GEODETIC COMPUTATIONS
GEODESY AND MILITARY PLANNING

As the science of measuring the size and shape of the earth, geodesy includes a number of technologies and institutional practices with distinct histories. The order of articles in this composite reflects a progression from older to newer forms of measurement as well as the emergence of a prominent military role during the Cold War. A separate composite entry, "Geodetic Surveying," addresses the application of geodesy within major regions.

Geodetic Triangulation. Triangulation is a method of terrestrial surveying in which points on the ground (often called stations) whose coordinates are to be determined are the vertices of triangles. The vertices are permanently marked or monumented points so they can be recovered for future use. Individual triangles are joined together to form chains or networks (fig. 284). When triangulation must take into account the figure and size of the earth because a large land area is encompassed, it is called geodetic triangulation. Developed in the eighteenth century, the principles of geodetic triangulation were important throughout the twentieth century in framing topographic and other forms of large-scale mapping.

In geodetic triangulation, the horizontal angles at each point in each of the triangles are measured with precise optical instruments called theodolites. Usually, all of the angles in every triangle are measured to provide redundancy as well as data for estimating the precision of the measurements. A surveyor who has measured the angles and knows the length of one side can use trigonometry

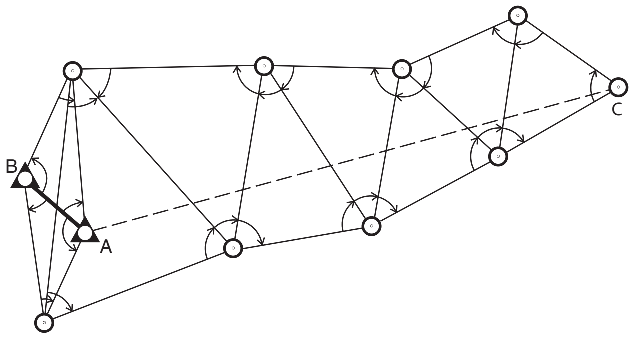

FIG. 284. SIMPLE TRIANGULATION NET. The known data are: length of baseline AB, latitude and longitude of points A and B, and azimuth of line AB. The measured data are: the angles to new control points. Computed data are: latitude and longitude of point C and other new points, length and azimuth of line AC, and length and azimuth of all other lines. Burkard's *Geodesy for the Layman* was a useful introduction to geodesy provided gratis by the Defense Mapping Agency.
After Burkard 1959, 26 (fig. 14).

to compute the lengths of the remaining sides of any triangle. To compute the coordinates (latitudes and longitudes) of the network points, the surveyor must know the scale of the network, its orientation, and the coordinates of a starting point. Scale is provided either by measuring one side of one of the triangles (called a base line) or by calculating the intervening distance from the coordinates of two of the network points. Orientation is provided either by measuring the astronomic azimuth along one of the sides of one of the triangles or by knowing the coordinates of two of the network points. In either case, the coordinates of at least one point must be known.

Because the horizontal angles are measured optically, the points forming a triangle must be intervisible. This requirement has limited the use of geodetic triangulation, particularly for projects in comparatively flat regions. Unless the area has substantial topographic relief so that stations are readily intervisible, towers must be erected to raise the theodolites, targets, and personnel to obtain a clear line of sight. The expense of erecting towers and the associated liability of the personnel working on them is one of the reasons why geodetic triangulation was usually undertaken by national mapping organizations or their counterparts at the state or provincial level. Also, to minimize the effect of lateral refraction on the line of sight, the horizontal angles in the more accurate triangulation surveys have typically been measured at night, when the atmosphere near the ground is most stable.

Prior to the development of electronic distance measuring (EDM) instruments and the use of satellite geodesy, geodetic triangulation was the most accurate method for determining the latitude and longitude of a station. Geodetic triangulation stations are classified by their estimated accuracy between pairs of interconnected stations and are assigned an order and in some cases a suborder or class. The most accurate geodetic triangulation is classified as first-order, defined as having an error no greater than 1 part in 100,000 for the distance between the station and its directly connected neighbor. Second-order class I and second-order class II surveys must have accuracies of 1 part in 50,000 and 20,000, respectively, while the error in a third-order survey may not exceed 1 part in 10,000. Each order and class has other specifications, which might include the intended or permissible uses of coordinates, the geometry of the network, the accuracy of instrumentation used, and the number of repeat measurements required.

The computation of geodetic triangulation data generates horizontal control data that are expressed as a geodetic latitude and longitude for each station in the network. Horizontal control data provide the scale and orientation for all types of accurate charting and mapping projects. They also provide the means for fitting together local, regional, state, and national mapping projects. In addition to its use for mapping and charting, these data provide the means for locating national, state, and county boundaries; confirming and increasing the accuracy of local and city surveys; and assisting in the perpetuation of points (including the preservation or restoration of monuments) established by such surveys. They support military defense mapping projects and provide data for computing accurate directions and distances for long-range positioning. Geodetic triangulation data have been utilized in scientific investigations such as measuring seismic shifts and other earth movement and determining the size and shape of the earth. Toward the end of the twentieth century, direct measurement of angles became less important in geophysical research insofar as EDM instruments allowed direct measurement of distances in a triangulation system and global positioning systems provided accurate estimates of coordinates and elevations, eliminating the need for a network in many instances.

EDWARD J. MCKAY

SEE ALSO: Figure of the Earth; Photogrammetric Mapping: Geodesy and Photogrammetric Mapping; Property Mapping Practices

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Geodetic Trilateration. The National Geodetic Survey (1986, 252) defines "trilateration" as: "The method of extending horizontal control by measuring the sides rather than the angles of triangles. . . . Any method of surveying in which the location of one point with respect to two others is determined by measuring the distances between all three points" (fig. 285).

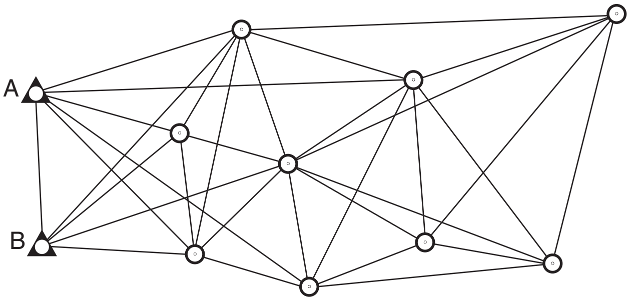

FIG. 285. TRILATERATION NETWORK. Networks as complicated as this are much more easily measured as a trilateration scheme than by triangulation. All sides in the network are measured.
Based on Smith 1997a, 66 (fig. 27).

For centuries triangulation formed the basis of national and other surveys over large areas (see fig. 284). With the development of radar in World War II and its subsequent use in the Shoran, Hiran, and Shiran systems, the possibilities for extending networks, measured to accuracies acceptable to high-order surveys over very long distances, was realized. The invention of electromagnetic distance measurement (EDM) through the use of Geodimeter Model 1, developed in 1953 by Erik Bergstrand of Sweden (Smith 1997b), and the Tellurometer model M/RA 1, in 1957 by Trevor Lloyd Wadley in South Africa (Smith, Sturman, and Wright 2008), also contributed to making trilateration useful. It took the profession some time to accept such new technologies. Early drawbacks to the use of EDM for trilateration were that the units were cumbersome and required heavy batteries. By century's end the weight of EDM equipment was considerably less for both the instruments and the power units, and the complicated reading systems of the early models had been reduced to digital readouts.

By the mid-1960s acceptance of trilateration was in place, and gradually the tedium of measuring all the angles of a triangulation scheme plus one base line to an accuracy approaching 1 part per million was replaced, first by a mixture of both angles and distances and then solely by the use of distances. This change of approach raised new problems for surveyors. EDM comes in two basic forms, one using optical systems where a light beam is sent to a distant reflector and reflected back, and another that sends a radio wave to a similar unit from where it is re-sent. In each case the time taken for the signal to travel the double path is measured and the resulting values converted into a distance.

The two systems are quite different. EDM was developed in the 1940s as a result of experiments to determine the velocity of light. Such experiments required accurately measured distances against which to test observations. When that velocity became known to a few parts per million the whole idea was turned around to use that knowledge to determine distance. Using light waves, the distances that can be measured are restricted by weather conditions along the line. This usually limits the usefulness of the system to some 40 or 50 kilometers. Using radio waves, the systems are operable in almost any conditions and hence can record far longer lines. Distances in excess of 100 kilometers are quite feasible if the intervening terrain allows intervisibility (Smith 1997a). To assure this usually requires that the two ends of the line be elevated with only much lower terrain between.

In triangulation, as computation of the sides and coordinates along a chain of triangles proceeds there is a gradual decrease in accuracy with the accumulation of small errors in each observed angle. In trilateration, where every side is measured to a similar accuracy, there is an overall consistency of accuracy throughout the chain of triangles. With modern computer adjustment methods it is feasible to achieve similar overall accuracies with both systems, but trilateration is generally much quicker to complete and, hence, more cost effective. By the turn of the twenty-first century, trilateration was being overtaken by the use of satellite techniques in the form of Global Positioning Systems (GPS).

J. R. SMITH

SEE ALSO: Electronic Distance Measurement; Figure of the Earth; Photogrammetric Mapping: Geodesy and Photogrammetric Mapping; Property Mapping Practices

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Gravimetric Surveys. Gravimetry—the measurement of the force of gravity as it varies from place to place and from time to time—began in 1672 when Jean Richer noticed that pendulums with a period of one second in Paris had a different period near the equator. Working in Peru in the 1740s, Pierre Bouguer found that gravity decreased from sea level to mountain top, as Isaac Newton had predicted. To explain this, Bouguer suggested that geological irregularities be taken into account. Nevil Maskelyne, in Scotland in 1774, observed the "deflection of the vertical" of his plumb bob. He reasoned that this factor explained why some terrestrial positions determined by geodetic triangulation differed from those determined by astronomical observation. In the early nineteenth century, observations made in the Trigonometric Survey of India showed that deflections of the vertical caused by mountains were less than expected, and those caused by the land under the ocean floor were greater than expected. To explain these observations, British scientists hypothesized that the outer portion of the earth's crust rests on the material of the interior in a state of equilibrium. This theory would later be known as isostasy, or isostatic compensation.

After encountering substantial deflections of the vertical and gravitational anomalies in the course of its survey along the 39th parallel, between 1878 and 1899, the U.S. Coast and Geodetic Survey's chief geodesist, John Fillmore Hayford, and his successor, William Bowie, developed a method for adjusting raw gravity data by assuming isostatic compensation at depth. They also compensated for the deflection of the vertical by calculating and accounting for the local mass balance around the observation point. In 1909, Hayford was able to create a profile of the geoid under the 39th parallel arc based on the compensated gravity values. He later developed the reference ellipsoid adopted by the international community in 1924.

During the nineteenth century, gravimetric instrumentation developed in Europe. Henry Kater, F. W. Bessel, the Hamburg firm of A & G Repsold, and others provided improvements that were noticed in the United States. American gravimetry began in the early 1870s, when Charles Sanders Peirce ordered a Repsold pendulum for the U.S. Coast Survey. Later Thomas C. Mendenhall developed a portable pendulum apparatus that was used to establish gravimetric control points at 100- to 200-mile intervals over the entire country.

Gravimetry at sea began in the 1920s, when F. A. Vening Meinesz of the Netherlands designed a complex gravity pendulum for use on a submerged submarine. With this instrument he discovered the exceptionally strong gravity anomaly belt that ran parallel to the deep sea trenches off Indonesia.

Geologists began conducting gravimetric surveys in the early twentieth century. Impelled largely by the correlation between gravitational anomalies and petroleum deposits, they favored torsion balances of the sort developed by Loránd Eötvös de Vásárosnamény, of the University of Budapest. By 1950 gravimeters had become relatively rugged, lightweight, and user friendly, and by 1960 they were widely used for gravimetric surveys. Development of sea- and airborne gravimeters followed soon thereafter.

World War II and the onset of the Cold War between the United States and the Soviet Union contributed to many further developments. Geodesists convinced the U.S. military of the importance of gravimetry. They (1) explained the difference between the ellipsoid and the geoid, and the fact that this difference caused errors in astronomical position determinations that might amount to several miles, (2) demonstrated how gravimetric data could be used to meld national geodetic maps into larger regional maps, (3) explained that an improved figure of the geoid would lead to improved values for the geodetic positions of potential targets, and (4) explained the importance of the deflection of the vertical at launch sites and the undulations of the geoid along the path from launch to target.

In November 1949, shortly after the Soviet Union detonated its first atomic device, the U.S. Air Force (USAF) learned that Soviet scientists had developed a more exact figure of the earth than the International Spheroid used in the West. Further, they learned that two-thirds of all the gravity measures in the world (24,000) had been made in the Soviet Union, and that the Soviets made much use of the combination of gravimetric and astronomic measures to obtain the deflection of the vertical.

By 1950 the USAF had established a worldwide gravity program in cooperation with other defense agencies and civilian institutions in various countries. The Air Force Cambridge Research Center (later Laboratory; AFCRL) conducted and sponsored research pertaining to new methods for obtaining precise geodetic and gravity data, the gravity data needed for various weapons systems, and an international gravity formula. The U.S. Defense Department's Aeronautical Chart and Information Center issued *Geodesy for the Layman* (1959 and later) and became the custodian of the USAF gravity library in 1960, responsible for operating, collecting, classifying, evaluating, and reducing activities for worldwide gravity data. It also investigated methods of using geologic, seismic, and other geophysical information to produce gravity values in the gravimetrically void areas of the world.

In 1962 J. E. Faller of Princeton developed a laser interferometer. An improved version, developed in collaboration with J. A. Hammond with support from the AFCRL, was purported to be the most precise gravity measuring instrument ever produced.

Geodesist John A. O'Keefe predicted that artificial earth satellites would yield important information about the earth's gravity field. In early 1959, he and his colleagues at the U.S. Army Map Service used irregularities in the orbit of the Vanguard 1 satellite to revise the long-accepted value of the flattening of the earth. Further analysis of these data led to identification of an odd harmonic in the figure of the earth—or, as reported in the press, the earth was pear shaped. Satellites designed for geodetic work provided a wealth of detailed gravimetric information.

Veikko Aleksanteri Heiskanen, director of the Finnish geodetic institute, Geodeettinen laitos, and founding director of the International Isostatic Institute, moved to the United States in 1950. With research support from the Department of Defense, he promoted a World Geodetic System centered on the gravimetric center of the earth. Such a system enabled geodesists to incorporate the several existing large-scale geodetic systems into one, compute the geographical coordinates of any point in the world where astronomical observations exist or which is plotted on a local map with a reliable grid, and compute the distances and directions between any required points in the world. Between 1959 and 1984, the Department of Defense developed a series of increasingly accurate, and originally security classified, World Geodetic Systems.

Heiskanen became director of the geodetic program at Ohio State University, the first such program in the Western Hemisphere. Most of the students in this academic program were affiliated with the USAF, which provided most of the funds for the program's research projects. Many of these projects pertained to gravimetry.

Geologist George Prior Woollard convinced the U.S. Navy that gravimetric observations could solve the problem of establishing the geodetic positions of islands beyond the reach of conventional geodetic ties. With funds from the Office of Naval Research (ONR), Woollard and his students made observations with gravimeters throughout the world. The military import of this project was not lost on the Soviet Union and explains why Woollard was not allowed to measure gravity at Potsdam—the site, since the early twentieth century, to which all gravimetric observations had been referred. By 1952 the Woollard team had established a network of over 500 primary gravity bases and 800 secondary bases in the politically accessible parts of the world. The ONR also provided funds for W. Maurice Ewing and his student J. Lamar Worzel to make gravity observations at sea. The Naval Oceanographic Office's Trident program established a large-scale and mostly secret program of gravimetric surveys at sea.

The Army Map Service initiated a wide-ranging gravimetric survey program in 1964. Its Inter-American Geodetic Survey promoted gravimetric surveys throughout South and Central America. There were many civilian gravimetric projects as well. In 1965, the American Geophysical Union issued a Bouguer gravity anomaly map of the United States.

The International Association of Geodesy formed an International Gravity Bureau, in Paris in 1951, and unveiled an International Gravity Standardization Net in 1971. This contained 1,854 reoccupiable stations distributed worldwide (except in China or the Soviet Union) with an adjusted precision of ± 0.4 milliGals.

DEBORAH JEAN WARNER

SEE ALSO: Figure of the Earth; Geodesy: Geodesy and Military Planning; Heiskanen, Veikko Aleksanteri; Molodenskiy, M(ikhail) S(ergeyevich); Tidal Measurement

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Satellite Geodesy. One principal objective of artificial earth satellite technology is to provide homogeneous coordinated positions of terrestrial locations worldwide. Orbits are selected to suit particular objectives: earth-stationary satellites for communications, low orbits for photography and remote sensing, and so on. Most satellites used for geodetic purposes are in near-circular orbits, at various inclinations to the equator according to design objectives (King-Hele 1962). Generally speaking the initial accuracies achieved for plan positions were better than those for heights. Mapping heights were obtained from remote sensing and photographic imagery.

Since Sputnik 1, the first artificial satellite, orbited the earth in October 1957, amateur radio enthusiasts at known ground stations could use the transmitted radio signal to determine the orbit of satellites and thus establish unknown ground positions from that orbit by analysis of the Doppler effect. Just as in classical astronomy, a ground segment is used to determine the positions of elevated objects, which in turn are used to establish a network of points worldwide.

Four main geodetic systems were developed by various agencies during the twentieth century (table 16). They exploit different technological advances available at the time of their development and each benefitted from the rapid improvement in computer systems, especially the speed with which processing could be achieved, and by advances in timing capability. One result has been that the natural timing system provided by the earth's orbital rotation and spin has been superseded by the more stable atomic Global Positioning System (GPS) time.

Because of the worldwide nature of the process, a generally accepted datum for all measurements has been adopted. Satellite systems yield coordinated positions in three dimensions based on purely geometrical principles. Unfortunately, the earth's gravity field, upon which heights depend, does not accord with this framework in a theoretical manner, but has to be measured against it and due allowances made when determining the heights of ground points. Also, traditional mapping systems in all countries of the world are based on local datums, which have to be transformed into or from the World Geodetic System (WGS) that the satellites use (Iliffe and Lott 2008). The accuracy of a system varies considerably depending on factors such as the number of measurements taken and the limits of accuracy governed by its design principles: absolute positions are much less accurate than relative ones (see table 16).

Satellite orbits are defined by an ephemeris of time-dependent parameters. Apart from passive balloon satellites, active satellites usually transmit an approximate broadcast ephemeris to the receiver at frequent intervals for immediate (real-time) approximate computation. Better values of precise ephemerides are obtainable at a later date for more accurate postprocessing. Tropospheric and ionospheric refraction data are also required for signal path definition. Other effects such as multipath and antenna calibration errors can affect results.

TABLE 16. Geodetic satellite systems

Satellite system	Stellar Triangulation	Doppler	SECOR	GPS/GLONASS[1]
Operational period	1960–75	1964–97	1965–68	1995 to present
Provider	NASA	U.S. Navy/ U.S.S.R.	U.S. Army	NASA/Russia
Satellites	3 balloons	6 each	4–6	24/18
Period	120 mins	108 mins	140 mins	12/11 hours
Height in kilometers	1600	1000	2000	20,000
Orbit inclination in degrees	47/81	90	85	55/65
Users	government mapping agencies	mariners; surveyors	government mapping agencies	universal
Absolute accuracy	10 m	100 m	10 m	3 m
Receivers/cameras required	two	one	three minimum	three minimum
Result delay	10 years	15 minutes	1 year	few seconds
Differential accuracy	5 m	4 m	3 m	3 mm
Receivers required	multiple	pair	multiple	pair
Result delay	10 years	6 hours	1 year	6 hours

[1] Global'naya Navigatsionnaya Sputnikovaya Sistema.

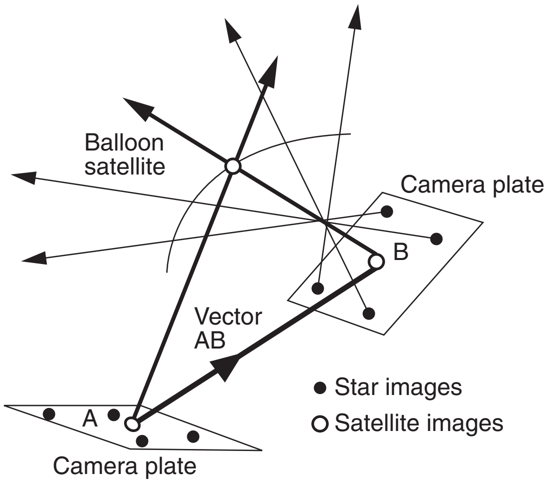

FIG. 286. GEOMETRIC RELATIONS OF STELLAR TRIANGULATION.

Like all technological advances, it is impossible to put an exact date on the adoption of a system. Satellite systems developed by military establishments only later become generally available to civilian users and mapmakers, although some private enterprises exploited the satellites in quite separate developments from the military (fig. 286).

Prior to satellites, surveyors experimented with observing flares dropped from aircraft to carry triangulations across wide water gaps, but with mixed success. The first of the four main geodetic satellite systems in the twentieth century was stellar triangulation. It began with Echo I, a 100-foot-diameter balloon, which the U.S. National Aeronautics and Space Administration (NASA) launched in 1960. Given the right conditions, when reflecting the sun's rays, it could easily be seen with the unaided eye against a background of the stars. Geodesists made precise observations with special cameras equipped with shutter devices to mark the stellar and satellite trails.

The photographic plates were later analyzed by interpolating in a stellar field to yield the right ascension and declination of the satellite at a known time, i.e., a vector in the astronomical system of coordinates. If a second camera at a distant point, say 100 kilometers away, made similar observations, another vector through the same satellite point was found. These two vectors defined a plane in which the line joining the two ground stations also lay. Two sets of simultaneous observations from these two stations to a later position of the satellite defined another plane. Thus the intersection of these two planes yielded the vector between the ground stations. Accuracies of a second of arc were readily achieved. In this way a completed network of vectors covering most of the globe was obtained (fig. 287). The network had to be scaled from ground distances obtained by other means, such as conventional triangulations. The observations and calculation of results took about ten years to complete (Schmid 1969).

The second geodetic satellite system, the U.S. Navy's Doppler system, consisted of four to six satellites. Be-

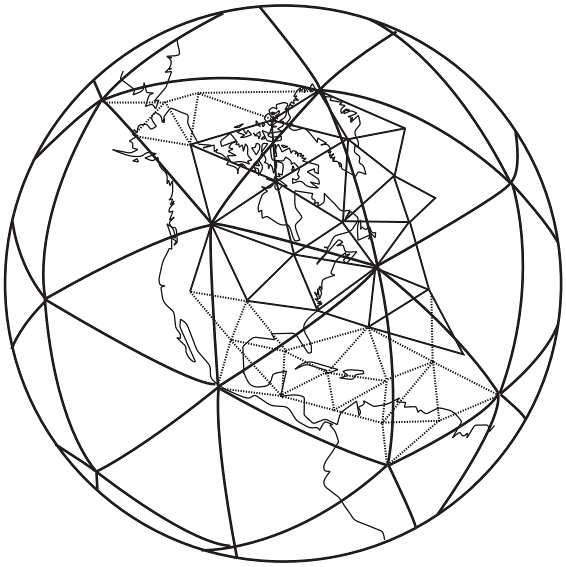

FIG. 287. GLOBAL NETWORK FOR STELLAR TRIANGULATION.

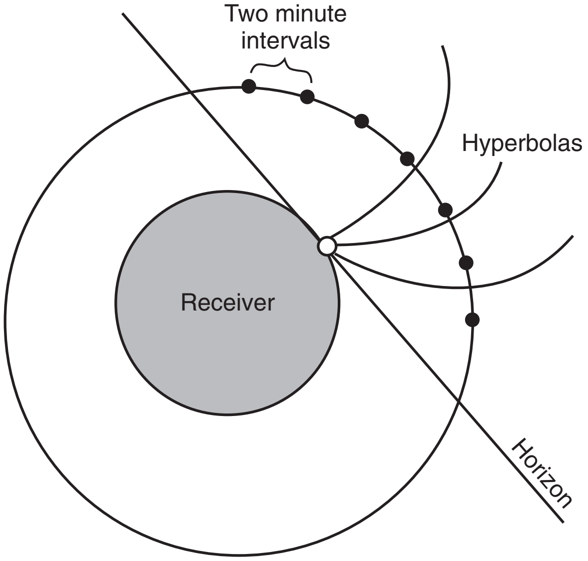

FIG. 288. TRANSIT DOPPLER.

cause there were so few satellites, the system did not give continuous coverage in all parts of the world. The satellites emitted two signals at 400 Mhz and 150 Mhz together with ephemerides information. The stable frequency at the receiver was mixed with a received signal that varied because of the satellite motion. Differences over two-minute intervals were counted. These Doppler counts are directly proportional to the range difference between the two instantaneously marked positions of the satellite and the receiver. Thus a hyperbola with the foci at the orbital marker positions passing through the receiver is defined (fig. 288).

During a typical pass, seven or eight such hyperbolas that intersect the observer's position are defined. Thus, a receiver's position can be determined from one pass of a satellite provided the orbit is also defined. This facility was clearly of great value to navigators, giving results accurate to about 100 meters. Ground-based surveyors were also able to improve quality by receiving many passes over several days and by exploiting the dual frequency could achieve an accuracy of 1 to 2 meters. Relative fixing or translocation of two sites a few kilometers apart could improve this by a factor of ten. Since receivers were also portable and relatively inexpensive, their use by private mariners and land surveyors became widespread (Stansell 1978).

In 1962 the U.S. Army developed the third system, microwave distance measurement from ground to satellite known by its acronym SECOR (sequential collation of range). Unlike the later GPS ranging satellites, the ground-to-air distances were measured by a returned signal over the double path. Each of four satellites was interrogated in sequence, a complicated system (fig. 289). SECOR was operational for about three years, enabling the establishment of a major worldwide network, which in conjunction with the Doppler network and others further improved our knowledge of the earth's geometry and motion and thus enabled a better reference coordinate system to be developed for later use by GPS.

In the SECOR system, the orbital position is used directly only for important housekeeping. A satellite is fixed by ranges from three ground stations while at the same time measuring a distance to a fourth unknown ground point. This procedure is then repeated for at

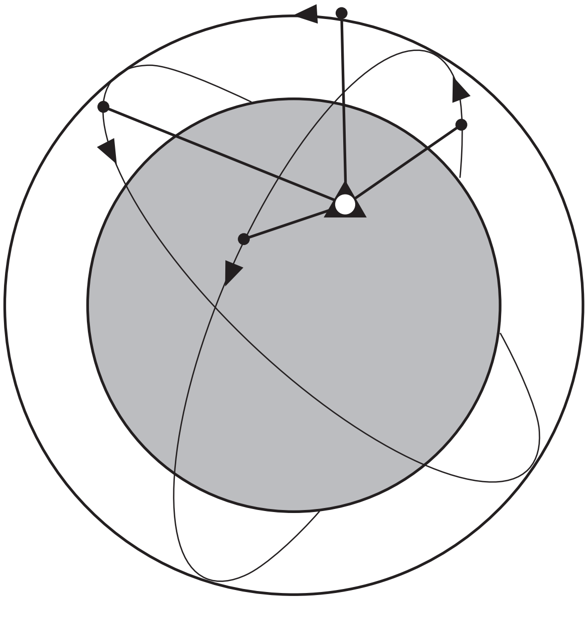

FIG. 289. SECOR LIMITED COVERAGE.

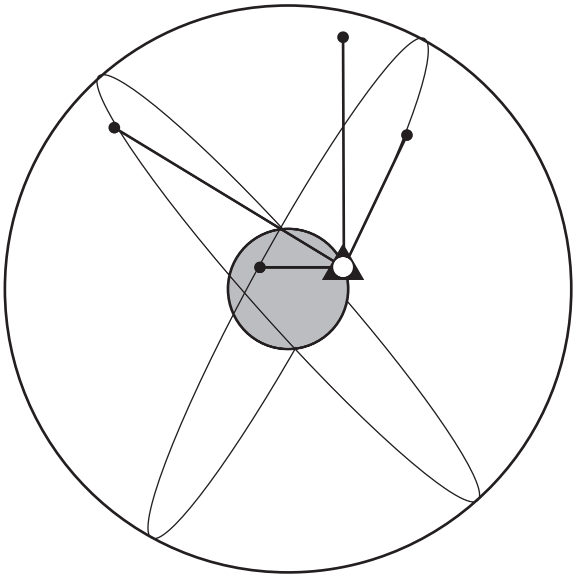

FIG. 290. GPS WIDE COVERAGE.

least two other satellite positions, giving good geometrical fixes of the unknown ground station and in so doing building up a closed network. Such a complex and expensive system was available only to the U.S. Army, with no civilian users (Bomford 1971).

Unlike SECOR, the GPS measures distances by a single direct time of flight from satellite to ground receiver (fig. 290). This is achievable only because of the development of very accurate satellite clocks and short-term stable clocks in the receivers. The system uses the orbit directly as part of the position determination of unknown points. For geodetic and mapping purposes, various refinement procedures are adopted. These refinements yield accuracies in the region of three millimeters, and when linked with precise geoidal separations, give height information to similar accuracy.

Whereas all previously mentioned satellite systems served solely to improve global and continental control networks and contributed toward a better understanding of the earth, including its dynamic state, the GPS system has extended its relevance to many everyday operations. High on the list of its plethora of spatial applications are surveying and mapmaking (Leick 2004).

ARTHUR L. ALLAN

SEE ALSO: Figure of the Earth; Global Positioning System (GPS); Property Mapping Practices; Tidal Measurement

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Geodetic Computations. Geodesy is the science that studies the shape and gravity of the earth and their variation with time. Geodetic computations process data from various types of observations in order to obtain optimal estimates of parameters describing the shape and gravity of the earth along with estimates of their accuracy. Coordinates of particular points are the parameters that describe the shape of the natural surface of the earth. However, the term "shape of the earth" relates to the geoid, a fictitious surface remaining after an extension of the mean sea level from the oceans to the continental part of the earth and the removal of the terrain relief. Since water remains in equilibrium when its free surface is everywhere perpendicular to the force of gravity, the determination of the shape of the earth as represented by the geoid is not a geometric problem but rather a problem of gravity field determination.

Knowledge of the gravity field is necessary for positioning using either classical or modern space techniques. Horizontal position (geodetic longitude and latitude) is determined by the direction perpendicular to a reference ellipsoid approximating the earth. Classical astronomical observations provide astronomical longitude and latitude, referring to the direction of the vertical. The deflection of the vertical from the ellipsoidal normal must be known in order to convert astronomical coordinates to the geodetic coordinates of cartographic practice. In 1928 F. A. Vening Meinesz extended the classical theory of George Gabriel Stokes for geoid determination to the determination of deflections of the vertical using gravity observations. Height was determined independently by leveling techniques where consequent height differences were corrected for the effect of gravity and summed to determine height differences between permanent control points. Although data obtained from space techniques provide three-dimensional positioning, cartographic representation still requires the separation into horizontal position depicted on a map and height represented by contour lines. In this respect heights above the ellipsoid provided by space techniques must be replaced by *orthometric* heights measured above the geoid, which is the proper zero-height reference surface. Thus gravity field determination, important in its own right, maintains its significance for positioning.

If we compare the beginning of the twentieth century with its end, the situation with respect to the relation between theory and practice of geodetic computations has been reversed. Presently the high accuracy and abundance of available observations poses significant challenges for both theoretical data handling techniques and appropriate mathematical modeling of relevant physical phenomena. One hundred years ago, however, geodesists had at their disposal a theoretical arsenal far beyond the observational and computational capabilities of that time.

In the beginning of the century mapping was based on regional or national triangulation networks, where computations were carried out with the help of logarithms using the adjustment method of condition equations in order to limit the effect of observation errors. The obtained consistent adjusted values of observed angles and distances of a few baselines were used to compute coordinate estimates. Computation difficulties necessitated many compromises, which did not allow the computation of the theoretically optimal solution, and even dictated simplified network designs consisting of triangle chains.

The first large-scale effort to integrate regional networks into a unified datum was the North American Datum of 1927 (NAD27). The computations for the adjustment of the western and eastern networks were completed in 1933. The next unification took place in Western Europe, where observations of the RETrig network (1954–79) were adjusted to obtain the European Datum of 1979 (ED79). The computations involved 3,597 network points, 25,111 observations, and 11,170 unknowns and achieved a relative accuracy of one to two meters. By that time advances in computers allowed the implementation of the method of observation equations, which allows the computation of unknown coordinates directly from observations, although some deviations from the theoretically optimal solution were still imposed by computational limitations. The replacement of invar wires by electronic distance measurement (EDM) instruments allowed a large number of baselines to be measured (2,732, or 11 percent of the total ED79 observations). The joint U.S.-Canadian effort (1974–86) led to the North American Datum of 1983 (NAD83), which covers the United States, Mexico, Central America, Canada, and Greenland. The U.S. network alone involved 259,000 points, 1,734,000 observations, and 929,000 unknowns. It was the last large-scale geodetic effort before space techniques replaced the classical methods.

The introduction of EDM instruments was the last advancement in terrestrial methods. This technology started with the development of radar during World War II. In 1949, Erik Bergstrand of Sweden introduced the Geodimeter (geodetic distance measurement), which used light to measure distances up to ten kilometers during daylight and twenty-five kilometers at night. In 1957 Trevor Lloyd Wadley of South Africa introduced the Tellurometer, which used X-band radio waves to measure distances up to fifty kilometers. Distance measurement using lasers was also introduced in the mid-1960s. The relevant technology formed the basis for similar distance measuring techniques in space geodesy. EDMs were integrated with theodolites in the 1980s into total stations appropriate for detailed surveying over small regions. However, EDMs had practically no effect on the basic methods of geodetic computations.

Despite practical difficulties, geodetic computation theory, driven by more modest surveying applications, witnessed some notable advances. One of them is related to the reliability of observations and in particular to the detection of blunders by the data snooping technique of W. Baarda. The use of planar coordinates for the analysis of observations capable of relative but not absolute positioning led to systems of equations with infinite solutions, one for every arbitrary definition of the coordinate system. Arne Bjerhammar of Sweden introduced in 1951 the concept of generalized inverses of matrices already introduced by Eliakim Hastings Moore in 1920, before their rediscovery and the consequent large development and application in modern mathematics by Roger Penrose in 1955. Related is the work of Peter Meissl of the Technische Universität Graz, who clarified the relation between particular generalized inverse solutions and the use of additional constraints on the coordinates, in particular the inner constraints leading to the unique solution obtained by the unique generalized inverse called "pseudoinverse."

Another line of development related to gravimetric computations of the height of the geoid above the reference ellipsoid. A series of theoretical developments took place in the 1950s mainly at the Finnish Geodeettinen laitos or through its series of publications. A significant breakthrough is the work of Torben Krarup of the Danish Geodætisk Institut, who attacked the problem of interpolating gravity data with more advanced mathematical tools including the use of Hilbert function spaces with reproducing kernels. This led to the possibility of processing simultaneously any gravity-related observation in order to predict any desired gravity-related quantity, using the technique of collocation. The method became very well known thanks to its popularization by Helmut Moritz of the Technische Universität Graz and the software development of Carl Christian Tscherning of the Geodætisk Institut. Further elaborations of the probabilistic aspects of the method, in particular by Fernando Sansò of the Politecnico di Milano, brought geodesy to the forefront of data analysis methods relating to unknown random fields, with similarities to the kriging method independently developed in geostatistics. Both approaches find their place within the general framework of prediction theory for stochastic processes independently pioneered in mathematics by Norbert Wiener and A. N. Kolmogorov. In addition to the gravimetric problem, collocation applies to a wide variety of geodetic problems and became one of the most important tools for geodetic computations.

The Soviet Union's launch of the first artificial satellite of the earth on 4 October 1957 found the geodetic community ready to exploit the new possibilities. At the Department of Geodetic Sciences at Ohio State University, founded in 1951 by the Finnish geodesist Veikko Aleksanteri Heiskanen, the research of George Veis, William M. Kaula, and Ivan Istvan Mueller developed the first computational techniques for the analysis of satellite tracking observations for both positioning and gravity field determination. Satellite positions serve as additional triangulation points, visible from widely separated stations, thus permitting the establishment of the first global geodetic networks with unprecedented accuracies. Starting from an accuracy of twenty meters a series of technological advances and data analysis techniques led to today's subcentimeter positional accuracy. Analysis of satellite orbits driven by gravitational attraction led to the determination of the gravity field of the earth on a global scale. The first estimate related to the gravity field showed that the earth was less flat than previously believed.

After a short experimental period, satellite geodesy became operational. The first period was dominated by satellite observations with ballistic cameras, where the satellite was photographed in the background of stars, providing the relative positions of worldwide tracking stations. This resulted in accuracies of the order of fifteen to twenty meters over the whole earth, with scale provided by terrestrial Geodimeter distance observations. Soon other tracking techniques were introduced utilizing interferometry, EDM, and measurements based on the Doppler phenomenon, which allowed the determination of network scale and positioning with respect to the geocenter around which satellite orbits evolve.

The first technique to survive the test of time was laser tracking of satellites equipped with reflectors, now known as satellite laser ranging (SLR), a method that was extended to the use of reflectors placed on the moon (lunar laser ranging, LLR). Laser ranging of satellites in low orbits brought a continuously improved knowledge of the earth's gravity field. This resulted in various earth models, pioneered by Richard H. Rapp at Ohio State University, which are sets of gravity field parameters obtained from the combination of satellite and terrestrial data as well as satellite altimetry, a technique whereby observations of the distance between satellite and sea surface are used to determine the shape of the geoid over the oceans. In the 1970s the powerful method of very long baseline interferometry (VLBI) was developed, which utilizes radio signals from extragalactic radio sources to determine the shape of global networks and the rotation of the earth with a centimeter-level accuracy. In 1990 the French introduced the DORIS system (Doppler orbitography and radiopositioning integrated by satellite), in which satellites track a terrestrial network of beacons emitting radio signals utilizing the Doppler phenomenon.

All the above techniques provided the basis for a unified high-accuracy mapping of the earth, but they required instrumentation and research that was limited to specialized academic centers and governmental agencies. Of particular importance has been international cooperation, coordinated by the International Association of Geodesy (IAG) in collaboration with the Committee for Space Research (COSPAR). The obtained results had great scientific value but little effect on routine mapping activities. The situation was to change drastically when the first satellite of the Navstar Global Positioning System (GPS) was launched in June 1977, marking the beginning of the GPS era for satellite geodesy. The ingenuity of geodetic researchers and instrumentation technologists must be praised for converting a system designed by the military for navigation with accuracy of ten to twenty meters at best into a geodetic system providing subcentimeter accuracy. Such accuracy was achieved by exploiting observations on the carrier frequency rather than the digital codes used in navigation, a procedure that necessitates the determination of the number of unknown integer wavelengths contained in the satellite-to-receiver distance (integer ambiguity).

In 1994, the IAG established the International GPS Service (IGS), which utilizes data from an extensive worldwide network of about 350 permanent stations and various data analysis centers to provide high-accuracy orbit and atmospheric condition information for use in professional mapping. Many countries are establishing additional densification of permanent GPS networks, which allow surveyors to obtain high accuracy by using a single receiver instead of two, in combination with data from a nearby permanent station.

The evolution of satellite geodesy computations started with great computational difficulties but was eventually boosted by the exponential growth of computer capabilities. Today GPS positioning computations are carried out by relatively inexpensive commercial software using modest personal computers. On the other hand, auxiliary data provided by the scientific community are the result of elaborate modeling and numerical procedures. Although computational cost is no longer of concern, the difficulties lie in the organization, handling, and evaluation of an ever-increasingly huge amount of data and the development of efficient physical mathematical and statistical models. The basis of highly accurate global positioning is the International Terrestrial Reference Frame (ITRF), consisting of the time variable coordinates of a very large number of fundamental stations involved in various space techniques (VLBI, SLR, DORIS, and GPS). Coordinates at a reference epoch, constant station velocities, and earth rotation parameters from the particular techniques are optimally combined at the International Earth Rotation and Reference Systems Service (IERS), a collaborative service of the IAG and the International Astronomical Union (IAU).

Before the end of the twentieth century GPS was already dominating professional applications. The traditional triangulation, trilateration, and traverse techniques based on theodolites and EDM instruments were gradually abandoned. GPS provides high-accuracy positioning by slow static methods (ten to twenty minutes per point) with elaborate postprocessing computations implementing auxiliary data provided by the IGS. Less accurate results can be achieved with greater speed in static or kinematic mode where the receiver is moving aboard a vehicle. Computations must be done in real time in order to ensure that the integer ambiguity has been resolved before proceeding any further. Real time operation requires data transmission through mobile phone connections between receivers or with a permanent station when a single receiver is used. The problem of data analysis in which the unknown parameters include integers has been the subject of much theoretical research aimed at producing very fast algorithms. The most successful results have been produced by P. J. G. Teunissen's group at the Technische Universiteit Delft.

The beginning of the twenty-first century finds professional mapping practice revolutionized with the use of GPS and its Russian counterpart GLONASS with even higher expectations from the newly planned European Galileo system. Lack of satellite visibility in urban areas is partly resolved by the very promising pseudolites (pseudo-satellites), which are ground-based transmitters of signals similar to those of satellites.

High-accuracy position determination has found applications other than those of traditional mapping, which are less demanding. Mostly these are of geophysical interest, such as the monitoring of crustal deformations for hazard prevention with simultaneous contributions from high-accuracy determination of the gravity field. The geodetic community expects a lot from the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission of the European Space Agency (ESA), in operation since 2009, for which the change rate of gravity vector components is measured by a gradiometer aboard a low-height satellite. Already valuable data have been successfully analyzed from the National Aeronautics and Space Administration's (NASA) Gravity Recovery and Climate Experiment (GRACE) mission, which uses satellite-to-satellite tracking between twin satellites that are also equipped with GPS receivers.

To meet challenges much more demanding than mapping (deformation of the solid earth, mass transport in the earth system, atmosphere-ocean dynamics, global water cycle), the IAG established a special project—the Global Geodetic Observing System (GGOS)—as a part of the United Nations Educational, Scientific and Cultural Organization's (UNESCO) Integrated Global Observing Strategy Partnership (IGOS-P). The GGOS project poses great challenges for innovative geodetic computation techniques where precise modeling of complicated geophysical phenomena is required. The great successes of space geodesy observation and data analysis techniques in the last four decades of the twentieth century provide the basis for great hopes in meeting these new challenges of the twenty-first century.

ATHANASIOS DERMANIS

SEE ALSO: Figure of the Earth; Photogrammetric Mapping: Geodesy and Photogrammetric Mapping; Property Mapping Practices

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Geodesy and Military Planning. During the long hot summer of 1936, Professor W. Maurice Ewing of Lehigh University sat in a humid U.S. Geological Survey laboratory in Washington, D.C. trying to repair and reassemble a rusted and damaged instrument. One of the pioneers of geophysics in the United States, Ewing had to restore to working condition the gravity-measuring apparatus invented by the Dutch geodesist F. A. Vening Meinesz. The latter had used the device to make seminal measurements of the earth's gravity while on board Dutch submarines in 1923 and 1926 and then later observations in the Gulf of Mexico on board the submarine USS *S-21* in 1928 with American colleagues F. E. Wright and Elmer B. Collins. They used submerged submarines to control roll, pitch, and yaw at sea and to provide a very stable surface for the instrument, which relied on swinging pendulums to record their motion on photographic film. Of the five swinging pendulums, two controlled the attitude of the device while the other three recorded variations in the gravity field and permitted scientists to negate mathematically the forward motion of the boat.

Ewing finished his work with the help of correspondence from Vening Meinesz just in time to join Princeton's Harry Hammond Hess, Lieutenant Albert J. Hoskinson of the U.S. Coast Guard, and the Navy's Captain Lamar R. Leahy on board the submarine USS *Barracuda* (V-1) to take gravity measurements in the Caribbean Sea and West Indies. This successful venture, called the Navy–American Geophysical Union Expedition of 1936, demonstrated the early and mature partnership between the U.S. Navy and gravity researchers in the United States. In the American experience, geodetic research and discovery frequently occurred in collaboration with the military. The latter needed an understanding of the earth's gravity to plan general navigation, progress at sea, the effective use of ballistic weapons, accurate surveying, and the best and safest use of aviation assets.

In the first half of the twentieth century international scientists sought a fundamental understanding of the variations in the earth's gravitational field. For Ewing, Hess, and their colleagues the anomalies near Puerto Rico and its neighboring submarine trench presented some fascinating challenges. With the end of World War II and the ensuing Cold War era, a comprehensive geodetic picture of the entire planet became critical, both for a scientific understanding of the world and for national defense.

During the 1950s the need for a World Geodetic System (WGS) became obvious in the face of the possibility of war between the United States and the Soviet Union. These conditions created a pressing need for global maps to provide geographic knowledge and to support targeting, navigation, and aviation. The advent of the space race and the development of ballistic missiles after the launch of Sputnik in 1957 added to these requirements. The inability of the existing geodetic systems to provide a truly accurate global picture made the development of a new WGS a natural next step. The existing geodetic systems like the European Datum (ED50), the North American Datum (NAD), and the Tokyo Datum (TD) could not reach the comprehensive level required to meet global needs. As the decade ended the international scientific community in collaboration with the U.S. Department of Defense began the process of combining existing systems and rereferencing them to an ellipsoidal model rather than the geoid. This effort led to the World Geodetic System 1960 (WGS60). In subsequent years, the addition of new data sets from around the world and improved systems of geodetic data collection from satellites and other platforms made improvements possible and occasionally altered the model on which the system rested.

WGS66 created a gravimetric geoid based in large part on a worldwide 5° by 5° mean free-air gravity anomaly field. Its successor, WGS72, benefitted from the largest data collection effort ever applied to the construction of a WGS. The later WGS84 system employs an ellipsoidal model and earth gravitational models (EGMs) with associated geoids. The initial 1° by 1° geoid for EGM84 and then a more refined 30′ by 30′ geoid for EGM96 were globally referenced with data from previous efforts augmented by extensive new gravity, satellite altimetry, and satellite laser ranging. On 17 April 2008 the National Geospatial-Intelligence Agency (NGA) in the United States implemented EGM08 to improve the use of the WGS. This model complemented the Global Positioning System (GPS) in defining accurate heights above mean sea level and improved accuracy by three to six times over previous EGMs and geoids. With EGM08, the global root mean square geoid error dropped from ±50 centimeters to ±15 centimeters and EGM08 provided a spatial resolution six times higher than EGM96. This improved the effect of the WGS across the board, from surveys, to navigation, to aviation, to defensive measures. It enabled greater accuracy in orbiting artificial satellites, a better determination of world sea levels, and a more efficient means of estimating the deflection of the vertical, critical to military operations and mission planning. Compensation measures based on gravity deflection of the vertical permitted inertial navigation systems both to correct position and velocity errors and to improve orientation control for a variety of defense systems.

In any definition of geodesy one naturally finds mention of the earth's gravity field, its variation, and the effect of this and the planet's rotation on its actual shape. However, geodesy also includes the study of the earth's magnetic field. This phenomenon profoundly affects military operations, weapon systems, and navigation, making it of critical concern for military planners and operators. Many magnetic fields contribute to the earth's magnetic characteristics. The main magnetic field rests in the earth's fluid outer core, a second, crustal field exists in the crust and upper mantle, and a third field emerges from the electrical disturbances in the upper atmosphere and the magnetosphere. Magnet sensors above the earth's surface measure the collective effect. The U.S. National Geophysical Data Center and the British Geological Survey produce the World Magnetic Model (WMM) with funds and direction from the NGA in the United States and the Defence Geographic Imagery and Intelligence Agency in the United Kingdom. The U.S. Defense Department, the U.K. Ministry of Defence, the North Atlantic Treaty Organization, and the World Hydrographic Office employ the WMM as their standard in navigation and heading systems. Civilian commercial groups and companies use the WMM and obtain it from the U.S. National Geophysical Data Center working on behalf of the NGA. Every five years a revised version of the model appears. WMM2005 expired in December 2009 and WMM2010 took its place.

The GPS became a complimenting critical tool in generating geodetic data and knowledge. The history of GPS development included accuracy tests done by the U.S. Navy's Transit satellite system, which used the Doppler effect, first noticed in tracking Sputnik, to establish position. By 1960 a constellation of five satellites provided a navigation fix once every hour to a network of manned monitors around the world established by the Defense Mapping Agency, a predecessor of the NGA. The U.S. Defense Department and the U.S. Air Force developed the GPS, which went operational in 1993. It immediately provided a very accurate means of performing submeter static and fast static positions for geodetic surveying anywhere in the world. GPS became a reality due to the need for geodetic surveying and then in turn became critical to the collection of precise geodetic data.

Concerned with gravity and the shape of the earth, geodesy as it affects military planning also touches on the way the earth is represented. Can we count on the apparent accuracy of a map based on the Mercator projection, a polar stereographic, or a conic projection? Since a geodetic globe would present difficulties for navigators on board ships and aircraft as well as for simple classroom presentation of a general or particular area, flat images of the earth with greater utility represent compromises. A globe would offer absolutely correct distances and directions. All areas would retain their natural shape and relative size. Parallels and meridians would always intersect at right angles and both great circles and rhumb lines would appear as straight lines of 180°. Since all of these attributes cannot coexist on the flat surface of the typical map, all maps must permit compromises well known to the user. For example, the Mercator projection remains very popular because a conformal character enables it to display most of the characteristics of the ideal map. Mercator even managed to calculate mathematically an alternate spacing for the parallels of latitude to compensate in part for the distortion of the relative size of some landmasses.

The Military Grid Reference System (MGRS) offers an excellent and unique way to bring geodetic and other geospatial map information directly to the flat map user. It employs an alphanumeric system for communicating Universal Transverse Mercator (UTM) and Universal Polar Stereographic (UPS) coordinates. The system provides a unique coordinate string for any given location on earth, using the meter as the standard of measure. A user may formulate a coordinate string by combining a grid zone designation with the 100,000 meter square identifier, and grid coordinate. The system reads first right and then up (see figs. 184 and 185). A set of coordinates derived via the MGRS presents a unique identifier, and no other set will appear similar in any way. The MGRS used on most maps and charts employed by military planners very often finds its way into civilian use.

Geodetic packages prepared by military planners and cartographers and applied to basic map and chart production illuminate the earth and render maps much more useful and complete. These reference packages include notes on the map's projection, grid diagrams, the MGRS, magnetic information for navigation, notes on necessary conversions, geodetic information to inform GPS use, and highly accurate measurements. One can find dependable supplementary information of this sort on many maps, especially image city maps, topographic line maps (1:50,000 and 1:100,000), Joint Operations Graphics (Air), and Digital Nautical Charts (DNC). The NGA also provides airfield packages to assist in the process of surveying. These products include data on vertical obstructions, satellite navigation information, and a detailed geodetic survey of the airfield area to ensure safety, both in flight and during departures and landings.

The DNC represents one of the most widely used products developed by military planners and employs geospatial and geodetic data and insights in a most practical way. Each of the twenty-nine regions in the DNC database covers a specific part of the world, offering data organized into harbor, approach, coastal, and general scale categories. The Defense Logistics Agency and the NGA, the author of the DNC, provide these products to the military community but also make them available for civilian and commercial use. The digital charts will work not only with military and naval navigation equipment but also numerous GIS systems. Beyond the surface-vessel application of the DNC, in 2005 the USS *Oklahoma City* (SSN-723) became the first submarine to achieve certification to employ the DNC and Tactical Ocean Data in a paperless navigational environment.

By January 2007 the near-universal collaboration between the United States and Canada extended to the use and enhancement of the DNC system. A combined effort to collect all available data on Canadian waters resulted in the Canadian Hydrographic Service assuming responsibility for maintaining the DNC as it pertains to Canadian waters, integrating new sources and preparing new data libraries for all of Canada's home waters.

GARY E. WEIR

SEE ALSO: Cold War; Cruise Missile; Electromagnetic Distance Measurement; Figure of the Earth; Global Positioning System (GPS); Photogrammetric Mapping: (1) Military Photogrammetry as a Precursor of Remote Sensing, (2) Geodesy and Photogrammetric Mapping

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Geodetic Surveying.

CANADA AND THE UNITED STATES
LATIN AMERICA
AFRICA
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Geodetic Surveying in Canada and the United States.

During the early decades of the twentieth century the figure of the earth was generally accepted by geodesists as approximating an ellipsoid of revolution, with the earth's rotational axis corresponding approximately to the semiminor axis of the ellipsoid. Following significant efforts in the United States to determine the size and shape of the best-fitting ellipsoid for the geoid to the conterminous states, the Clarke Spheroid of 1866, with a datum point or origin at Meades Ranch in Kansas at the approximate center of the United States, was selected. The geometry of the ellipsoid and algorithms for computing distances and coordinates on its surface were refined and documented (Hosmer 1930), and measurement of the gravity field of the earth and theories concerning it were developed (Bowie 1912).

Triangulation, a technique dating back to the 1600s, and traversing were the principal surveying methods employed during the early 1900s. Theodolites, zenith telescopes, various astronomic telescopes, and leveling instruments were used to make geodetic observations. Baselines were taped using high-quality steel and invar tapes and precise methods.

Most of the early geodetic surveying in the United States was accomplished by federal agencies, principally by the U.S. Coast and Geodetic Survey. This agency was a successor to the first surveying organization established by U.S. President Thomas Jefferson in 1807, originally named the Survey of the Coast. The instruments, methods, and scope of geodetic surveying activities were too specialized, complex, and costly for other government or private organizations to undertake. By 1927 triangulation arcs supplemented by some traversing spanned the United States, but these were widely spaced, and coverage was sparse (fig. 291).

Geodetic surveying in Canada began in 1905, with triangulation in the Ottawa area carried out by the

FIG. 291. THE U.S. HORIZONTAL GEODETIC CONTROL NETWORK IN 1927. The categories (top to bottom) are first-order triangulation, second-order triangulation, and first-order trilateration.
From Schwarz 1989, 18 (fig. 4.2).

Astronomical Branch of the Department of the Interior (renamed Geodetic Survey of Canada [GSC] in 1909). By 1908 two leveling parties were also active (Thomson 1967, 221–30). As the Canadian triangulation network was extended it was joined to the U.S. network, and Canada recomputed its networks to the North American Datum of 1927 (NAD27), thereby maintaining compatibility with the U.S. networks. In 1927, the Canadian network included an arc along the 49th parallel, area triangulation in southern Ontario and Quebec, and a triangulation loop in New Brunswick (McLellan 1974).

From 1927 to about 1965 both national geodetic agencies were involved in adjustments of their horizontal (NAD27) and vertical (NAD29) control networks and in densifying these networks with additional monuments. In the early 1960s they participated in initial space geodesy efforts to determine geodetic positions of points around the world and a refined figure of the earth.

The geodetic control networks consisted of thousands of mostly concrete monuments placed in Canada and the United States in organized patterns. The spacing and configuration of these points were determined by the requirement for intervisibility between adjacent points for the observation of horizontal angles and leveling lines, by geometric conditions required for strong networks, and by regional population densities. Instruments had improved and the networks were extended and densified with many new monuments. While the NAD27 horizontal and NAD29 vertical adjustments served the nations well until the mid-1960s, they contained a number of problems that increased in importance during the decades between 1930 and 1970 (Schwarz 1989).

Improved leveling instruments and processes along with better theodolites and the introduction of the Bilby (portable steel) tower in 1926, made geodetic surveying more accurate and efficient, but the most significant development occurred in geodetic surveying instrumentation with the invention of electronic distance measurement (EDM) devices in the 1950s, using visible monochromatic light or microwave frequencies. EDM devices reduced the time needed to measure baselines, measured them with greater accuracy, and made it possible to measure the lengths of triangulation sides directly, thus opening the way to more accurate, faster, and less expensive network configurations. Electronic ranging techniques from aircraft (Shoran and Aerodist) were developed and used along with new triangulation and traversing designs to extend the geodetic network to Canada's northern mainland and Arctic islands, in support of Canada's National Topographic System mapping program. Automatic, self-leveling levels were also introduced during this period, which streamlined leveling procedures.

After the first Soviet satellite was launched in 1957, scientists at the Applied Physics Laboratory at Johns Hopkins University in the United States realized that the Doppler effect on signals from the satellite could be used to derive geodetic coordinates. This spawned a revolution in geodetic positioning methods. Additionally, photographic techniques using BC-4 cameras to photograph the background of the stars relative to a satellite's position were used to position geodetic points around the world, connecting networks separated by oceans. However, it was the satellite Doppler technique that inspired the development of other space-electronic techniques, the most important being the Global Positioning System (GPS), which revolutionized both horizontal and vertical geodetic surveying. Because of the accuracy and global capability of the space systems, the departments of defense in both countries played major roles in geodetic positioning in North America and the world between 1960 and 2000. This was particularly true in the United States, where the Defense Mapping Agency and the Naval Surface Weapons Center developed new techniques and instrumentation.

As a result of the thousands of new observations and control stations added to the networks in Canada and the United States and the impact of newer technologies such as EDM and satellite Doppler, it was generally agreed that the horizontal and vertical networks on the continent needed to be redefined and readjusted. These efforts were the focus of geodetic surveying efforts in the United States and Canada in the period 1975 to 1985.

The North American Datum of 1983 (NAD83) project was a large international effort involving the digitizing and accuracy evaluation of geodetic observations for horizontal networks in Canada, Denmark (Greenland), the United States, Mexico, and Central America. In the United States it also involved the digitizing of large amounts of additional data related to the control stations such as station descriptions. To prepare for the readjustment, numerous new measurements were made to strengthen existing networks. These included additional EDM measurements, triangulation, and, in the United States, high-precision transcontinental traverses. It also included the satellite Doppler positioning of many points in the Canadian and U.S. networks that strengthened them and enabled the realization of a new geocentric datum (which in future years facilitated accurate positioning with GPS). Because GPS was then a nascent technology, only eight GPS positions in the United States were included in the adjustment.

The geocentric reference system chosen for NAD83 is known as the BIH Terrestrial System 1984 (BTS84) produced by the Bureau International de l'Heure, together with the global reference ellipsoid of the Geodetic Reference System 1980 (GRS80) adopted by the

FIG. 292. CANADIAN TRADITIONAL HORIZONTAL CONTROL NETWORK. Central part of the Canada landmass showing much of the 8,000 station primary geodetic framework, comprising triangulation arcs, Aerodist trilateration, and satellite Doppler positions included in the NAD83 continental adjustment.

From Craymer 2006, 153 (fig. 1). Permission courtesy of the Canadian Institute of Geomatics, Ottawa.

International Association of Geodesy. A simultaneous adjustment of some 1,785,772 observations involving 928,735 unknowns was completed in 1985 (Schwarz 1989, ix–xii). The Geodetic Survey of Canada contributed its 8,000-station primary network to this adjustment and followed it, in cooperation with other federal and provincial agencies, with the integration, internally, of Canadian secondary networks for a total of 105,000 points (Pinch 1990, 12) (fig. 292). Because of the need for computing the geoid for purposes of the adjustment, the gravity field in both countries underwent a similar revitalization.

Similar to the horizontal networks, significant errors in the vertical networks in North America had become apparent by the mid-1970s. In the United States, for example, the National Geodetic Vertical Datum (NGVD) had been added to and forced to fit in many areas of the country, which distorted the network. Therefore around 1980 a similar redefinition and revitalization of this network began. The North American Vertical Datum of 1988 (NAVD88) project included the same countries as the NAD83 horizontal datum project. Over 500,000 permanent benchmarks were included. The datum surface was defined to be an equipotential surface passing through a point on the Great Lakes. This surface closely corresponds with mean sea level on the coasts of the United States. The Canadian Basic Net comprising 76,000 kilometers of post-1960 leveling (some 43,000 benchmarks) was adjusted simultaneously in 1991 with the U.S. networks (Babbage and Roberts 1999, 51). Following analyses of their Basic Net, however, Canada decided not to adopt NAVD88, and did not proceed with readjustment of their remaining networks. The Canadian Geodetic Vertical Datum of 1928 (CGVD28) remained in use, although work was under way to implement a new height reference system based on geoid modeling (Véronneau, Duval, and Huang 2006), a system better suited to current Canadian needs and conditions.

Unquestionably, the single most important breakthrough in geodetic surveying in the twentieth century was the development of methods for using GPS to position points relative to one another with centimeter accuracy and without the need for intervisibility between them. GPS provides far more flexibility in placing points where they are easily accessible and of greater use, and it also provides vertical positioning, thereby supporting developments toward an accurate geoid model that in turn provides the capability for using GPS to derive elevations above sea level. Canada and the United States began using GPS as *the* method for geodetic surveying in the 1980s.

The United States established a network of continuously operating reference stations (CORS) in the 1990s (Stone 2006). The concept is that at points whose coordinates are needed, GPS receivers (rovers) can be placed and used to interrogate the CORS. The CORS are then used as highly accurate differential stations. This results in first-order geodetic control (Zilkoski, D'Onofrio, and Frakes 1977). Similar developments took place in Canada, where federal and provincial agencies have put in place the Canadian Spatial Reference System (CSRS) comprising active networks of active control points (ACPs) along with the standard passive monumented control points (Craymer 2006). Monumented stations in the United States and Canada still provide geodetic control for those who wish to use it. High-accuracy monumented stations are needed for the monitoring of tectonic plate motion, which is important for geophysical purposes as well as for maintaining the accuracy of geodetic control networks.

GPS, combined with other technologies in the 1990s, has produced a quantum leap in geodetic positioning capabilities worldwide. Canada and the United States participate in continuing international projects to improve GPS satellite tracking, modeling of the geoid, and monitoring the accuracy and stability of positional reference frames. In the United States and Canada the NAD83 is accurately related to the International Terrestrial Reference Frame, based on stable directions observed by radio telescopes to very distant radio sources, which appear motionless from the earth over long periods of time. The use of GPS for accurate, low-cost geodetic positioning of points on the surface of the earth is now commonplace, passed along from the specialized expertise of geodetic surveyors into the hands of people in other position-dependent land measurement and geographical disciplines such as geophysicists, cartographers, land surveyors, and geographical information system experts.

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SEE ALSO: Figure of the Earth; Geodesy; Global Positioning System (GPS); Photogrammetric Mapping: Geodesy and Photogrammetric Mapping; Property Mapping: Property Mapping in Canada and the United States; Tidal Measurement

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Geodetic Surveying in Latin America.

Geodetic activities in most of Latin America started in the late 1930s, mainly in support of mapping. During the first fifty years, many of these activities were sponsored by the Inter-American Geodetic Survey (IAGS)—a unit of the U.S. Defense Mapping Agency (DMA) (later the National Imagery and Mapping Agency [NIMA] and then the National Geospatial-Intelligence Agency [NGA])—through supporting geodetic surveys, networks processing, and training. The technology available at that time was based on optical techniques, which were used in astronomic determinations as well as in establishing triangulation chains and geodetic leveling lines.

As in other cartographic sciences, geodesy benefited from the technology revolution of the last half of the twentieth century. The development of electronic distance meters allowed the establishment of traverses that hastened the establishment of horizontal geodetic networks. The advent of artificial satellites—first, the Navy Navigation Satellite System (NNSS), also known as the Transit system, and later the Global Positioning System (GPS)—has brought a true revolution, not only in terms of improving the accuracy and logistics of new geodetic points, but also by effectively allowing the connection of national geodetic networks. This later development has supported the establishment and adoption of unified, geocentric, continental, and global geodetic reference systems. The Sistema de Referencia Geocéntrico para América del Sur (SIRGAS) project, which started in 1993, under the sponsorship of the International Association of Geodesy (IAG), the Pan American Institute of Geography and History (PAIGH)/Instituto Panamericano de Geografía e Historia (IPGH), and the NGA, is representative of these initiatives in the region. The meaning of the SIRGAS acronym changed to Sistema de Referencia Geocéntrico para las Américas in February 2001 to represent the expansion of the scope of the project to the remaining regions of the Americas, including the Caribbean.

The establishment of national horizontal geodetic networks started in some countries in the late 1930s with the objective of determining astronomic coordinates of cities and villages for map updates. Later, triangulation was used to establish horizontal points that in most cases spread out in chains along parallels and meridians. Distance measurements with invar tapes and astronomic azimuth determinations collocated with astronomic latitude and longitude determinations at Laplace stations complemented the observations of the network.

The availability of electronic distance meters made possible the establishment of geodetic traverses in the 1970s and 1980s, and by the early 1990s the classical methods (triangulation and traverses) were abandoned. Geodetic positioning based on the Transit system started in the 1970s, especially in regions like the Amazon, where the adoption of classical methods was not possible. In these regions many geodetic stations were established by point positioning for mapping ground control.

When GPS became available in the early 1990s, many countries began using it to establish their geodetic networks. Whereas some countries complemented the existing classical geodetic networks with GPS points, others established completely new national networks using this system. GPS has improved the level of accuracy of the networks by at least one order of magnitude (from 1:100,000 to 1:1,000,000).

The characteristics of GPS geodetic positioning, based on a differential approach, caused a rethinking of the features of geodetic control networks. The result of this reflection gave birth to a new category of network, the Active Control Network, where each station is equipped with a GPS geodetic receiver that continuously tracks the satellites. In this way, users do not need to occupy the reference stations, as the institution responsible for geodetic activities in each country provides the GPS data collected at each reference station. Examples of such networks in Latin America are the Red Argentina de Monitoreo Satelital Continuo (RAMSAC), the Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS (Global Navigation Satellite System) (RBMC), and the Red Geodésica Nacional Activa (RGNA) of Mexico.

Following the same concept, the International GNSS Service (IGS), formerly the International GPS Service, formally began its operation on 1 January 1994. This IAG service is a voluntary worldwide federation of more than 200 agencies that pool resources and permanent GPS and GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema) station data to generate precise GPS and GLONASS products.

The establishment of vertical geodetic networks in Latin America started around the same period as horizontal networks. Based on the classical method of spirit leveling, these surveys were referenced to mean sea level observed during a few years at one or more tide gauges in each country. Despite all the advances that satellite positioning brought to geodesy, there is no effective method that completely replaces the classical survey for the determination of the physical height of stations. Satellite positioning solutions give heights above a reference ellipsoid that need to be transformed to heights above the geoid using a model. The problem is that geoidal models developed for Latin America do not have the same degree of accuracies as those given by spirit leveling (i.e., a few millimeters), in spite of all efforts carried out by the IAG. It is expected that the new satellite gravity missions CHAMP (Challenging Minisatellite Payload), GRACE (Gravity Recovery and Climate Experiment), and GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) will contribute to the refinement of geoidal models and thus improve height determinations in the twenty-first century.

Gravity information supports the determination of the shape of the earth (the geoid). Gravity observations started to be collected in the region in the 1940s. The first results of the gravity adjustment for the Americas were presented in 1967 (Woollard et al. 1967). Many of the gravity campaigns have been conducted using Worden and LaCoste & Romberg gravity meters from IAGS.

The South American Gravity Project (SAGP), developed by the University of Leeds with the support of oil companies, was initiated in 1989. The three-year SAGP project was responsible for the compilation, processing, and validation of gravity data from public and private companies in South America (Green and Fairhead 1993).

Two other projects followed SAGP: the Anglo-Brazilian Gravity Project (ABGP) and the South American Gravity Studies (SAGS). Both projects were developed with the main purpose of infilling gravity gaps and densifying gravity networks in South America (fig. 293). In addition to densification stations, absolute gravity stations were established to support the densification campaigns.

In 1944, a Committee on Geodesy was appointed by the PAIGH Cartographic Commission in order to promote cooperation in solving problems common to member countries, such as the development of a common continental datum. In 1967 a joint effort was carried out by the participating countries to make data available, to observe astronomic points, and to improve the existing geodetic control. Based on the existing and connected triangulation networks, the reference datum was modified producing several alternatives, which were then tested. The effects of each modification were evaluated in terms of geoidal heights and deflections of the vertical. The alternative that represented the best fit to South America, according to the predefined criteria, was then selected. The results were submitted to the PAIGH Committee on Geodesy during the XI Pan-American Consultation on Cartography meeting in Washington, D.C., in 1969, which recommended the adoption of the new South American Datum of 1969 (SAD69) (Fischer 1972).

Despite the PAIGH recommendation to South American countries to adopt SAD69, many countries continued to use their former geodetic systems. By the early 1990s the ready availability of GPS made SAD69 obsolete. GPS had an intrinsic accuracy at least ten times better than all previously established systems. This meant that referring new GPS points to an old reference frame would imply a deterioration in the quality of the coordinates determined by GPS, highlighting the need for a new unified geocentric reference system for the continent. Based on this necessity, the SIRGAS project was created and accepted at an international meeting in Asunción, Paraguay, in October 1993, by representatives of most South American countries, as well as IAG, PAIGH, and DMA (Fortes et al. 2006).

The SIRGAS project encompasses the definition and

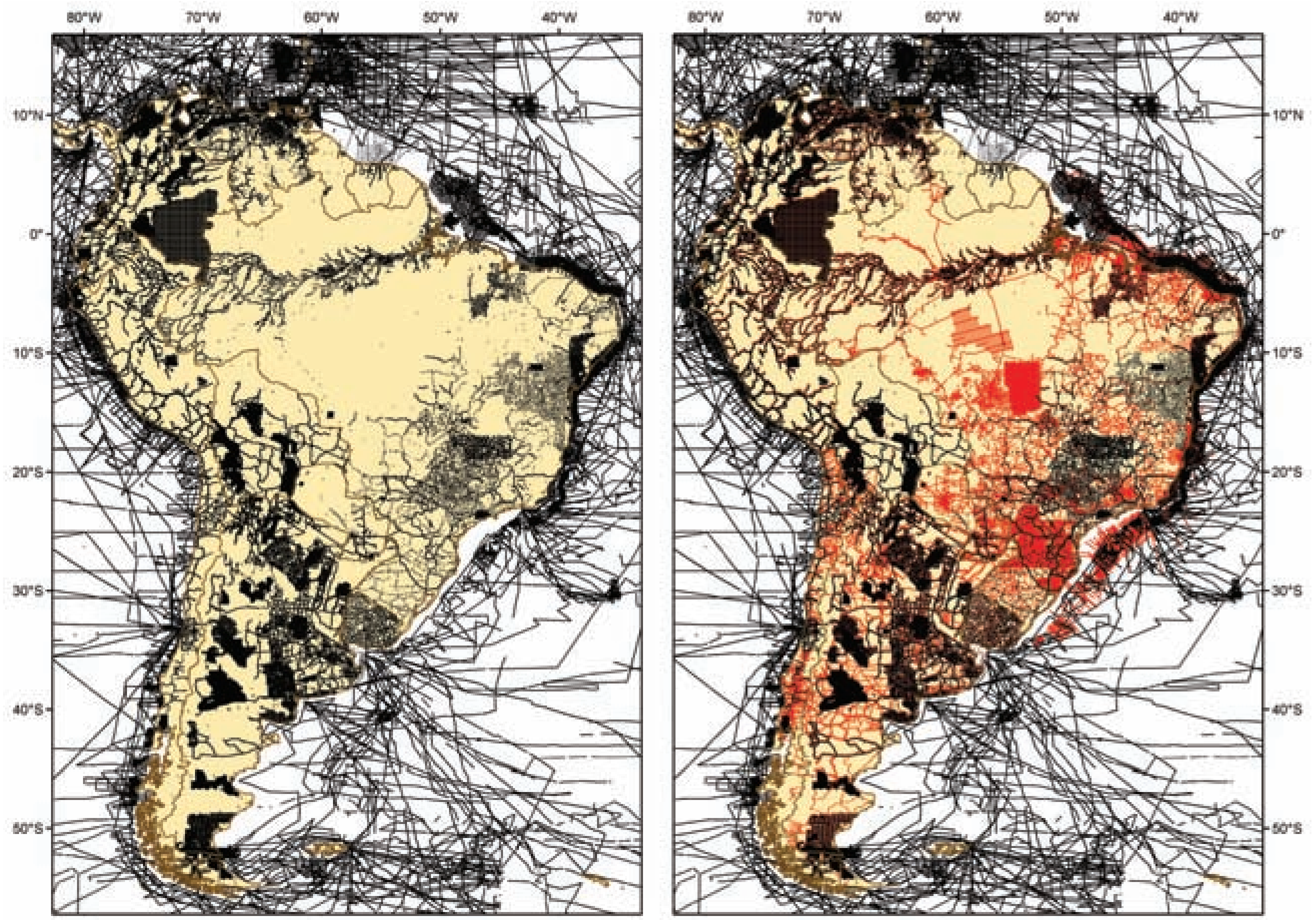

FIG. 293. SOUTH AMERICAN GRAVITY PROJECT (SAGP) (1989–91) (LEFT) AND INFILLING OF GAPS BY THE ANGLO-BRAZILIAN GRAVITY PROJECT (ABGP) AND SOUTH AMERICAN GRAVITY STUDIES (SAGS) IN 2012 (RIGHT).
Images courtesy of GETECH, Leeds.

realization of a unified reference frame for the Americas, consistent with the International Terrestrial Reference Frame (ITRF), and also promotes the definition and establishment of a unique vertical reference system for the region. It is operated by three working groups.

Working Group I, Reference System, is responsible for the definition of a three-dimensional geocentric system for the Americas and for its realization and maintenance through a reference frame consisting of a set of station coordinates and velocities. Two GPS observation campaigns of ten days' duration were performed: the first in 1995 and the second in 2000. During the first, fifty-eight stations were simultaneously measured in South America and neighboring areas and processed by two analysis centers, the Deutsches Geodätisches Forschungsinstitut (DGFI) in Germany and the DMA in the United States, and combined into a unique solution referred to as ITRF94. Because geodetic coordinates, at the level of accuracy obtained by GPS, change with time, the final coordinates were referred to the 1995.4 epoch, which corresponded to the observation campaign period of time (SIRGAS 1997).

Besides the reobservation of fifty-six of the fifty-eight stations from the first campaign, the second campaign succeeded in densifying and extending the network to Central and North American countries by the addition of eighty-five new stations. It also focused on the connection of existing height data to the geocentric reference system through the observation of forty-three stations at tide gauges. Three processing centers—at Instituto Brasileiro de Geografia e Estatística (IBGE), DGFI, and the Bayerische Kommission für die Internationale Erdmessung (BEK)—performed the data processing, with the final combined station coordinates referred to as ITRF2000, reference epoch 2000.4, also corresponding to the observation campaign period of time (Drewes et al. 2005). The distribution of the resulting 184 stations is presented in figure 294.

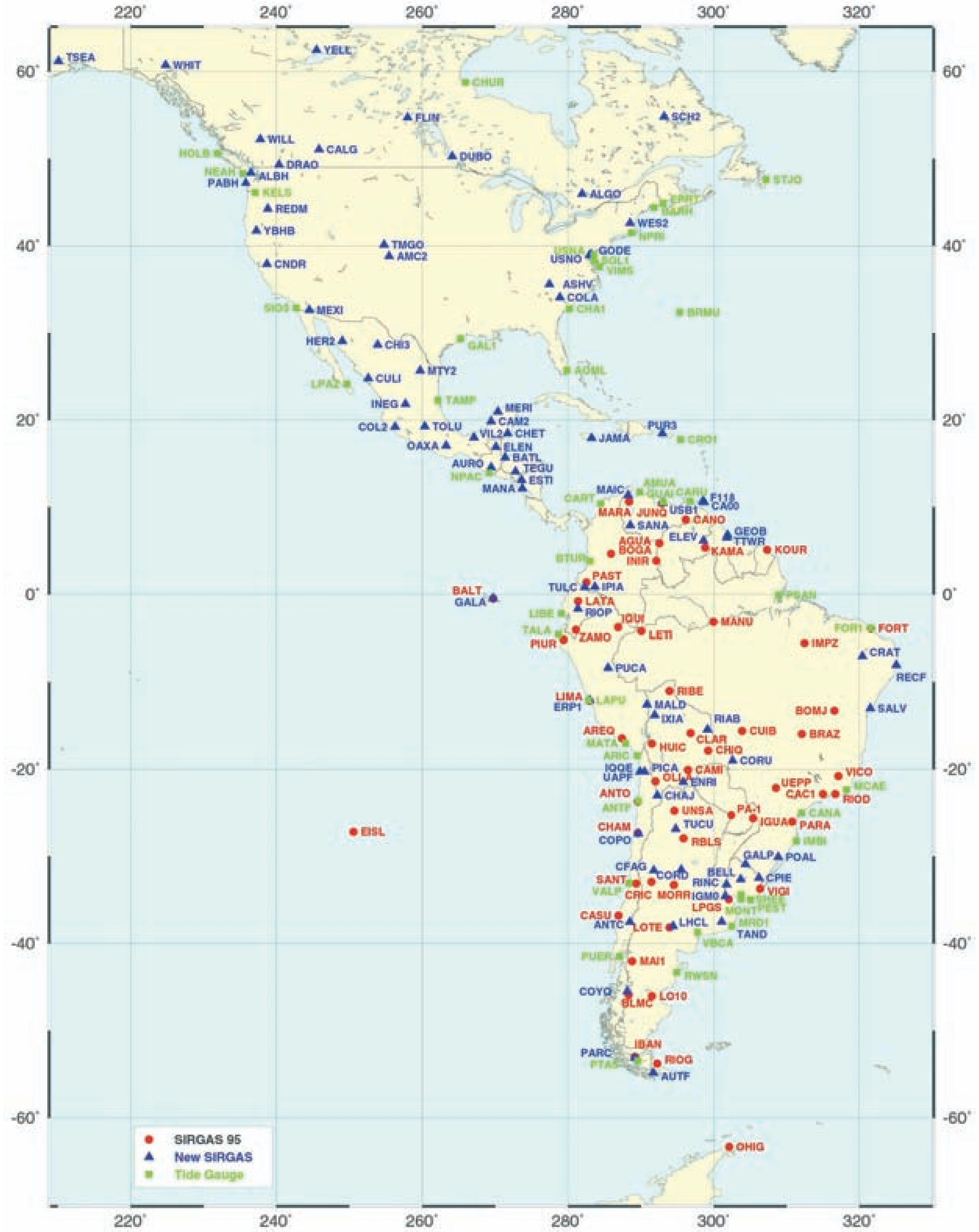

FIG. 294. THE GEOCENTRIC REFERENCE SYSTEM FOR THE AMERICAS, SIRGAS 2000 GPS CAMPAIGN STATIONS (TOTAL 184).

Image courtesy of Luiz Paulo Souto Fortes.

The maintenance of the SIRGAS reference frame is accomplished throughout the active control networks in Latin America (composed of more than eighty continuously operating GPS stations in 2006), whose data are processed weekly by the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC-SIR) in Germany (Seemüller 2004). Working Group II, Geocentric Datum, is in charge of the definition, realization, and maintenance of the geodetic datum in the member countries consistent with the SIRGAS reference frame and the promotion of the connection and transformation of national geodetic networks to the geocentric datum. To date, a number of Latin American countries have officially adopted either SIRGAS 95 or SIRGAS 2000 as their new national reference frame. The Working Group III, Vertical Datum, deals with the definition of a modern unified vertical reference system for Latin America, the establishment of the corresponding reference frame, and the transformation of the existing classical height datums to the new system (Fortes et al. 2006).

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SEE ALSO: Figure of the Earth; Geodesy; Global Positioning System (GPS); Holdich, Thomas Hungerford; Inter-American Geodetic Survey; Photogrammetric Mapping: Geodesy and Photogrammetric Mapping; Property Mapping: Property Mapping in Latin America; Tidal Measurement

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Geodetic Surveying in Africa. The development of the geodetic framework of Africa, as in other parts of the world, has been closely linked to innovations in survey methods. Parts of the network based on classical survey techniques date back to the nineteenth century, and extensive work was added during the 1930s and the decades following World War II. At the end of the twentieth century the quality of the network was variable, and although extended and refined in later years, it reflected the initial inaccessibility of large parts of the continent as well as the varying aims and financial and technical capacities of the colonial survey departments and government agencies involved.

Broadly speaking, three types of geodetic frames can be distinguished. Of the more than fifty African countries, only a few (South Africa, some countries in East Africa situated on 30°E, Egypt, and countries in the Maghreb) boasted regular geodetic networks based on first-order triangulation. By contrast, many large and arid countries situated in northwest and central Africa had networks resulting from primary traverses and isolated control points acquired by means of astronomical surveys alone. The third type of network was a combination of the two previous survey methods and was generally found in large and relatively inaccessible countries, such as the Democratic Republic of the Congo, Angola, Ethiopia, and Libya (FAO 1999). Geodetic surveying had, however, undergone a revolution since the 1970s, and by the end of the century satellite technology had begun to erase the practical problems emanating from this variable pattern.

In any discussion of the history of geodetic surveying in Africa, the Arc of the 30th Meridian takes center stage (Zakiewicz 1997). In 1879 geodesy on this continent obtained a champion of exceptional scientific vision when Sir David Gill was appointed Her Majesty’s Astronomer at the Cape of Good Hope. Realizing that no survey existed in the Southern Hemisphere sufficiently accurate to be of value for geodetic purposes, Gill immediately started negotiations with British authorities, to whom he proposed a gridiron network of trigonometric chains covering the whole of South Africa. Once this network was completed, he proposed the triangulation be extended northward along the 30th degree of longitude to Cairo, from where it could be connected with F. G. W. Struve’s Russian-Scandinavian Arc. Gill kept pursuing this ideal with the utmost vigor, rendering the measurement of the Arc of the 30th Meridian an epic tale of almost unbelievable perseverance and dedication.

The first leg of the Arc was measured from 1883 to 1892, when a team of Royal Engineers under the command of Colonel William George Morris, and with Gill's guidance, executed the geodetic survey of Natal and the Cape Colony to a very high degree of precision. The Anglo-Boer or South African War of 1899–1902 interrupted Gill's plans for the rest of South Africa, but in 1902 the British War Office approved the geodetic triangulation of the Transvaal and Orange River Colony, which was completed in 1906, again under the leadership of Morris and with Gill as scientific adviser. As part of this survey, the Arc was carried as far north as the Limpopo River, a distance of approximately 1,600 kilometers. In the meantime, between 1897 and 1901, Alexander Simms, under Gill's direction, extended the Arc in Southern Rhodesia (now Zimbabwe) almost to the Zambezi River. In 1906–7 Captain H. W. Gordon connected Simms's chain to the Transvaal triangulation. The 800-kilometer section through Northern Rhodesia (now Zambia) was surveyed by the Swedish geodesist Tryggve Rubin, who in March 1906 terminated his measurements near the Tanganyika (now Tanzania) border for financial reasons. Thus, when Gill retired from office in 1907, the Arc of the 30th Meridian extended from the Cape almost to Lake Tanganyika.

From 1907 to 1909 further progress was achieved when, upon conclusion of the work of the Uganda-Congo Boundary Commission, a newly formed joint Anglo-Belgian team measured the so-called Uganda Arc from 1°N to 1°S. It was highly unfortunate that after this survey World War I and a lack of finances stopped work on the Arc for more than twenty years.

All along, the War Office considered the completion of the Arc of primary importance. In 1931 a party of Royal Engineers, under the command of Major Martin Hotine, was dispatched to carry Rubin's chain from 10°S in Northern Rhodesia, farther north through Tanganyika. In 1933 Hotine took the Arc up to the border of Urundi (now Burundi) at 5°S. In 1937 the Tanganyika Survey Department completed the 400-kilometer connection between Urundi and Uganda, thereby extending the Arc from the Cape to the equator.

The northern segment of the Arc began in Egypt. The geodetic triangulation along the Nile commenced near Cairo in 1907, and by 1930 the Egyptian section was completed as far south as Adindan, at 22°10′N.

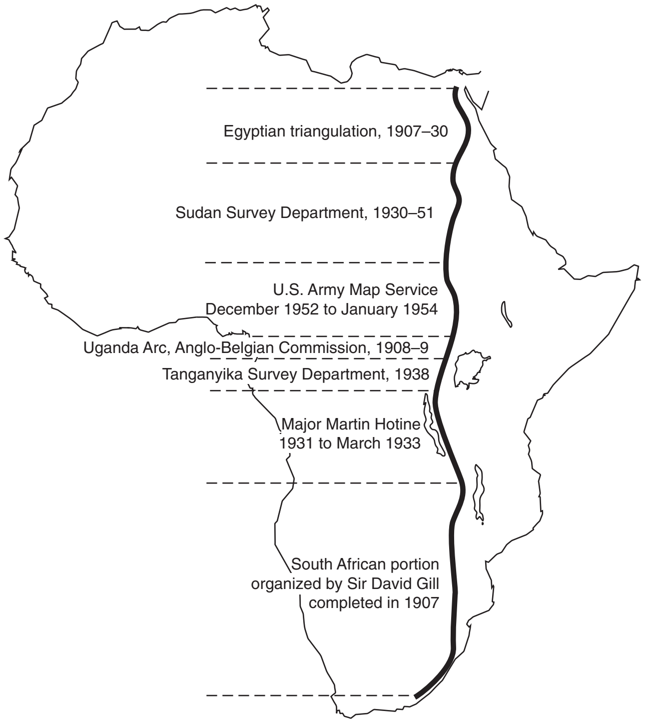

FIG. 295. THE MEASUREMENT OF THE ARC OF THE 30TH MERIDIAN, 1883 TO 1954.

Due to economic problems, the measurement of the Arc across the Sudan only began in 1935, but eventually all survey work came to an end due to World War II. The work in the Sudan was resumed in 1947, and by 1952 the Abu Qarn base, at 10°N, was measured. This left a gap of approximately 1,000 kilometers in the Arc between the Abu Qarn base in the Sudan and the Semliki base in Uganda of which about 500 kilometers passed through the impassable Sudd marshes. In 1952 the U.S. Army Map Service, in collaboration with the Sudan Survey Department, began this survey. In January 1954 the last gap in the Arc of the 30th Meridian was closed—Sir David Gill's dream of a continuous Arc from the Cape to Cairo had at last become a reality (fig. 295). Unfortunately, the seventy-five years that had elapsed since its initiation had by then impaired the usefulness of the Arc insofar as new electronic distance-measuring instruments had come into use and satellite technology was making the measurement of arcs for geodetic purposes obsolete. The U.S. Army Map Service did, however, use the results of the Arc for the computation of a new figure of the earth, and even before the final closure, adjustments were carried out for various sections of the Arc. The adjustment for the section between Southern Rhodesia and Uganda was conducted by the British Directorate of Overseas Surveys, the results of which were termed the New 1950 Arc Datum (McGrath 1983). Referenced to the Clarke 1880 ellipsoid, this datum, together with its slightly different successor, the 1960 Arc Datum, became the foundation of all surveying and mapping work in East and Central African countries. Likewise, the Geodetic Survey of South Africa was based on the Cape Datum, which was referenced to the Modified Clarke 1880 ellipsoid—a situation that lasted until January 1999, when the new South African Hartebeesthoek 94 Datum (referenced to the WGS 84 ellipsoid) came into use.

Meanwhile geodetic work in the rest of Africa was conducted in a piecemeal fashion. From 1924 to 1936 Egypt ran a geodetic chain from Cairo westward along the coast as far as Tripoli and eastward up to the border with Palestine. During the 1880s and 1890s France, which had a strong presence in northwest Africa since the middle of the nineteenth century, commissioned its Service géographique de l'armée to undertake a geodetic triangulation in Tunisia and Algeria. Connecting chains covering the coastal area of Morocco were added during the 1920s. Until 1940, when it was superseded by the Institut géographique national (IGN), the Service géographique de l'armée was also responsible for the geodetic infrastructure (mainly primary traverses and astronomical observations) of francophone West and Equatorial Africa (Finsterwalder and Hueber 1943).

Before World War II the most notable geodetic work in the Belgian Congo (now Democratic Republic of the Congo) was undertaken by the Comité spécial du Katanga (CSK), a privately managed state agency founded in 1919. The mining activities in the Katanga (now Shaba province) necessitated geodetic control, and by 1942 southern and eastern Katanga had been triangulated and the network linked to the Arc of the 30th Meridian in Tanganyika and Northern Rhodesia (Finsterwalder and Hueber 1943). After the establishment of the Institut géographique du Congo Belge (IGCB) in 1949 the geodetic network was extended westward to link Katanga to the Angolan coast. From 1960 until 1972 extensive adjustments along this link resulted in the establishment of the so-called Arc of the 6th Parallel (south) (Meex 1997).

Between 1885 and 1915 Germany undertook geodetic surveying in German South-West Africa (Namibia) and German East Africa (Tanzania). The German agencies concerned were the Königliche Preußische Landesaufnahme and its civilian successor, the Reichsamt für Landesaufnahme. In German South-West Africa an east-west geodetic chain, initially measured between Swakopmund and Gobabis, was extended to the Okavango River in the north and the Orange River in the south (Finsterwalder and Hueber 1943). This framework was in use until the 1980s, when the South African Chief Directorate of Surveys and Mapping undertook a satellite resurvey of the geodetic network of Namibia. In German East Africa, an Anglo-German Boundary Commission (1902–6) observed a primary chain along the border with Kenya, and in 1912–14 a network of primary triangles was established in the east of the colony (Rowe 1933, 173).

From 1883 until 1911 surveying in Angola and Moçambique (Mozambique) was organized by the Portuguese Ministério da Marinha e Ultramar, which assigned this responsibility to the Comissão de Cartographia. In 1911 this ministry was divided into the Ministério da Marinha and the Ministério das Colónias. From 1951 to 1974 the latter ministry was known as the Ministério do Ultramar. Until 1951 the Ministério das Colónias coordinated the work of the Comissão de Cartographia, which often collaborated with the Portuguese army for the surveying of terrestrial areas. One such survey was a geodetic triangulation that was performed in Moçambique from 1932 to 1936 (Finsterwalder and Hueber 1943). Geodetic measurements were also made in Angola, but the particulars are unknown. After 1936 until independence geodetic work was regulated by the Junta das Missões Geográficas e de Investigações Coloniais (JMGIC), a department of the Ministério do Ultramar.

Apart from the work done by boundary commissions and the work on the Arc of the 30th Meridian, little geodetic work was undertaken in British Africa in the interwar years (Winterbotham and McCaw 1928; McGrath 1976). The necessity of survey frameworks for development was, however, realized (Worthington 1938, 36), and during the 1930s the Colonial Survey Committee commissioned the measuring of various geodetic chains in Uganda, Tanganyika, the Gold Coast (Ghana), and Nigeria (McGrath 1976; Rowe 1933; Calder Wood 1936). In 1946 effective central control over the surveying and mapping of British dependencies was at long last reached with the establishment of the Directorate of Colonial (later Overseas) Surveys. During the 1950s and early 1960s primary chains were measured in Uganda, Kenya, Nyassaland (Malawi), Northern Rhodesia, and Basutoland (Lesotho) as well as in Nigeria, Sierra Leone, and Gambia in West Africa (McGrath 1983). In Tanganyika the original German observations executed before World War I were recomputed and embodied in a new triangulation scheme, and in Bechuanaland (Botswana) a primary framework was observed using Tellurometer traverses. Until 1984, when it was incorporated into the Overseas Surveys Directorate of the British Ordnance Survey, the Directorate of Overseas Surveys undertook valuable work in maintaining and extending geodetic networks on the continent.

Since the 1970s the use of satellite systems such as the U.S. Navy Navigation Satellite System (NNSS), the Navstar Global Positioning System (GPS), and the Russian GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema) for position fixing radically altered the nature of geodetic surveying. Worldwide, this new technology led to increased international cooperation in geodesy and the development of unified geodetic frameworks. The latter became especially necessary in Africa, where the continent's colonial heritage accounts for survey systems of different countries based on different datums referenced to different spheroids. Early in the twenty-first century an African initiative called the African Geodetic Reference Frame (AFREF) sought to alter this situation by creating a network of continuous, permanent GPS stations throughout the continent

(Wonnacott 2005). In 2001, the project gained the formal support of the International Association of Geodesy (IAG) and the United Nations Economic Commission for Africa (UNECA), which saw AFREF as a key step toward a precise geoid for Africa and a uniform and consistent coordinate system for the entire continent.

ELRI LIEBENBERG

SEE ALSO: Figure of the Earth; Geodesy; Global Positioning System (GPS); Holdich, Thomas Hungerford; Photogrammetric Mapping: Geodesy and Photogrammetric Mapping; Property Mapping: Africa; Tidal Measurement

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Geodetic Surveying in Europe. The geodetic activities in Europe at the beginning of the twentieth century were guided by the International Association of Geodesy (IAG) constitution of 1886. National institutions responsible for geodetic surveying followed the IAG recommendations related to the establishment of geodetic networks, whose main purpose was to support cartographic coverage of the countries. The IAG was a successor of the Europäische Gradmessung, subsequently the Internationale Erdmessung, a group of twenty nations. During World War I the Internationale Erdmessung was dissolved, and in 1919 the International Union of Geodesy and Geophysics was founded (Levallois 1988; Torge 1993).

Until the introduction of space geodetic techniques the prescribed methodology consisted of establishing triangulation networks. The layout was either a continuous net or a system of chains. The latter was initially adopted by the majority of the countries, given its lower costs and implementation time. The geometry of triangulation networks was defined by angles or direction measurements using highly accurate theodolites. The orientation was controlled by the establishment of Laplace stations at selected sites where astronomical observations for azimuth and longitude were performed. The scale of the triangulation networks was given by the length measurement of selected sides.

An important development that improved distance measurement was the discovery of invar, an iron-nickel alloy, near the end of the nineteenth century. Its low coefficient of thermal expansion made it desirable for the measurement of baselines, replacing wooden and other metal rulers and tapes. The invar wires were used until the introduction of the electronic distance meters or electromagnetic distance measurement (EDM) in the middle of the twentieth century. EDM instruments were used to measure the sides of the geodetic networks. In countries where the network was sparse, traverses were used to replace triangulations or to control the scale of the network as, for example, in Finland (Parm 1976). To maintain the scale consistency of the instruments Väisälä baselines were established in almost all countries of Europe and in many other areas of the world for instrument calibration. The lengths of these baselines were determined very accurately by the multiplication of a very precise optical length reference.

Until World War II the different European nations each developed their own geodetic reference systems or geodetic datums. They were based on the choice of a reference ellipsoid, a point of origin, and associated parameters: astronomical latitude and longitude, north-south (ξ) and east-west (η) components of the deflection of the vertical, astronomical azimuth of one direction, and the geoid undulation (N).

The reconstruction of Europe after the war motivated the integration of these datums into a common one. Primary triangulation chains were selected by the Western European countries to form a continuous network, the Réseau Européen 1950 (fig. 296). The U.S. Coast and Geodetic Survey computed the network, and the resulting coordinates were referred to as ED50 (European Datum 1950), which had its origin point at the Helmertturm in Potsdam, Germany. At this point were assigned the values of the vertical deflection components ($\xi = 3.36$ arc seconds, $\eta = 1.78$ arc seconds) and the geoid undulation ($N = 0$ m). The associated reference spheroid was the International ellipsoid, determined by John Fillmore Hayford and adopted by the International Union of Geodesy and Geophysics in 1924; its parameters are the semimajor axis $a = 6{,}378{,}388$ meters and the flattening $f = 1/297$. Many countries adopted ED50

FIG. 296. *RÉSEAU EUROPÉEN*, 1:6,000,000, 1949. There are several versions of the network and map. Size of the original: 72.8 × 67.7 cm. Image courtesy of the Cartothèque, Institut géographique national.

as the official geodetic datum, serving as a basis for their cartographic and surveying activities.

In 1954 the IAG created the subcommission RETrig (Réseau Européen Trigonométrique). Its main purpose was to continue the computation of the European geodetic network and to increase its quality, including new and more accurate measurements. A new version of the European Datum was adopted in 1979 (ED79) based on dense triangulation networks (Kobold 1980). The importance of including Doppler observations in the next phase of the computations was recognized at that time, and they were finished in 1987 when a new solution, ED87, was adopted. The work of RETrig was very fruitful and contributed to the development of computation techniques.

Many Eastern European countries, integrated with the former Soviet Union, adopted the Pulkovo Datum of 1942, with its origin at the Pulkovo Observatory. The 1942 Krasovskiy ellipsoid, defined by the semimajor axis a = 6,378,245 meters and the flattening f = 1/298.3, was adopted as the reference surface.

The development of the vertical datums in Europe followed the approaches of the geodetic networks very closely. At the beginning of the twentieth century several tide gauges had already been installed to provide a reference for heights (vertical datums) in each country or group of countries. Leveling lines were established in order to fulfill particular needs, and gravity measurements were also performed to reduce spirit leveling observations. The countries adopted different height systems. For instance, normal heights are used in France and Sweden, orthometric heights in Finland and Spain, and normal-orthometric heights in Austria and Norway.

In 1955 the REUN (Réseau Européen Unifié de Nivellement) commission of the IAG initiated its work aimed at the unification of Western European leveling networks. The computations were performed in geopotential heights and the origin was the Normaal Amsterdams Peil in Amsterdam. Each country selected the most appropriate leveling lines to fulfill the accuracy requirements and the need for continuous loops across the region. The first solution, REUN 1957, was computed and followed by several others until the late 1980s, when REUN was discontinued. The work was continued later by the EUREF (European Reference Frame) subcommission. G. Bomford (1980) provided details concerning the instrumentation and techniques used in the establishment of classical horizontal and vertical datums.

Artificial satellites were used for geodetic purposes in Europe very early. In the 1960s a set of observation projects were performed using satellites Echo 1, Echo 2, and PAGEOS (Passive Geodetic Earth Orbiting Satellite) launched by the U.S. National Aeronautics and Space Administration. In 1963 the French and Algerian networks were connected. This test campaign was extended in 1965 by the connection of the Portuguese mainland and the Azores archipelago networks (fig. 297). In 1967 a new connection was established between Europe (France) and Africa (Senegal and Chad). Spatial triangulation was used allowing for the first time the connection of networks at long distances (Levallois 1988, 247–65).

At the end of the 1960s the first measurements were made of distances to artificial satellites and to the moon using laser beams and telescopes. This technique is known as satellite laser ranging (SLR) or lunar laser ranging (LLR), and its applications in the fields of earth dynamics, gravity field, and rotation are all crucial for establishing accurate global geocentric reference frames. Another space technique contributing to the reference frame maintenance is the VLBI (very long baseline interferometry), developed in the 1970s. This technique uses the determination of the distance between two radio telescopes that receive radio signals from a quasar. By the end of the twentieth century about twelve SLR sites and ten VLBI sites operated in Europe. Some observatories integrated several space geodetic techniques (e.g., Matera in Italy and Wettzell in Germany).

FIG. 297. CONNECTION EUROPE–AZORES USING THE SATELLITE ECHO 1. Image shows the locations of photographic observations in 1965.
Size of the original : 8.1 × 8 cm. From Levallois 1988, 257 (fig. 108).

The first Doppler observation, EDOC-1 (European Doppler Observation Campaign), took place in 1975 and used the satellites of the Transit constellation. In 1977 EDOC-2 was organized, consisting of thirty-nine stations in fifteen countries, and resulted in a set of homogeneous coordinates in Europe close to a quasi-geocentric global geodetic system.

The Navstar GPS (Global Positioning System) succeeded the Transit system as a geodetic tool in the middle of the 1980s. The high accuracy and reliability of the GPS made it suitable for establishing a new reference frame covering the whole European continent, replacing the ED solutions. Recognizing the potential of space-based geodetic techniques for the establishment and maintenance of global and continental geodetic reference frames and the need for a modern and precise continental reference frame in Europe, the IAG constituted the EUREF subcommission in 1987 to continue the work of RETrig under this new perspective.

In 1990, EUREF defined the ETRS89 (European Terrestrial Reference System 1989) as a system with the origin at the earth's center of mass and tied to the stable part of the Eurasian plate (EUREF 1990). The corresponding reference frame was conceived as the geodetic infrastructure for multinational projects requiring precise georeferencing. The ETRS89 is tied to the ITRS (International Terrestrial Reference System), maintained and made available by the IERS (International Earth Rotation Service), which also produces the corresponding ITRF (International Terrestrial Reference Frame) and the relationships among the different frames. The IERS was established in 1987 by the International Astronomical Union and the International Union of Geodesy and Geophysics, replacing the International Polar Motion Service and the earth-rotation section of the Bureau International de l'Heure.

A set of markers homogeneously covering the European continent was established by EUREF to make the ETRS89 available to the users. The EUREF89 GPS campaign, the first one at the continental level, was organized in 1989, allowing the determination of ETRS89 coordinates of ninety-two stations across Western Europe. After the end of the Cold War the Eastern European countries joined EUREF efforts, resulting in coverage of all but three European countries.

In 1996 the EPN (EUREF Permanent Network) was created. By the end of the twentieth century about 120 stations were integrated into the EPN. This covered the European continent homogeneously and made continuous observations with high accuracy GPS receivers (fig. 298). The EPN is a densification of the International GPS Service and contributes to the ITRS and the monitoring of tectonic deformations in Europe.

At about the same time, EUREF was charged to continue the work of REUN and produce the UELN95/98 (Unified European Levelling Network) solution. This was extended to the majority of the Eastern European countries and defined as the EVRS (European Vertical Reference System) to express the height information.

A link between the vertical and geospatial components was established in 1997 through the EUVN97 (European Vertical GPS Reference Network), a Europe-wide GPS campaign consisting of 196 sites collocated at nodal points of the UELN and near tide gauges. As a result, the parameters were obtained to transform the national height systems into a common European height reference system (Ádám et al. 2002).

FIG. 298. GPS TRACKING STATIONS OF THE EUREF PERMANENT NETWORK IN JUNE 2000.
From Carine Bruyninx, "Overview of the EUREF Permanent Network and the Network Coordination Activities," presented at EUREF Symposium, June 22–24, 2000, Tromsø, Norway, fig. 1 (online publication). Permission courtesy of Dr. Carine Bruyninx, Royal Observatory of Belgium, Brussels.

Geodetic surveying in Europe was carried out by the national mapping agencies of each country. These institutes were generally civilian. In the 1980s the European national mapping agencies formed CERCO (Comité Européen des Responsables de la Cartographie Officielle), later transformed into the EuroGeographics consortium including the cadastral agencies as well. The research activities in geodesy were carried out by geodetic institutes and laboratories at university and governmental research sites.

During the twentieth century European geodesists and institutions published a considerable number of textbooks (e.g., Bomford 1980; Levallois 1969–71; Jordan, Kneissl, and Eggert 1956–72). They also contributed to technical journals and reports. Notable technical journals included *Allgemeine Vermessungs-Nachrichten* (Germany), *Bollettino di Geodesia e Scienze Affini* (Italy), *Geodeziya i Aerofotos"yëmka* (Russia), and *Survey Review* (United Kingdom). Important report series were Suomen geodeettisen laitoksen julkaisuja (Finland), Publications on Geodesy (Netherlands), and the publications of the Deutsche Geodätische Kommission bei der Bayerischen Akademie der Wissenschaften (Germany).

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SEE ALSO: Figure of the Earth; Geodesy; Global Positioning System (GPS); Photogrammetric Mapping: Geodesy and Photogrammetric Mapping; Property Mapping: Europe; Tidal Measurement

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Geodetic Surveying in Russia and the Soviet Union. During the twentieth century, the Russian geodetic survey service operated throughout the vast area of the country, covering more than 22,000,000 square kilometers. Most of its territory consisted of sparsely populated or virgin mountain terrain, taiga, tundra, wetlands with many rivers and lakes, and a broad area of permafrost.

In 1897 Korpus voyennykh topografov (KVT), the corps of military topographers—the service that carried out the majority of topographic and geodetic surveys in the Russian Empire—completed the adjustment of the first-order triangulation series, which was established in the country in the nineteenth century. Apart from the KVT, geodetic surveying was also conducted by Mezhevoye vedomstvo (the estate surveying department); Gornoye vedomstvo (the mining department); Pereselencheskoye upravleniye (administration for the development of Eastern Russian agricultural lands and resettlement of European Russians to them); Gidrograficheskoye upravleniye (the hydrographic administration of the admiralty); Ministerstvo putey sobshcheniya (the ministry of transportation); Imperatorskoye Russkoye geograficheskoye obshchestvo (IRGO, the imperial Russian geographical society); and a number of other agencies. However, their activities had little impact on the mapping of the country's territory because they were not coordinated. Triangulation was carried out independently in every province, with different control points used in each project, resulting in substantial coordinate discrepancies at the junctions of triangulation networks. The adjustment of the first-order triangulation failed to eliminate the discrepancies, making apparent the inadequate state of triangulation in Russia. Therefore, in 1910, the KVT conducted a new first-order geodetic survey, which put an end to the chaotic development of first-order triangulation in Russia. Despite its limited personnel (in 1906 the corps consisted of 513 topographers and geodetic surveyors), the KVT produced a substantial body of work. However, given the vastness of the country, it was not enough (see fig. 1017). Moreover, by the end of World War I, a substantial number of the geodetic networks established by the KVT came to be located outside Russian borders (Sudakov 1975).

On many occasions a number of prominent Russian scholars and public figures argued for the establishment of a national geodetic service. Their proposals were discussed at the meetings of the Akademiya nauk and the RGO; however the idea was successfully implemented only after the Bolshevik Revolution of 1917.

In March 1919, despite the raging civil war and collapsing economy, a governmental decree established the Vyssheye geodezicheskoye upravleniye (VGU) for the topographic exploration of the country's territory (see table 18 for the name changes of this organization during the twentieth century). During the twentieth century, the VGU closely collaborated with Voyenno-topograficheskaya sluzhba (the military topographic service), and all geodetic projects had to meet technical requirements jointly approved by the two institutions.

By 1923 the Soviet geodetic survey service had begun to carry out systematic triangulation and topographic surveys at 1:50,000 scale, primarily in central parts of Russia, Ukraine, the Volga region, and the Ural Mountains. As the state could not provide sufficient funding and the geodetic survey service lacked both qualified personnel and high-precision instruments, the projects were of limited scope. For that reason, in the 1920s the geodetic survey service concentrated more on analyzing the results of earlier works and on establishing basic principles for future projects. After careful consideration some very important decisions were made: the first-order triangulation networks were transformed into an astronomical-geodetic network; the Bessel spheroid was adopted for geodetic network calculations; the zero mark of the Kronstadt tide gauge (on the Baltic Sea) was adopted as the vertical datum; the Gauss-Krüger orthogonal coordinate system was adopted as standard; and a new system of dividing topographic maps into sheets was introduced. In order to facilitate and speed up surveying, 1:50,000 and 1:100,000 scales were adopted as standard for national surveys, rather than the 1:25,000 scale that was preferred by some governmental agencies. Feodosiy Nikolayevich Krasovskiy, a leading geodesist, estimated that it would take between 100 and 150 years to map central Russia if the scale of 1:25,000 had been adopted.

Extremely important events for the Soviet geodetic survey service included: the establishment of Tsentral'nyy nauchno-issledovatel'skiy institut geodezii, aeros"yëmki i kartografii (TsNIIGAiK, the scientific research institute of geodesy and cartography), Moskovskiy geodezicheskiy institut (MGI), which was later named Moskovskiy institut inzhenerov geodezii, aerofotos"yëmki i kartografii (MIIGAiK, the Moscow institute of geodetic engineering, aerial photography, and cartography), and several technical schools for geodesy; the adoption of air photography for topographic surveys; and the onset of geodetic instrument production in the country. The first-order national triangulation scheme and program was developed by Krasovskiy and ensured the necessary precision of the traverse networks (Sudakov 1967).

In the 1930s, the country went through rapid industrialization and the collectivization of agriculture. The demand for geodetic networks was so high that the geodetic survey service lacked the resources to meet it. Many institutions carrying out geodetic surveys and projects emerged following their own guidelines. The general condition of geodetic networks was considered unsatisfactory due to these numerous digressions from adopted schemes and schedules. Typical surveys conducted between 1929 and 1935 show that guidelines were poorly coordinated and projects overlapped. The adjustment of leveling and triangulation networks, carried out between 1932 and 1935, revealed a 1.875-meter divergence between European and Siberian leveling. The disparity in a point's position between the Pulkovo coordinate system adopted in the western part of the country and the Svobodnyy coordinate system in its eastern part was up to 270 meters in latitude and up to 790 meters in longitude (Kashin 1999). There was little alternative, for a period at least, to retaining the Pacific system of altitudes in Siberia, as well as the Svobodnyy, Magadan, Tashkent, and other coordinate systems, along with the Pulkovo one.

From 1926 to 1935, while undergoing numerous reorganizations and losing its independence, the geodetic survey service failed to reach its main goal, which was to reconcile the competing interests of various agencies (which instead prevailed over the general interests of the Soviet states) and to coordinate their topographic and geodetic projects. In 1935 and 1938 the Soviet government reorganized the geodetic survey service. It established Glavnoye upravleniye geodezii i kartografii (GUGK), subordinate to the Soviet security police and responsible for the mapping of the country's territory. The geodetic survey service considerably improved its material resources and organized the manufacturing of high-precision surveying instruments. The size of its personnel also steadily increased. It would not be an exaggeration to suggest this was the period when Soviet geodesy and cartography entered its golden age, which lasted until the late 1980s (see figs. 1018–20). Between 1931 and 1944, 180 engineers and technicians entered the ranks of the geodetic survey service every year, while more than 1,000 specialists in this field had graduated from secondary schools and higher institutions by 1975. By 1985 the total number of engineering and technical personnel in the geodetic survey service had reached 25,000.

In this period, which lasted more than fifty years, the Soviet geodetic survey service developed a modern astronomic-geodetic network (AGN) covering the whole territory of the Soviet Union and characterized by its high density and uniformity. Its creation enabled the geodetic survey service to achieve its two main objectives within a relatively short period: to complete in less than twenty years the mapping of the country at 1:100,000 scale and to produce in less than thirty years topographic maps for the whole country at 1:25,000 scale. It was possible because of considerable advancements in science, the development of a modern surveying instrument manufacturing industry, photogrammetry, computing technology, a widespread implementation of aerospace methods, improved organization of topographic and geodetic projects, and the dedication of the geodetic survey service personnel.

From 1938 to 1940 the major guidelines for topographic and geodetic projects were standardized (table 17). The *Osnovnyye polozheniya o postroyenii gosudarstvennoy opornoy geodezicheskoy seti SSSR*, indispensable regulations for establishing the state geodetic control network, were implemented (fig. 299). These could be used for geodetic control of surveying at 1:10,000 scale. The construction of geodetic networks and topographic surveying was concentrated in the European part of the country and Western Siberia. First-order triangulation was also carried out in the Far East, in Kazakhstan, and in Central Asia.

From June 1941, when Nazi Germany attacked the Soviet Union, the major aim of the Soviet geodetic survey service was to provide the army with maps and catalogs of coordinates and to carry out surveys in strategically important areas (Baranov and Kudryavtsev 1967). Even before victory over Nazi Germany, the geodetic survey service began to restore damaged geodetic networks, to update maps, and to develop networks for surveys of industrial areas of the country at 1:10,000 scale, and at 1:100,000 scale for other areas.

In 1946, after a scheduled adjustment of the first-order triangulation and the leveling control network, a governmental decree introduced uniform systems of geodetic coordinates and heights—the 1942-System with the Pulkovo datum point and the Baltic Height System with the Kronstadt tide gauge as the datum point.

TABLE 17. Topographic surveys in the Soviet Union completed by the outbreak of the Great Patriotic War, 1941–45

Scale	Area surveyed to 1918 (km²)	Area surveyed 1918–32 (km²)	Area surveyed 1933–37 (km²)	Area surveyed 1938–40 (km²)	Total
1:10,000 or larger	1,800	139,500	179,700	8,100	329,100
1:21,000	13,100	7,400	1,200	1,200	22,900
1:25,000	-	259,300	273,200	65,700	598,200
1:42,000	98,600	49,400	-	-	148,000
1:50,000	-	644,300	189,700	400,000	1,234,000
1:84,000	541,600	139,500	-	-	681,100
1:100,000	-	550,500	408,200	370,700	1,329,400
1:200,000	-	30,300	344,300	160,600	535,200
Total	655,100	1,820,200	1,396,300	1,006,300	4,877,900

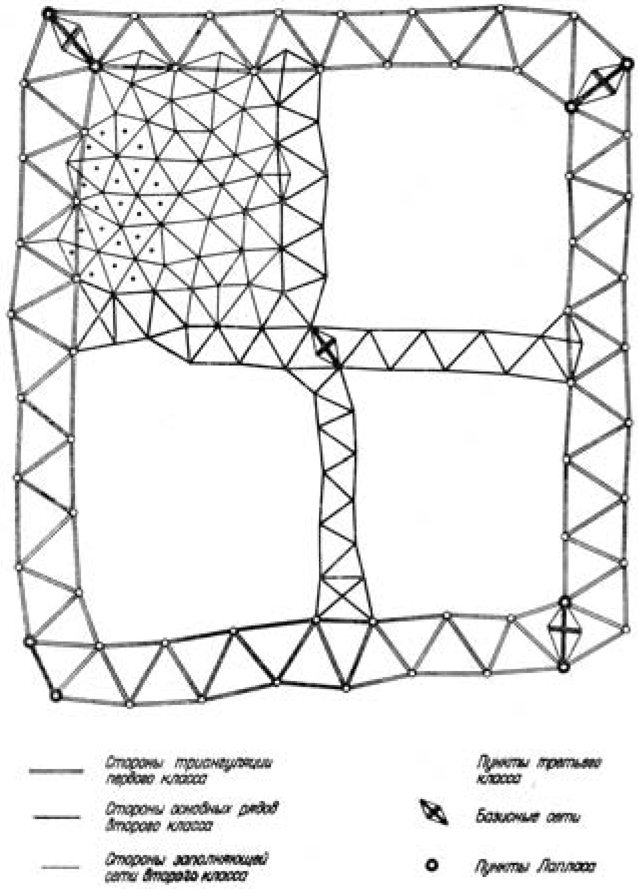

FIG. 299. DIAGRAM FROM *OSNOVNYYE POLOZHENIYA O POSTROYENII GOSUDARSTVENNOY OPORNOY GEODEZICHESKOY SETI SSSR*, 1939, SHOWING THE GEODETIC NETWORK OF THE SOVIET UNION. The key at the bottom identifies first-, second-, and third-order triangulation sides (left) and first-order points, baselines, and Laplace stations (right).
From Sudakov 1967, 70.

The Krasovskiy reference ellipsoid (semimajor axis = 6,378,245 meters; flattening ratio = 1/298.3) was adopted for calculating geodetic points.

The AGN point coordinates, which had been earlier established within regional systems, were recalculated for the 1942-System. This encompassed the entire European part of the Soviet Union, Kazakhstan, Central Asia, and Western Siberia, while stretching further eastward as a narrow belt to the Far East. From the mid-1950s to the late 1960s major projects were carried out in the northern and eastern regions of the country, where intensive exploitation of natural resources was taking place. It was essential to construct the AGN for the whole territory of the Soviet Union and to develop second- and third-order geodetic networks for surveys at 1:25,000 and 1:10,000 scales and extensive networks for surveys at 1:5,000 scale and larger (Sudakov 1967). In the early 1970s the geodetic survey service completed the adjustment of the AGN on a block-by-block basis; a single coordinate system was adopted for the whole country.

The application of visible and radio wavelength electromagnetic distance measurement equipment enabled the transition to the construction of second- and third-order polygon networks to replace existing triangulation networks. The geodetic survey service expanded its surveys considerably at scales between 1:10,000 and 1:2,000 for land reclamation purposes. Fourth-order short-sided polygons formed the main geodetic basis for topographic surveying at the scales of 1:5,000 and larger. In the late 1960s the application of optic and radio technology in surveying enabled the development of the space geodetic network (SGN). All SGN points were integrated with the AGN points and were used for subsequent network adjustment. The global navigation system, GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema), was also created. At the same time much work was done in high-risk seismic areas of the country, where the geodetic survey service carried out repeated leveling and established geodynamic test areas for periodic high-precision geodetic surveys in order to trace pre-earthquake warning signs.

In the 1950s and 1960s the Soviet geodetic survey service carried out substantial topographic and geodetic surveys in the western parts of China and in Syria, Afghanistan, Iraq, and Indonesia. Since the 1970s the GUGK actively collaborated with geodetic survey services of developing nations by training their personnel, supplying equipment, and carrying out aerial surveys, and topographic, geodetic, and cartographic projects. The most important projects, such as developing geodetic networks and making and updating topographic maps, were conducted in Cuba, Nicaragua, Mongolia, Afghanistan, Laos, Yemen, Somalia, Angola, Mozambique, and Ethiopia. Collaboration with other countries was particularly strong in using data produced by remote sensing. The Soviet geodetic survey service took part in mapping the moon and other planets of the solar system. In 1970 the GUGK began its work in the Antarctic, where Soviet research stations carried out observations of the space-based geodetic complex, established control gravimetric points, and conducted large-scale topographic surveys (*Natsional'nyy otchet geodezicheskoy sluzhby SSSR za '89*, 1990).

In the mid-1970s the observation of the first-order state gravimetric network began. Moscow, Lyodovo, St. Petersburg (Leningrad), and Irkutsk were included as fundamental points in the World Gravimetric System. Gravimetric surveying was also carried out on the continental shelf. The adjustment of the state gravimetric network was completed in 1986.

The AGN was completed in the 1980s and consisted of 164,360 first- and second-order triangulation points. The network was supplemented with 170,000 third- and fourth-order extension geodetic network points, which served as the major geodetic basis for the whole range of topographic surveys, beginning with a scale of 1:500 (Kashin 1999). From 1983 to 1993, in order to increase the precision of the AGN, the Doppler Geodetic Network (DGN) was created in its weakest points by applying the Transit navigation system; its 134 points were evenly distributed across the country's territory, being combined with the AGN points.

In 1992 a unified Soviet geodetic survey service ceased to exist. Due to reduced funding allocated to the Russian geodetic survey service, the scope of its projects was reduced considerably, and high-precision gravimetric surveying, shelf topographic surveying, and other projects in the Antarctic were virtually abandoned.

During the last decade of the twentieth century, the AGN was adjusted. Autonomous methods for coordinating satellites involving the widely used global navigation systems GLONASS and GPS (Global Positioning System) were introduced into topographic and geodetic surveying. Also introduced were digital technologies for the production and revision of topographic maps and plans at scales ranging from 1:500 to 1:1,000,000. By the mid-1990s the total coverage of leveling networks exceeded 600,000 kilometers, of which more than 160,000 kilometers were first-order leveling networks. The scheduled general adjustment of the first- and second-order state leveling networks was also carried out. From 1995 to 1996, as a result of a joint adjustment of the AGN, SGN, and DGN, a new high-precision reference system of geodetic coordinates, SK-95, was established aimed at covering the whole territory of Russia with equal precision. The SGN is an implementation of a geocentric coordinate system, which is part of the global system of the earth's geodetic parameters (PZ-90). Thus, high-precision geodetic coordinate systems were created, the referential system SK-95 and the geocentric system PZ-90, with securely established parameters of mutual positioning. Adjusted values of AGN point coordinates allow sufficient precision in establishing uniform parameters of transition to the geodetic coordinate systems PZ-90 and WGS84, within which the satellite systems GLONASS and GPS operate (Brovar et al. 1999).

ALEXSANDR SUDAKOV

SEE ALSO: Figure of the Earth; Geodesy; Global Positioning System (GPS); Moskovskiy institut inzhenerov geodezii, aerofotos"yëmki i kartografii (Moscow Institute of Geodetic Engineering, Aerial Photography, and Cartography; Russia); Photogrammetric Mapping: Geodesy and Photogrammetric Mapping; Property Mapping: Russia and the Soviet Union; Tidal Measurement; Tsentral'nyy nauchno-issledovatel'skiy institut geodezii, aeros"yëmki i kartografii (Central Research Institute of Geodesy, Air Survey, and Cartography; Russia)

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Geodetic Surveying in Australia. Geodetic survey made little progress in Australia in the first half of the twentieth century because of the country's vast size and fragmented approach to land survey. Local trigonometric surveys initiated in the individual colonies in the 1830s had stalled by the time of Federation in 1901 because of a shortage of surveyors, who also had to meet the needs of land grants, roads, civil projects, town sites, ports, and coastal surveys. Cadastral surveys were not linked to a national framework, and geodetic survey remained a low national priority, leaving Australia with a number of different geodetic origins and datums, such as the Everest spheroid and several Clarke spheroids.

The first meeting of state surveyors general, held in 1912, identified an integrated geodetic survey as its top priority. However, little was achieved until 1932, when the Royal Australian Survey Corps became operational and commenced a first-order triangulation chain from South Australia across Victoria and through eastern New South Wales (fig. 300). This endeavor tied together individual state networks and led to the adoption of Sydney Observatory as the origin for all mapping in eastern Australia (FitzGerald 1934).

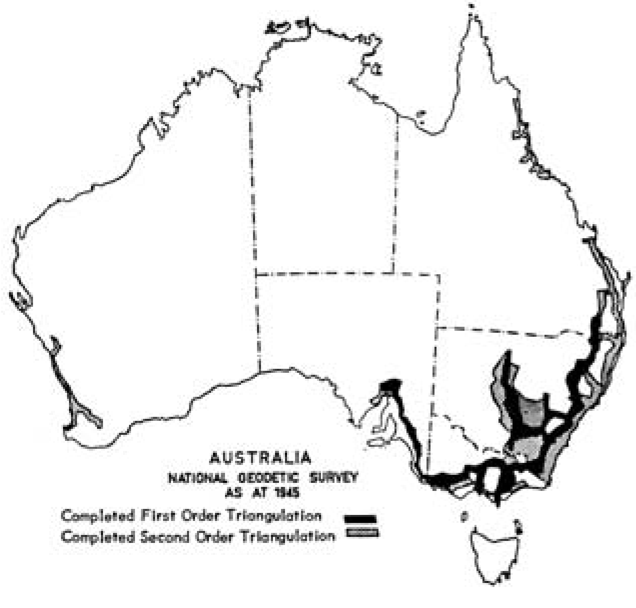

FIG. 300. STATUS OF FIRST- AND SECOND-ORDER TRIANGULATIONS IN 1945.
Size of the original: 7.3 × 7.7 cm. From Lambert 1968, 127 (fig. II). © 1968 United Nations.

In 1945 state and federal bodies established the National Mapping Council. A resolution passed at the council's first meeting recognized the variable quality of state networks, which were largely unrecoverable, and identified completion of the geodetic triangulation as a top national priority. Although a small National Mapping office was established within the federal government in 1947 and trigonometric observations commenced in 1951, progress was hampered by limited visibility in flat, featureless terrain. Because ground control was urgently needed, military and civilian field parties used astronomical observations to fix positions in remote areas of the continent so that topographic mapping could proceed in parallel with the geodetic survey (Hocking 1985).

In the second half of the twentieth century geodesy advanced markedly beyond the triangulation techniques perfected by the Survey of India. The introduction of electronic distance measuring (EDM) equipment in the 1950s, electronic computers in the 1960s, and satellite positioning in the 1970s heralded a transition from datums based on regional best-fit ellipsoids to global datums and complex approximations of the geoid. By the end of the century, geodesy in Australia was using permanent Global Positioning System (GPS) installations to monitor movement of the Australian tectonic plate (approximately 6 cm per year) and offering rapid online computation of GPS observations on a geocentric datum.

The reliance on triangulation techniques to establish the Australian geodetic framework was overcome when Bruce Philip Lambert, director of National Mapping, introduced EDM equipment, first the Geodimeter in 1954 and then the Tellurometer in 1957. New techniques for distance measurements and loop traverses, controlled by reciprocal azimuth observations, were quickly developed, and a geodetic framework was established across the continent by the end of 1965 (Ford 1979).

Field data from 2,506 stations, including 533 Laplace astronomical stations, established along 53,000 kilometers of Tellurometer traversing posed a massive mathematical challenge, which was undertaken in 1966 using mainframe computers. Positions were computed according to a best-fit local spheroid, the Australian National Spheroid, which was assumed to coincide with the geoid at its origin point, the Johnston Geodetic Station (Bomford 1967; Lambert 1968). The newly computed positions were accepted by the National Mapping Council as the Australian Geodetic Datum 1966 (AGD66), which provided the first homogeneous positional data set across the country, a remarkable achievement in just ten years (fig. 301).

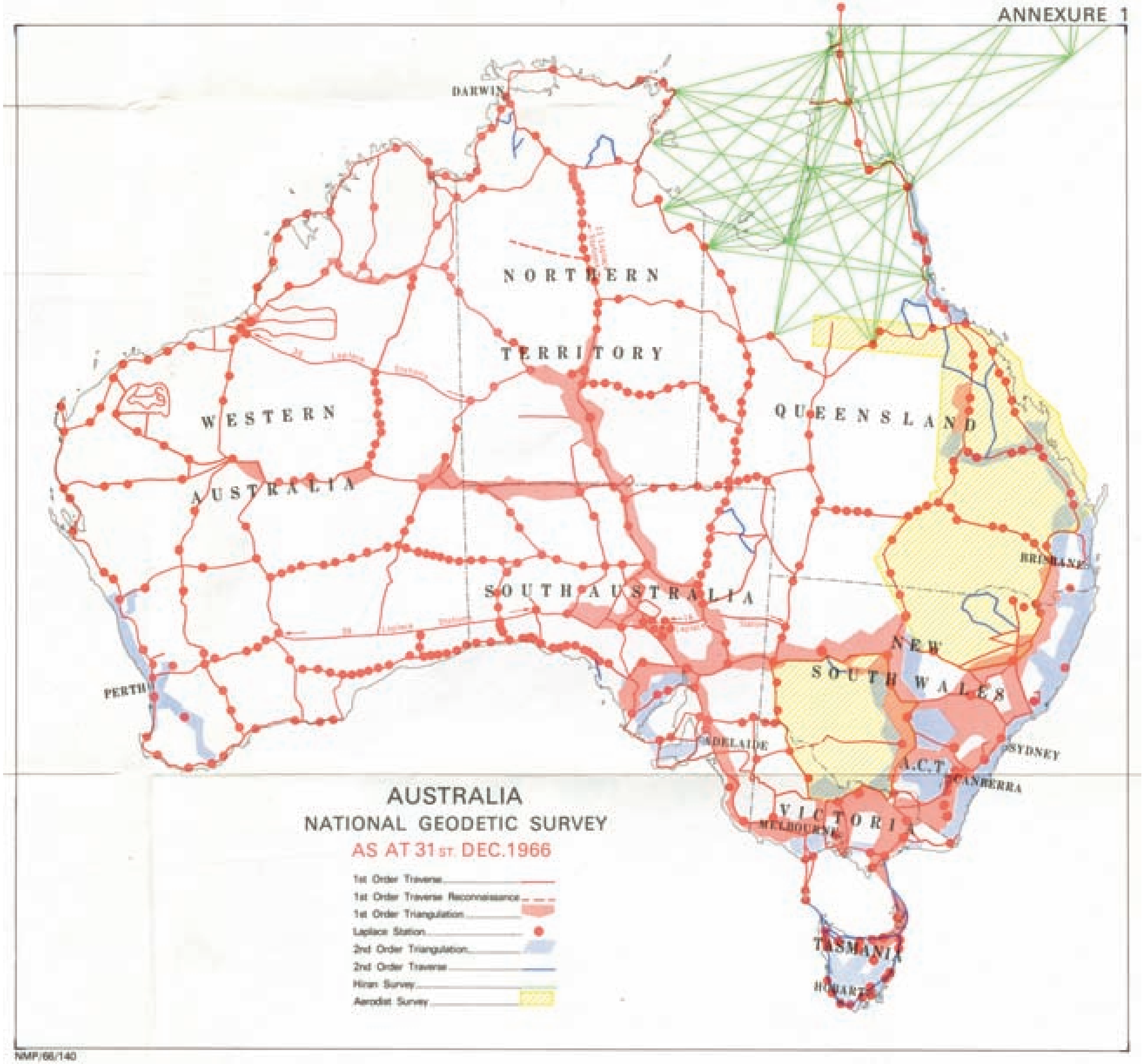

FIG. 301. NATIONAL GEODETIC SURVEY 1966. Size of the original: 19.9 × 21 cm. From Lambert 1968, loose map sheet in pocket, end of volume. © 1968 United Nations.

With a nationwide horizontal datum defined, geodetic work continued on a national vertical datum. In 1971 a simultaneous adjustment of 97,230 kilometers of two-way leveling was completed. It was constrained to mean sea level at thirty tide gauges around the coast. The resulting datum surface was termed the Australian Height Datum (AHD) and was adopted by the National Mapping Council at its twenty-ninth meeting in May 1971 as the Australian Height Datum 1971 (Roelse, Granger, and Graham 1975). This remained the vertical reference datum into the early twenty-first century.

In 1982 a new national adjustment computation was performed to correct some deficiencies in the AGD66 coordinate set. This readjustment incorporated all previous data as well as an additional 5,498 terrestrial and space-based Transit Doppler observations (Leppert 1978). While it used the Australian National Spheroid as before, the readjustment included geoid-ellipsoid separations, which had previously been assumed to be zero at the Johnston origin. The National Mapping Council accepted the new coordinate data set in 1984 as the Australian Geodetic Datum 1984 (AGD84). Although the

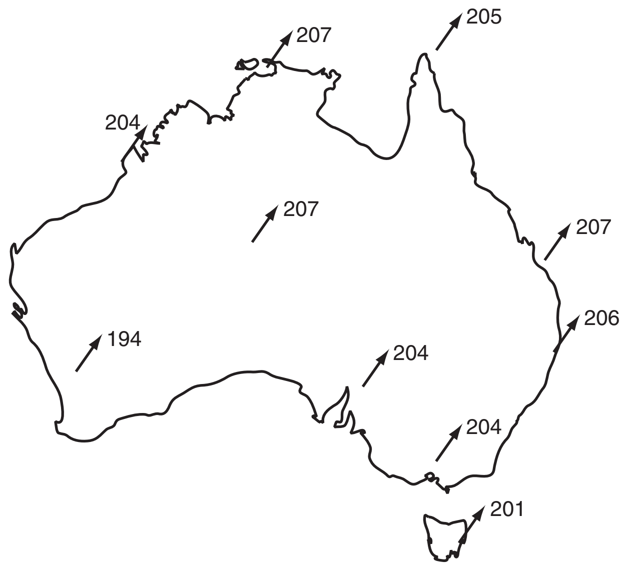

FIG. 302. COORDINATE SHIFTS IN METERS FROM AGD84 TO GEOCENTRIC DATUM 1994.
After Manning 2006.

council recognized the need for Australia to eventually adopt a geocentric datum, it was not clear at that time which reference ellipsoid to use.

With the introduction of GPS in the late 1980s the need arose for improved accuracy in the geodetic framework and a transition to an earth-centered datum, in which the spheroid is aligned with the earth's center of mass rather than with a point of origin on the earth's surface. This strategy, which permits a more even distribution of separations between the spheroid and the geoid, required the development and application of new techniques to ensure direct compatibility with coordinates based on satellite positioning. A new framework with a geocentric origin was based on eight continuous GPS stations whose positions were established using the International Terrestrial Reference Frame (as calculated for the 1 January 1994 epoch). The adjustment was also based on systematic GPS observations at additional stations used for the 1984 datum and all former terrestrial observations (Steed 1995). Calculations were carried out using least-squares adjustment software developed by Australia's Department of Resources and Energy.

For a large country like Australia, the shift to an earth-centered datum can make sheet boundaries quaintly (if not radically) obsolete for existing quadrangle maps, together with the parallels and meridians shown thereon. Because previous positions had been calculated on a local (rather than earth-centered) figure of the earth, the Geocentric Datum of Australia 1994 (GDA94) and its coordinate sets required a variable shift of roughly 200 meters for coordinates across Australia (fig. 302). Relating new and old coordinate systems required the computation of spatial-transformation grids for each state (Collier, Argeseanu, and Leahy 1998). With this massive task complete, GDA94 was introduced across the country in 2000 as a joint project of the state and federal governments (Manning 2006).

JOHN MANNING

SEE ALSO: Figure of the Earth; Geodesy; Global Positioning System (GPS); Photogrammetric Mapping: Geodesy and Photogrammetric Mapping; Property Mapping: Australia and New Zealand; Tidal Measurement

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Geodetic Surveying for the Planets. The advent of planetary exploration in the twentieth century encouraged cartographers to map extraterrestrial bodies, which led to a host of conceptual and technological challenges. The making of the earliest planetary maps required the processing of digital images transmitted from spacecraft or collected from telescopic observations, assembling those images into a photomosaic, and then, in the earliest maps, manually painting a picture of the planetary surface on a map projection. Even this inexact process of mapmaking, made easier with better spacecraft and computers, required the solution of several geodetic problems that were less than trivial, and much different from those encountered by terrestrial cartographers (Greeley and Batson 1990).

The first challenge was that of geodetic control. On the surface of the earth, geodetic control points, used as reference locations, are typically established by land survey or satellite photography. This process was more troublesome in planetary mapping because it was difficult to establish the precise locations of landmarks either using satellite or telescopic imagery. In early extraterrestrial cartography most of the control points used for planets and smaller bodies like the moon were the centers of impact craters defined by centroid calculations based on their rims (Davies 1990, 141). These networks were difficult to establish with any degree of accuracy and were computed using analytical photogrammetry. In 1958 the Austrian astronomer G. Schrutka-Rechtenstamm used telescopic observations to calculate the first modern geodetic control network for the moon. The base of this network was the crater Mösting A, a location suggested by the astronomer F. W. Bessel as early as 1839. During the 1970s satellites like Mariner, Viking, and Voyager provided data that allowed reference networks to be established on Mars, Jupiter, and Saturn.

The second problem encountered in early planetary mapping concerned topography, the calculation of which presented a series of interrelated problems. In earth mapping, elevations are referenced to sea level, which does not exist elsewhere and therefore had to be artificially defined. Also, the control networks that were established on extraterrestrial surfaces were not as accurate as those devised for the earth, which made it difficult not only to fix locations precisely and reference photographic images but also to calculate the planet's shape. Both of these problems were central to the establishment of a topographic datum or geoid to which topographic features could be referenced.

Establishing a reference geoid for the planets was a highly mathematical endeavor requiring careful measurement and the use of spherical harmonics. The geoid used for earth is the equipotential surface on which gravity is constant and corresponds to mean sea level. To establish an equipotential surface for a planet like Mars, which has no readily available physical analog like the sea, required gravity measurements. Because no gravity measurements existed for solar system bodies in the 1970s, the deflection of the orbiting satellite's path as it passed over various topographic features like mountains, craters, and canyons was carefully tracked and used to calculate the equipotential surface.

The accurate determination of the shape of the planets was also important. According to the laws of physics, any elastic body that rotates around a fixed axis will assume the shape of what is known as an ellipsoid of equilibrium. Depending on the size of the planet, the material properties of its mass, and its rotational velocity, various forms of the ellipsoid are possible. The composition and rotational velocities of the planets vary greatly, from the giant gaseous Jupiter, which rotates quickly, to rocky worlds like Venus, which rotates much more slowly. In order to map these shapes, more flexible map projections were developed so that the planets could be mapped conformally and their cartographic features then transferred easily to other map projections. One approach allowed the shape of the ellipsoid to vary along its three axes, thus providing a general projection useful for a wide variety of planetary shapes (Snyder 1985).

As the investigations of the planets expanded during the 1970s, the mapping of smaller bodies like asteroids, comets, and satellites required unprecedented map projections (fig. 303). Because of their low mass and typically slow rotational velocities, these bodies lack the gravitational force needed to form figures of equilibrium and thus have extremely irregular shapes. The first projections for irregular bodies developed in the early 1970s utilized cylindrical projections and were limited to a narrow range of applications; they gave good representations of the circumequatorial regions of the body if it was moderately ellipsoidal but contained massive distortions if the shape was more complex, as it is for many asteroids and small moons. Sculptor Ralph J. Turner (1978) developed the first truly useful model for Mars's closest moon Phobos, based on an azimuthal projection. Geographers Philip J. Stooke and C. Peter Keller (1987) mathematically modified Turner's projection to form a conformal projection useful for nonspherical worlds.

JOHN W. HESSLER

SEE ALSO: Astrophysics and Cartography; Figure of the Earth; Geodesy; Lunar and Planetary Mapping; Mathematics and Cartography; Tidal Measurement

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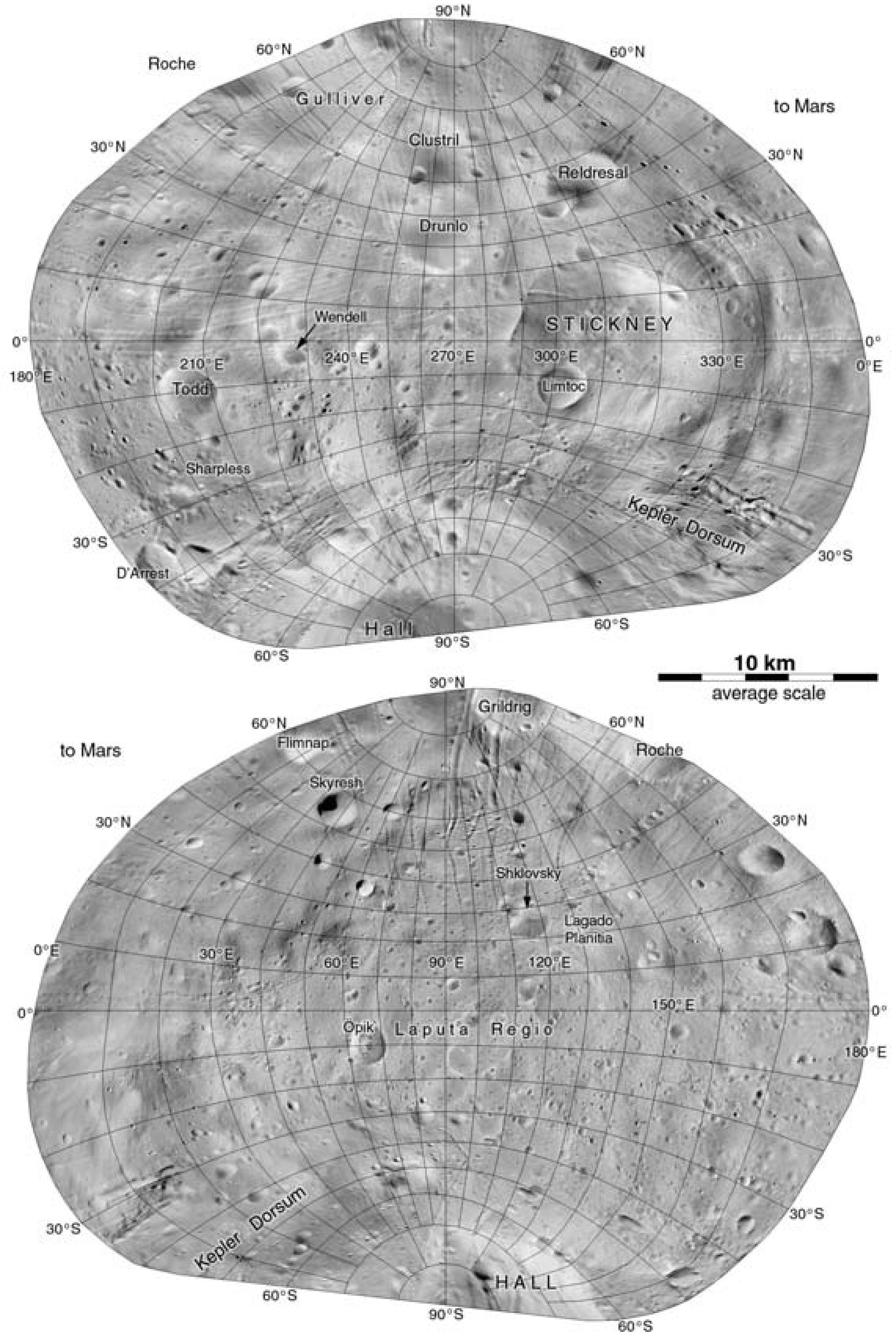
(*Facing page*)

FIG. 303. NONSPHERICAL PROJECTION FOR PHOBOS. Mars's moons were the first small and irregularly shaped objects to be photographed in detail and at high resolution. Consequently they have often been the test cases for new mapping methods.

Image courtesy of Philip J. Stooke, University of Western Ontario.


90°N
60°N
60°N
Roche
Gulliver
to Mars
Clustril
30°N
30°N
Reldresal
Drunlo
Wendell
STICKNEY
0°
0°
210°E
240°E
270°E
300°E
330°E
180°E
0°E
Todd
Limtoc
Sharpless
Kepler Dorsum
30°S
30°S
D'Arrest
Hall
60°S
90°S
60°S
10 km
average scale
90°N
Grildrig
60°N
60°N
Flimnap
to Mars
Roche
Skyresh
30°N
30°N
Shklovsky
Lagado Planitia
0°E
30°E
60°E
90°E
120°E
0°
150°E
0°
Öpik
Laputa Regio
180°E
30°S
30°S
Kepler Dorsum
HALL
60°S
90°S
60°S

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Geograficheskoye obshchestvo SSSR (Geographical Society of the USSR). See Russkoye geograficheskoye obshchestvo (Russian Geographical Society)

Geographic Information System (GIS).

Computational Geography as a New Modality. By the end of the twentieth century, computer-based applications of geographic information science and technology were widespread in many areas of human endeavor. Spatial, and increasingly spatial-temporal, factors were recognized as decisive in many phases of personal and societal planning and decision making. This stands in sharp contrast to the situation prevailing earlier in the century, when the role of spatial factors was poorly understood, and the limited availability of spatial data and tools for spatial analysis and visualization severely restricted the ability to deal with spatial problems on an effective operational level. To understand and appreciate the revolutionary change during the last four decades of the twentieth century requires an awareness of the very different circumstances that prevailed prior to the advent of geographic information system (GIS) technology.

Geographic space, as well as the heterogeneous distribution of resources within that space, exerts a significant and complex influence on human behavior and the spatial structure of society. Attempts to identify and understand the content of the geographic space that encompasses us, as well as the way that geographic space, as abstracted from the things contained within it, impacts human behavior have engaged humans on an informal level for most of our existence. The development of more formal views of these concerns forms the basis for the modern science of geography. The great extent and high complexity of the space that humans occupy presents substantial barriers to its understanding. The early, ultimately successful effort to create a conceptually formal and operationally viable method of recording and reproducing representations of distant, out-of-sight portions of earth-space in the form of maps introduced a new, highly significant modality into geography through the introduction of cartography. The impact of this new modality was characterized by Arthur H. Robinson as something "as profound as the invention of a number system" (1982, 1). The complex concepts underlying the creation and use of maps, such as scale, projection, and symbology, have challenged cartographers and the users of maps ever since, as have the substantial problems involved in the acquisition of the very large volumes of spatial data needed to characterize and understand the world.

Analog maps proved to be highly useful, both conceptually and in practice, but they possess inherent limitations with respect to the amount of spatial data that can be accommodated. The basic workflow of spatial data acquisition, analog map creation, map storage, and extraction and ultimate use of the stored spatial data is highly labor and resource intensive. The traditional map restricts the level of analysis of its stored spatial data that can be supported when only the human eye-brain system serves as the primary extraction and analysis tool. A few aids (e.g., for measuring distance and direction) were developed to assist visual analysis, but any significant ability to deal with difficult spatial questions was lacking given the extraordinary amount of time and resources required to generate the desired answers.

When responses to difficult spatial questions are not easily obtained, these questions often end up not being posed. The resulting myopic views became widespread within the intellectual community and within the realm of practical geographic applications. Consequently, potentially important concepts relating to the role of spatial factors in shaping individual and societal behavior were implicitly relegated to the category "out of sight, out of mind." The subsequent failure to pose difficult questions created a profound, and mostly unrecognized, constraint upon our conceptual views of space and human behavior. The role of distance in human interaction was a subject for limited discourse, but usually within the context of a simplified two-dimensional isotropic space; a space that was often further simplified by an implicit reduction to a single dimension (i.e., dealing with distance but not direction). Also falling below the intellectual horizon in geography and cartography were even more complex questions that required explicit consideration of time as well as space (Peuquet 2002). The interaction between these limited conceptual views and the minimal tools available for acquisition and analysis of spatial data is reminiscent of Ouroboros and obviously, in retrospect, awaited a revolutionary new modality to break the vicious circle of concepts limiting tools and tools limiting concepts.

In the early 1960s developing computer technology began to be applied to store and manipulate digital representations of spatial data (Hershey 1963; Horwood et al. 1963). Development of specialized graphic output capabilities revealed the potential for flexible creation and display of many different forms of maps. The early computer-generated maps were simple ones, and their creation required, at the time, very substantial resources (e.g., Tobler 1959). The potential for flexibility in scale, map projection, symbology, etc., became evident as, somewhat later, did the ability to create previously underutilized cartographic representations (e.g., cartograms), the manual creation of which involved inordinate levels of effort (Harness 1838; Wright 1936; Skoda and Robertson 1972; Tobler 2004).

The potential for enhancing spatial analysis within a computational environment was also emerging, and early efforts by Edgar M. Horwood (Horwood et al. 1963) and others (e.g., Hägerstrand 1967; Marble and Anderson 1972; Baxter 1976) demonstrated that computational approaches to spatial analysis were not only viable but were capable of illuminating new conceptual horizons (fig. 304). Initial attempts at computation-based spatial analysis encountered major difficulties due to the lack of knowledge of how to represent spatial data within the computer and the lack of useful spatial analysis algorithms. Much of the early conceptual work undertaken involved the challenging formalization of existing cartographic notions and the equally difficult adaptation of simplistic spatial analysis approaches to the far more challenging problems posed by a highly heterogeneous space. Early computational efforts often relied upon local "hand crafted" software solutions that were laborious to utilize and difficult to transfer elsewhere. Attempts to create interoperable computer-based solutions (e.g., Marble 1967) were inhibited by the major differences existing in computer hardware and operating systems.

The initially limited supply of digital spatial data also proved to be a major impediment in the conceptual and operational adoption of computer-based spatial analysis and mapping approaches. There appeared to be no viable way to convert even a portion of the existing analog spatial data into useable digital form (e.g., the generation of structured topological databases instead of what A. Raymond Boyle so neatly labeled a "bowl of spaghetti"). Major problems were also encountered with attribute categorizations used in existing maps that had only minimal utility when viewed within a broader operational context. During the late 1970s and early 1980s the data conversion bottleneck slowly diminished, first through Boyle's invention of the free-cursor digitizer and by the subsequent development of reliable high-speed scanners.

The conversion of analog maps posed two major problems: development of the electromechanical hardware for "reading" analog maps and creation of the software needed to translate the captured analog data into reusable digital form. In retrospect, conceptual issues underlying creation of the software proved to be a greater intellectual challenge than development of the hardware (Peuquet and Boyle 1984). Efforts toward direct digital data acquisition by remote sensing, and the later introduction of Global Positioning Systems (GPS), induced major changes, and by the early 1990s the spatial data supply situation had begun moving from a severe drought to a flood that would challenge existing capabilities.

The early development of integrated software systems designed to store, manipulate, analyze, and display spa-

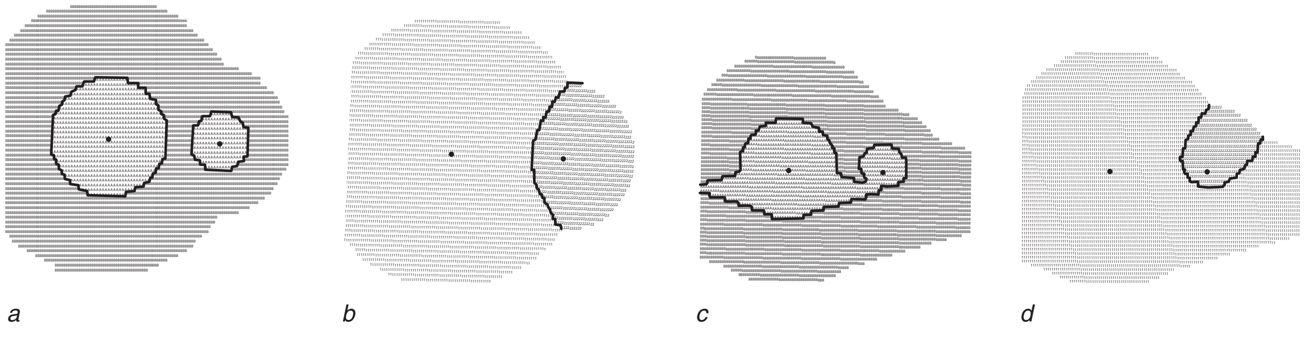

FIG. 304. MAP OUTPUT FROM AN EARLY ATTEMPT TO UNDERTAKE ANALYTIC SPATIAL MODELING WITHIN A COMPUTATIONAL ENVIRONMENT. The basis for the figure is the traditional Thunen agricultural rent model. The case illustrated here involves two market centers (one of which is dominant) and two crops with differing market prices and transport costs. Parts *c* and *d* illustrate the impact of a road that distorts transport costs, and hence space in its vicinity (Marble and Anderson 1972). Note: boundaries were enhanced by hand to aid interpretation. The four parts of the figure show: (*a*) pattern of agricultural land use in the simple case; (*b*) tributary areas of the two urban centers in the simple case; (*c*) pattern of agricultural land use when a cost-space distorting road is included; and (*d*) tributary areas of the urban centers when a cost-space distorting road is included.

After Marble and Anderson 1972, 34–35 (figs. 17 and 18), 42–43 (figs. 25 and 26).

tial data was closely tied to the localized availability of spatial data. Many of these systems were one-of-a-kind efforts, such as the LUNR (Land Use and Natural Resource) system in New York State, and most failed due to poor system design and difficulties arising from poorly understood spatial data structures and algorithms. The most successful of the early integrated systems was an effort undertaken for the Canadian government under the leadership of Roger F. Tomlinson. This system began in the mid-1960s and was still in operation at the end of the century. Named by Tomlinson the Canada Geographic Information System, or CGIS, its success and usability gave the world the now generic term "geographic information system," or GIS (Tomlinson and Boyle 1981; Tomlinson and Toomey 1999). Covering a significant portion of Canada, CGIS created useful maps and implemented the simple map overlay analysis procedure, which was known for over a century but seldom used due to the substantial manual effort involved (Simpson 1989).

By the mid-1970s, a number of GIS activities were under way with both public and private sectors involved in the development of comprehensive GIS software that was adaptable to a variety of computing environments (Marble et al. 1976; Dangermond and Smith 1988). The failure rate was high, and the typical focus was on custom map production while providing only minimal spatial analysis capabilities. During the late 1970s and early 1980s a number of major lessons were painfully learned with respect to GIS system design and software development. By the late-1980s GIS was clearly emerging as an increasingly powerful and practical tool for identifying and attacking the substantial spatial problems found in the public and private sectors.

The attainment of a viable operational level for GIS technology required over two decades, and achieving it consumed the intellectual efforts of most of a generation of talented professionals. Their seminal work remains poorly documented because of the pressures of competitive private-sector development and the less-than-friendly attitude toward GIS topics exhibited by many professional journals. It was only in the late 1980s that the first academic journal devoted to GIS was established *(International Journal of Geographical Information Systems*), and at nearly the same time the *American Cartographer* finally published two special issues ("The Computer and Cartography," 14, no. 2 [1987], and "Reflections on the Revolution," 15, no. 4 [1988]) that addressed the changes that were taking place and a possible future. The first formal GIS reader (Peuquet and Marble 1990) also appeared at this time.

The ability to do highly useful things with GIS technology led to an increased appreciation of the important role played by space in structuring human society. This, in turn, stimulated the posing of questions that had previously been ignored. Commercial mapping establishments also began the difficult transition to the world of digital databases and map production (Calkins and Marble 1987). Yet the attention of much of the intellectual community in cartography and geography remained focused on using GIS to do old things in new ways rather than on exploring the possibilities of thinking about and doing completely new things.

The conceptual component of the GIS revolution advanced more slowly than the practical applications of the technology due, in part, to the absorption of many individuals in academia with seeking solutions to operational questions pertaining to the new spatial data structures and algorithms required to ensure the viability of the burgeoning GIS technology. The conceptual constraints on spatial thinking and visualization of spatial data began to unravel with some reluctance (Goodchild 1992; Marble and Peuquet 1993). Although GIS technology slowly became a component of geographic and cartographic education, the thrust was largely toward developing familiarity with specific GIS packages rather than on the opportunity provided by GIS technology to dissolve preexisting constraints on spatial thinking. Conceptual contributions did appear (e.g., Nystuen 1963; Hägerstrand 1967; Gatrell 1983; Peuquet 1988; Tomlin 1990), but they were slow to impact preexisting views, and it was not until late in the century that serious discussions regarding the relationship between the operational tool (GIS) and what came to be called "geographic science" began to appear (Marble 1990; Goodchild 1992). It is interesting that acceptance of new conceptual approaches took place somewhat more easily in disciplines that share a concern with problems of space and human behavior, such as archaeology, but that were not immersed in the demanding problems faced in creating the new modality.

During the last decade of the century advanced operational users increasingly began to demand capabilities from GIS technology that outdistanced its existing conceptual base. One of the clearest examples of this is the emerging interest in moving beyond static spatial views to broader dynamic ones explicitly incorporating both spatial and temporal components (e.g., Miller 1991; Peuquet 2002). Dealing with dynamics instead of statics has generated significant challenges for both cartography and geographic science, but it represents an important shift in the previously restricted conceptual views of space and its role in structuring human society.

Strong interactions are frequently encountered between tools and problems in many disciplines (Marble 1990). In cartography and geographic science the advent of modern computing provided the necessary basis for development of an urgently needed new modality.

Moving from this potential to a set of operational and widely accepted tools for spatial analysis and visualization required a massive effort from professionals in geography, cartography, and other disciplines. The availability of these powerful tools, often collectively referred to as GIS, exerted a substantial impact on the scope and direction of conceptual developments and operational applications in cartography, geographic science, and other disciplines. Technological changes that permitted the direct acquisition of large quantities of digital spatial data were also critical to ensuring the viability of the new modality. Despite these substantial developmental efforts, little scientific attention has been directed as yet toward understanding the impacts induced by the introduction of the new modality on individuals and on society in general. Future researchers desiring to analyze the societal and disciplinary impacts of the new modality will be challenged by inadequate data pertaining to the early global diffusion of GIS technology as well as by the lack of early scientific studies of its impact.

The changes that have arisen in geography, cartography, and human society resulting from the adoption of the new modality continue and, indeed, are rapidly accelerating. Continuing developments in information technology support two powerful trends that will have substantial impacts. First, the widespread access via the Internet to user-friendly tools for cartography and spatial analysis, coupled with easy access to large quantities of spatial data, makes it possible for individuals to undertake many mapping and spatial analysis activities that would previously have been out of their reach. Importantly, in creating and using these new cartographic and geographic products, the basic level of spatial awareness within society has been greatly increased. Second, a substantial acceleration in conceptual studies that fully embrace integration of all three spatial dimensions as well as the full incorporation of temporal dynamics into spatial analysis is evident. Doubtless these trends will generate a significant impact, but any forecast of their outcome would be as useful as an attempt in, say, 1975 to forecast the situation at the end of the twentieth century.

DUANE F. MARBLE

SEE ALSO: Academic Paradigms in Cartography; Digital Library; Electronic Cartography: Data Structures and the Storage and Retrieval of Spatial Data; Fractal Representation; Geocoding; Map: Electronic Map; Mathematics and Cartography; Statistics and Cartography

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GIS as an Institutional Revolution. A silent revolution swept through the United States and across the world when geographic information systems (GIS) infused the very fabric of institutions, changing how they accomplish their missions and organize themselves. No force, other than the information revolution itself, has so pervasively impacted operations and organizational structures across all categories of government, business, and academe. At the end of the twentieth century, though, GIS remained a faceless force unrecognized by the public and even by national leaders. Television shows, especially forensic crime shows, portrayed GIS routinely, though rarely by name. Journalists marveled at GIS accomplishments from car navigation to precision bombing without mentioning its name. Funding agencies supported countless "geospatial" applications while science policy ignored basic research in the technology itself and especially the sciences behind it—geography, cartography, and geographic information science (GISci). Still, the juggernaut of technology pressed onward, and the benefits grew by leaps and bounds.

In retrospect, the GIS revolution had three main phases. From the mid-1960s to about 1980, GIS was a homegrown technology available at only a few well-endowed institutions. Commercial GIS products appeared in the 1970s (first Comarc and then ARC/INFO), but institutional adoption was inhibited by cost, functionality, and lack of understanding among potential users. The decade of the 1980s was a transitional phase in which use grew and homegrown systems gave way to commercial systems. Starting around 1990, institutional usage based on commercial systems grew from widespread to nearly ubiquitous.

What accounts for this remarkable transformation? How large was the movement? How was GIS employed in each sector? How did GIS impact the institutions themselves? Where is GIS heading? The following paragraphs address these questions.

Perhaps the greatest conundrum of GIS is that it is both new and old. Even a conservative assessment of its innovative power would say that in all advanced nations GIS transformed practically every institutional function that involves location, movement, or flow. Many other technologies (e.g., genetic engineering, nanotechnology) transform processes, products, and themes in massive ways, but few can claim such a universal impact based on a fundamental dimension (space, in this case). For precedents in time and space, one must look to the clock or calendar in ancient times, John Harrison's chronometer in 1761, described in Dava Sobel's *Longitude* (1995), or Alfred L. Loomis' advancements in the precise measurements of time in the 1930s as recounted in Jennet Conant's *Tuxedo Park* (2002).

Conversely, challenges to prove there was anything new at all about GIS were often difficult to answer. GIS really was the modern digital manifestation of geography, cartography, geometry, geodesy, topology, remote sensing, spatial statistics, and quantitative spatial modeling that had been around for decades, centuries, or millennia. For the vast majority of GIS functions, the innovation was that spatial functions could be done faster, better, and cheaper. Geographic analyses could be performed routinely by almost any institution. Geographic analysis tools formerly available only to specialists (geographers, cartographers, remote sensing specialists), could be transferred to all types of nonspecialists. In short, age-old tools became commodities that could be purchased and used by all, and widespread use of such powerful tools carried enormous implications for science and society.

In addition, GIS brought about at least one change in kind that transcended all science and institutional practice. For hundreds of years, the bane of human understanding has been integration across disciplines, a difficulty that actually grew worse with the explosion of specialized knowledge beginning in the early Renaissance. In modern times, the inherent difficulty of understanding complex interactions among diverse phenomena was worsened by institutional and disciplinary barriers deliberately imposed by society upon itself. As a result, few peers, even those who valued scientific integration, realized how important space was to integration. Take any list of diverse phenomena (geology, biology, economics, population, and religion, for instance) and ask yourself what they hold in common. The answer is that they interact when and only when they occur in the same *space*. Indeed they cannot avoid interaction when they occur in the same space. Thus, anyone who seeks understanding of such interactions will be forced to define, view, and analyze space precisely as geographers and cartographers do.

By century's end GIS was forcing institutions to bridge disciplinary and thematic barriers. At the most elementary level, institutions had to ensure that databases were compatible across their own organizational branches and missions. That required communication. The pursuit of broad analytical models required an even greater shared understanding of methods, techniques, and paradigms. It was clear that if a single, unified GIS were ultimately established to serve an entire institution, a meeting of minds, methods, and paradigms was absolutely essential.

In the early twenty-first century, pundits viewed GIS as a revolutionary force in science and society, not because it made better maps, but because it forced the disciplines to talk to one another. That rang true in all institutions from academe to government to business, where the barriers may be between organizational branches rather than scholarly disciplines.

In the 1970s GIS insiders began to recognize the industry's wide reach and potential for steady long-term growth. In 1975, for instance, managers and staff at Oak Ridge National Laboratory (ORNL), in Oak Ridge, Tennessee, were bullish about the future of GIS (Dobson and Durfee 1998). Around 1980, R. G. Edwards, an ORNL computer scientist who contributed much to early GIS development, said rather casually that he did not believe there would ever come a time in the careers of his contemporaries when the demand for GIS labor would not exceed the supply. About a decade later at an annual meeting of the Association of American Geographers (AAG), Roger F. Tomlinson, widely recognized as the father of GIS, boldly predicted the GIS industry would need about ten times as many new GIS professionals as university programs were prepared to produce over the next ten years.

One measure of both institutional impact and business impact would be the size of the GIS worldwide market, but something seemed amiss in the figures that kept surfacing. For instance, an estimate that put the market's annual revenues at $30 billion by 2005 (Gaudet, Annulis, and Carr 2003, 21) was quoted by several universities as justification for expanding academic programs in GIS and by the U.S. Department of Labor in projecting workforce growth. Daratech's year 2000 market survey results showed the worldwide GIS industry at $6.9 billion, but the same market research company's estimate was $1.75 billion for 2003, $2.02 billion for 2004, and $3.3 billion for 2005 (Anonymous 2003, 2004, 2006). All of these figures, even $30 billion, intuitively seemed low to anyone who considered that the worldwide market for chewing gum was about $5 billion. Problematic discrepancies among GIS market projections could not be resolved because all of the major surveys were proprietary and too expensive for academic study. At the time, Daratech's report on GIS sold for $1,600, while Icon Group International's report on chewing gum could be purchased for $325.

The U.S. Department of Labor recognized "geospatial" as a high-growth industry. In 2005, they issued a $700,000 grant jointly to the AAG and the Geospatial Information Technology Association (GITA) to estimate industry growth. Even so, the phase 1 draft report contained definitive projections of workforce demand. Duane F. Marble (2005–6) forcefully called for a "firm notion of just what makes up the geospatial industry and exactly what will define our future technical workforce requirements" before meaningful projections could be made.

Once an institution opted in favor of GIS, the most important decision was whether to establish an enterprise GIS (von Meyer and Oppman 1999) to serve collective needs or merely adopt GIS at the level of individual missions, functions, projects, or branches. An *enterprise GIS*—the term emerged around century's end—promised generally greater efficiency, security, and permanence as well as greater depth and breadth of geographic representation to serve a wide range of applications. Conversely, a *project-level GIS* tended to be focused on individual applications and seemed highly fragmented when viewed from an overall institutional perspective.

A hypothetical two-stroke test of permanence was sometimes envisioned. If a project were to be wiped out by the stroke of a pen and simultaneously all key personal died instantaneously, what would happen to the data, algorithms, and unpublished results? In a true enterprise system, those materials would reside securely in a central data collection, and someone would know how to restore them for future use. In a project-level GIS, they might be lost for all practical purposes.

GIS was born in government. Early centers included Environment Canada, the U.S. Census Bureau, the U.S. Geological Survey (USGS), ORNL, and the State of Minnesota (Cooke 1998; Greenlee and Guptill 1998). Surprisingly perhaps, military organizations were not instrumental. Even though they can be credited with major advances in many components of GIS, especially image processing and automated mapping, they were somewhat late to embrace the analytical potential of GIS per se. For instance, staff at ORNL who spent many years assisting various federal agencies, including the U.S. Army and Air Force (Dobson and Durfee 1998), found them quite willing to fund applications but not fundamental development. This hesitancy persisted throughout the 1980s and well into the 1990s.

By century's end GIS had penetrated all levels of government from local to global (U.S. National Academy of Public Administration 1998) and had also become an indispensable component of e-governance. Its reach was worldwide, and it could be found at fairly sophisticated levels of operation even among the world's poorest countries. In all advanced nations and many less developed nations, GIS was serving a broad range of applications, including cadastral registration of land ownership, tax assessment and collection, planning and zoning, public works, military strategy, transportation planning, and emergency management.

The agencies that contributed most to the advancement and adoption of GIS by the U.S. government were the USGS, the National Geospatial-Intelligence Agency (formerly the National Imaging and Mapping Agency, and before that the Defense Mapping Agency), the U.S. Census Bureau, and the National Oceanic and Atmospheric Administration. The Federal Geographic Data Committee linked these and other agencies in a cohesive, cooperative framework that may well be unmatched in other spheres of federal activity.

By the early twenty-first century, many individual states within the United States could boast total or nearly total adoption of GIS by all county and municipal governments. Such widespread adoption led to the founding of the National States Geographic Information Council and substantial attention by the National Association of Counties.

Even so, GIS was far from universal at century's end. In Kansas, for instance, about half of all county governments employed GIS in at least one office, but the other half (mostly rural counties) did not employ GIS at all. Similarly, enterprise GIS was not as widely practiced as it should have been for the good of the nation. One glaring example was the persistence of project-level GIS at the Centers for Disease Control and Prevention (CDC). In 2001 and for several years thereafter, at a time when citizens rightly expected all institutions of government to work at maximum efficiency for protection from biomedical hazards—natural, accidental, or terrorist induced—this key institution failed to embrace GIS at the enterprise level.

Academic, government, and business interests in the United States were represented collectively by several professional organizations, namely, the American Congress on Surveying and Mapping, the American Geographical Society, the American Society for Photogrammetry and Remote Sensing, the Association of American Geographers, the Geospatial Information & Technology Association, and the Urban and Regional Information Systems Association. A generally similar division of activity could be found in Canada and the countries of Western Europe.

While government had been the main driver and financial supporter of GIS development, at least one professional association and two universities stood out as early centers of GIS development in the United States. Prior to World War II, the American Geographical Society was the sole geographic research center devoted to geography. Its accomplishments included John Kirtland Wright's earliest expression of points, lines, and areas—concepts central to GIS—and key beginnings of quantitative geography by Wright and William Warntz.

After World War II, many geographic research centers were established at universities with funding from a variety of state and federal government agencies, notably the National Science Foundation. Harvard University and the University of Minnesota helped initiate GIS in the 1970s (Chrisman 1998), and they were soon joined by the University of California at Berkeley, University of Kansas, Purdue University, University of Washington, and University of Wisconsin (Foresman 1998, 6–7). A key turning point was the establishment of the National Center for Geographic Information and Analysis, which showed academic and political support for GIS and, in turn, produced scholarly results that earned even wider acceptance. By century's end GIS was practiced at some degree in practically every institution of higher learning, many high schools, and some elementary schools. Eighty universities or university systems became institutional members of the University Consortium for Geographic Information Science, and that is a fair indicator of how many universities practiced enterprise GIS. Of these, about 85 percent were led or co-led by geography departments.

Most GIS impacts were positive and their benefits enormous, but all revolutions carry risks. In this case, major concerns were voiced about privacy, control, and enslavement (Pickles 1995; Monmonier 2002; Dobson and Fisher 2007). Particularly troubling was a new category of human tracking devises based on GIS, the Global Positioning System (GPS), and two-way radio transmission. Human tracking was a growing component of a larger industry called location-based services (LBS). Most LBS applications involved goods in transit, as when Federal Express packages were tracked every step of the way from sender to receiver. Locator tags were placed on each product, package, pallet, or vehicle or, more recently, on each person in transit. Although tracking goods normally did not trigger controversy, it was sometimes difficult to distinguish between goods and people, as when the product was clothing or when vehicles were tracked and their drivers and occupants were known. One stark measure of current institutional impact was the Xora company's claim that they were monitoring the geographic location of 50,000 U.S. workers in a practice openly called "geofencing." Naturally, such practices raised ethical and legal questions among workers.

In summary, GIS has changed institutions in fundamental ways that alter missions, operations, and organizational structures. A new title, chief geographic information officer, emerged in organization charts as explicit recognition of GIS's vital role in government enterprises. Geography—as both a scientific discipline and a body of knowledge—has always been important to institutions, though not always by that name. "Location, location, location" is a long-standing mantra of business, and it's no less true of most governmental functions and academic research. Maps and cartography have been important as well, and by century's end their digital manifestations were impacting science and society more deeply and pervasively than their analog manifestations ever did. Society appeared to be marching steadily toward a new milieu in which spatial intelligence ranked on a par with mathematical and linguistic intelligence.

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SEE ALSO: Electronic Cartography; Geocoding; Geographic Names: Applied Toponymy; Map: Electronic Map; National Center for Geographic Information and Analysis (U.S.); Standards for Cartographic Information

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GIS as a Tool for Map Analysis and Spatial Modeling. The possibility that computerized maps could be analyzed more efficiently and effectively than traditional paper products provided part of the motivation for the creation of geographic information system (GIS) technology from its very earliest days. For example, the Canada Geographic Information System (CGIS) was designed to address the need identified in the late 1950s and 1960s for map analysis in support of planning, management, and decision making for the vast areas of land and natural resources in that country (Tomlinson 1998). While there was clearly a sense that computerization would allow for automation of traditional approaches to map analysis, like the overlay of multiple thematic layers, it was also the case that concurrent conceptual and methodological developments in a wide range of fields, including human geography, regional science, geosciences, and computer science, were making new kinds of spatial analyses possible. The early integration of traditional map analysis methods with quantitative methods from a wide range of academic and professional fields set a pattern that would continue as GIS software and applications matured throughout the latter decades of the twentieth century. The development of GIS software in the 1960s and 1970s required solutions to a wide range of automation and database design questions focused on how to structure spatial data, incorporate topological relationships into these structures, and link multiple attributes and geographical units. Solutions to these questions facilitated analyses that examined multiple attributes about places, multiple places with shared attributes, and spatial interactions among places.

Because of the wide range of intellectual traditions contributing to the development of the map analysis and spatial modeling capabilities of GIS, we have organized the intellectual traditions into three main areas: computational foundations from computer science and mathematics, regional spatial analysis from geography and planning, and geosciences and remote sensing.

Computational Foundations

Efforts to use computers to analyze spatial data started with the view of computers as computing machines rather than as the information management systems they would later come to be. Due to resource constraints and the intellectual interests of the developers, these efforts focused on implementing in computer code classical techniques from spatial analysis, mathematics, statistics, multidimensional analysis, network theory, and a wide variety of geographical models (Johnston 1979). This section focuses on several important research directions that later served as the computational foundations of GIS and the models they facilitated by the end of the century. Though the goals of much of the research were not directed toward developing an information system, the development of GIS was closely linked to the results of this research.

COMPUTATIONAL GEOMETRY. The ability to measure geometry and perform spatial queries makes GIS distinct from other information systems. However, until the early 1970s, quantitative comparisons of vector data in GIS were still extremely difficult. In the 1970s, the developers of vector (noncell based) GIS were heavily invested in solving basic computational geometry problems such as geometric searching, point-in-polygon, triangulation, convex hull, construction of Voronoi diagrams (or Thiessen polygons), and line intersections. During this period, GIS developers benefited from parallel developments in computer science and computational geometry. Many efficient algorithms were developed for geometric computation in automated cartography and GIS. These algorithms also defined the early vector data structures, including the topological data structure developed for map overlay procedures (Peucker and Chrisman 1975). These developments resulted in vector GIS software by the late 1970s. In this period, the Harvard Laboratory for Computer Graphics and Spatial Analysis developed the first vector GIS (called ODYSSEY), the Center for Urban and Regional Analysis at the University of Minnesota developed the Minnesota Land Management Information System, and the Geographic Information Management and Manipulation System (GIMMS) was developed by Thomas C. Waugh at the University of Edinburgh. As geometric computation matured, most vector GIS included a built-in topological data structure that allowed more sophisticated analytical capabilities. In 1982, Environmental Systems Research Institute (ESRI) released its ARC/INFO vector-based GIS. Similar packages such as CARIS (Computer Aided Resource Information System) by Universal Systems Ltd. in Canada and Infomap by Synercon in the United States were developed in the late 1980s, followed by Intergraph's Modular GIS Environment (MGE) in 1989.

MAP ALGEBRA AND TOPOLOGICAL RELATIONSHIPS. A fundamental function in GIS is to describe the spatial interrelations and linkages among geographic objects. Borrowing from theories in logic and inspired by Ian L. McHarg's overlay analysis, GIS software included map algebra tools for combining multiple raster or vector data sets through Boolean logic and arithmetic operators. These basic overlay tools would become essential analytical components in GIS software in the latter decades of the century. As map algebra, which is mainly based on the location and attributes of geographic objects, became formalized within GIS, topological relationships were explored to describe spatial interrelationships between discrete objects. For example, the 9-intersection scheme developed in 1991 by Max J. Egenhofer and John R. Herring (1994) used discrete points, lines, and regions to describe the geometries of geographic objects. This scheme provided a formal definition of topological relationships and was included as part of the Open Geospatial Consortium specifications and the International Organization for Standardization's ISO/TC 211 established in the mid-1990s. By the end of the century, some of these relationships had been implemented in commercial GIS and spatial database systems, allowing users to formulate qualitative queries about the topological properties of spatial objects such as connectivity and adjacency.

Research into the intrinsic uncertainty in GIS data, particularly in the context of multicriteria spatial decision support systems, revealed the necessity to deal with ambiguity and vagueness in spatial features and attributes. For this reason, fuzzy set theory was invoked to address the implications of these uncertainties in spatial analysis (Sui 1992). Fuzzy set theory was developed in the 1960s by Lotfi Asker Zadeh and has been applied in artificial intelligence and information science since the 1970s. With this approach, the geometry and/or attributes of geographic objects are converted into memberships in fuzzy sets. The fuzzy set memberships of multiple layers are combined with fuzzy logic. GIS software, though often not specifically using fuzzy set terminology, was adapted by using rescaling and arithmetic functions to implement fuzzy set theory in spatial analysis.

SIMULATION. Simulation techniques, including Markov simulation and cellular automata, were introduced into spatial analysis in the 1960s and 1970s to describe complex dynamics of geographic processes that are intractable by deterministic approaches. For example, in an effort to estimate future United States cropland availability, Bruce O. Burnham (1973) used Markov simulation to generate dynamic models based on transition probabilities (probabilities associated with various changes of state in a system) that are determined by the observed land use state at locations. Though the model outputs (land use) could be displayed as maps, the simulation was not performed using a GIS because locational information was not explicitly used in the model.

A variety of dynamic cellular models enhanced these Markov formulations by incorporating spatial interactions into the calculation of probabilities of change. For example, Torsten Hägerstrand (1967) developed cellular models using local interaction rules to investigate diffusion of innovation and its effects on regional-level behavior and spatial patterns. Cellular automata (CA), developed in the 1960s, is a simulation method that uses simple rules to represent complex dynamics resulting from social, physical, biological, and computational processes in complex dynamic systems. It was introduced to geographic analysis by Waldo R. Tobler in his efforts to model urban development in Detroit (Tobler 1970). Due to the simplicity of handling cell-based raster data, CA simulation could be implemented with ad hoc programming tools. Iterative spatial filtering and map reclassification operations could be used to implement simple CA models in a raster GIS. PCRaster, developed at Utrecht University in the early 1990s, extended map algebra functions to include representations of time and dynamics for creating simple CA models. IDRISI, a raster GIS and digital remote sensing system developed by J. Ronald Eastman in 1987, implemented a spatial modeling component in the early 2000s that combines a Markov process representation of state changes with a cellular model to introduce spatial interactions.

The cell-based formulation of CA limits it to representing change; it cannot be used to represent either movement of objects or continuous space. In an effort to allow the modeling of object movements in a continuous space, object-based process models, including agent-based models (ABMs) and individual-based models, were adapted by GIS researchers beginning in the late 1990s. The object-oriented modeling framework of ABMs involves identification of autonomous agents (or individual objects) and a temporal framework within which the agents perform actions. The agent has the ability to satisfy internal goals or objectives through actions and decisions based on a set of internal rules or strategies. These agents may be dynamic in either state or space and may, through their actions, change the state or location of other objects, processes, or environments around them. GIS, in general, was not developed to include operators that explicitly describe movement of features (Gimblett 2002). As a result, early work on ABMs and GIS involved loosely or tightly coupling GIS with object-based process modeling tools such as Swarm or Repast. Later, there were also efforts to combine spatial data and process models within a single integrated system, such as the Object-Based Environment for Urban Systems (OBEUS) (Torrens and Benenson 2005).

MACHINE LEARNING AND SPATIAL DATA MINING. There is a long history of using maps for visual exploratory analysis (e.g., the well-known 1854 John Snow cholera map). Following the rapid development of GIS spatial data infrastructure in the 1990s and the resulting abundance of geospatial data, along with concurrent advances in computer processing, rendering, and visualization capabilities, the ability to discern unnoticed patterns embedded in GIS data drew the attention of GIS developers and researchers. Geospatial data mining was pursued as a process of selecting, exploring, and modeling large amounts of spatial data to uncover unknown patterns. A wide range of tools contributed to spatial data mining, including machine learning, spatial statistics, and visualization. There are two major data mining approaches: top-down and bottom-up. The top-down approach is used to test a hypothesis based on models. For example, patterns can be described in some form of statistical model that is fitted to the data, such as a fractal dimension for a self-similar data set, a regression model for a time series, a Markov model, or a Bayesian network. A bottom-up approach, on the other hand, searches the data for frequently occurring patterns or behaviors—or, conversely, for anomalous or rare patterns (Miller and Han 2001). Exploratory analyses and geovisualization can be used as bottom-up approaches. Specific tasks for which geospatial data mining methods have been developed include clustering analysis, classification and regression trees analysis, association rules, and outlier detection.

Geovisualization emerged in the 1990s as a framework for integrating visualization approaches in scientific computing, cartography, image analysis, information visualization, and exploratory data analysis. In addition to 2-D, 3-D, and multidimensional data representations, dynamic 2-D and 3-D displays created by data animation also were used to depict trends and patterns showing how attributes change over time and space (Slocum et al. 2001). Many data mining algorithms and geovisualization techniques became essential components in GIS software developed by the late 1990s. Tools incorporated into GIS software around the turn of the twenty-first century included the Geostatistical Analyst in ArcGIS and the Earth Trends Modeler in IDRISI Taiga. Both software modules provided tools for trend analysis, geovisualization with brushing capability, outlier detection, and statistical distribution description. More specialized GIS for exploratory spatial data analysis also emerged in the early 2000s. For example, the GeoDa software package, developed by Luc Anselin in early 1990s as middleware between ARC/INFO and SpaceStat for spatial data analysis evolved into a standalone package in its 2003 release.

Regional Spatial Analysis

The earliest applications of spatial analysis and modeling within GIS were in the inventory and planning of land resources. While early applications in the 1960s and 1970s used relatively simple analytical tools, like overlay of weighted map layers, developments in the planning and social science disciplines provided a much richer set of planning and analytical tools that later would be integrated within or coupled to GIS software. For example, advances within regional science, statistics, and decision science were laying the groundwork for tools that could be used for optimization of a variety of spatial problems, building on both mathematical and computational solutions. These tools took on various forms, depending on whether they were applied to continuous surfaces (usually represented as rasters), polygons representing spatial zones, or spatial networks. Optimization and planning tools would find increasing application and become standard tools for solving problems ranging from route planning to market analysis and legislative redistricting.

Parallel to the development and application of these spatial planning tools, advances in quantitative social science and spatial statistics were under way and new tools were becoming available for quantitative analysis (in parallel with advances made in the geosciences). These tools were aimed at quantification of spatial patterns in point, line, and polygon data sets and testing of patterns relative to some statistical model (Ripley 1981). They would be applied to questions ranging from the existence of spatial inequality and segregation to clustering of diseases in space. Early attempts to use parametric statistics on spatial data were confounded by spatial heterogeneity, spatial dependence, violations of distributional assumptions, and other complications that required development and application of a wide range of simulation tools to the statistical testing process. Progress on these tools was hampered early on by computational limitations that were later ameliorated.

SPATIAL STATISTICS. Methods for description and inference about the presence of patterns, as well as for modeling statistical relationships among mapped variables, were developed and later incorporated into GIS and spatial analysis software so that users could examine and understand spatial patterns. Statistical approaches to characterization of patterns took a variety of forms. For brevity, we focus on the two dominant types of patterns for which statistical tests were developed in the social sciences: point patterns and patterns of spatial association in aggregate social science data.

Point pattern description used approaches described as first-order, in which statistics were aimed at describing variations in the densities of points, or second-order, in which statistics described the distances between points (Bailey and Gatrell 1995). First-order methods involve counting points in areas and comparing the distribution with some statistical model to determine whether the points are more or less clustered than expected at random. Second-order methods, like Ripley's *K*, compare the numbers of pairs of points observed at separations of various distances with the numbers that would be expected if the points were randomly distributed. Research throughout the 1970s and 1980s extended these methods to various kinds of cases (e.g., clustering of multiple variables and space-time clustering), but the closed form statistical nature of these tests imposed restrictive assumptions. Stan Openshaw et al. (1987), Martin Kulldorff and Neville Nagarwalla (1995), and others developed simulation-based approaches to cluster detection that would help relax the distributional assumptions of the parametric tests. These methods for point-pattern analysis were developed independently of GIS software and were often implemented in statistical or stand-alone spatial-statistical packages. The scripting and programming capabilities of commercial GIS packages, however, later allowed for most of these methods to be implemented within GIS.

Many social science data sets became available in aggregate form such as census enumeration districts. U.S. census data, for example, first became available digitally with the 1970 census in the form of DIME (Dual Independent Map Encoding) files, which were succeeded by TIGER (Topologically Integrated Geographic Encoding and Referencing) files. Methods of analysis for spatially aggregated data were developed in ways that would account for both the various effects of aggregation on the measurements (often referred to as the MAUP—modifiable areal unit problem) and the varying topological structure of irregular units. Descriptions of spatial autocorrelation in variables measured over irregular geographical units were developed earlier and popularized by A. D. Cliff and J. K. Ord (1969). The join-count statistic was developed for noncontinuous measurements, whereas Moran's *I* and Geary's *c* statistics were commonly used for continuous measures. From the 1970s through the 1990s, research continued on alternative representations of the topological structure within these statistics. Facilitated by GIS, they were extended from global to local applications (Anselin 1995). This latter development allowed for the creation of maps depicting variations in the strength of spatial dependence.

Several techniques were developed in the 1960s and 1970s for the transformation of aggregate data to address the MAUP. For example, Tobler developed a pycnophylactic smoothing technique that achieved a smooth transition among enumeration units while maintaining the aggregate values originally assigned to the units (Tobler 1979). The dasymetric mapping method depicted quantitative areal data using boundaries that divide the mapped area into zones of relative homogeneity with the purpose of best portraying the underlying statistical surface (McCleary 1969). Later, the dasymetric mapping principle was used to develop areal interpolation techniques that transform aggregate data to different (or finer) mapping units than the original enumeration units.

Independence of observations has always been an assumption implicit in regression analyses. Therefore, the nonindependence of spatial observations posed a challenge to statistical estimation of regression parameters. Global measures of spatial autocorrelation were developed initially to diagnose this problem. Furthermore, spatial heterogeneity challenged stationarity (invariance to shifting in time or space) assumptions in regression analyses. Spatial autoregressive models were developed to account for the effects of spatial dependence on such estimations. Geographically weighted regression was developed as an approach to allow estimated parameters to vary in space, thereby loosening the stationarity assumption (Fotheringham, Charlton, and Brunsdon 1996). Implementations of these models were facilitated by iterative maximum likelihood and Markov chain Monte Carlo estimation methods that became available with increased computer power in the 1990s. Though not generally implemented within GIS software packages, these spatial statistical methods are often used in conjunction with data preparation and visualization tools available in GIS.

SPATIAL INTERACTION MODELS AND LOCATION-ALLOCATION. Motivated by the need for robust analysis in planning and resource allocation, during the 1960s to 1980s regional scientists developed statistical and mathematical models for characterizing the spatial structures and processes associated with social, organizational, and physical environments. These models answered two major types of questions: (1) how do goods, services, money, and ideas "flow" among various locations? and (2) where are the optimal locations for service centers and how is demand optimally allocated to service centers? The answers to the first question quantified the degrees of regional spatial interaction and have direct applications in transportation and land use planning. The answers to the second question were used to define service areas and market territories for business planning. These models, though not developed within GIS originally, all had spatially explicit components for describing the spatial distribution of populations, organizations, and resources and aimed at quantifying the spatial interactions among them. They also contributed to the application of GIS in transportation and business in the 1980s. The methods and models involved in regional science analysis and later implemented in GIS aimed to solve questions of shortest path and route planning, spatial interactions, network flow, facility location, travel demand, and land use–transportation interaction (Rodrigue, Comtois, and Slack 2009).

One of the first spatial interaction models with transportation and land use components was the Lowry model, developed in 1964 for the Pittsburgh region. The model assumed that regional and urban land use change is a function of the expansion or contraction of the basic sector, which in turn has impacts on employment in the retail and residential sectors through a multiplier effect. Employment in the basic sector influences the spatial distribution of the population and of service employment, which in turn determines the commuter traffic flows among zones in the region. The level of influence is related to transport costs and is quantified by a gravity-based friction of distance function. The Lowry-type models were usually solved as equilibrium problems. Many of the models developed in regional science were implemented within stand-alone computer programs. It was not until the mid- to late-1980s that specialized GIS packages, such as TransCAD, emerged as turnkey systems for planners and engineers.

Location-allocation techniques were designed to simultaneously determine the location of facilities and allocation of demand to the facilities. The goal could be to minimize transportation costs, maximize patronage, or maximize the quality of service. Many basic methods were required to facilitate location-allocation, including finding shortest paths and delineating service areas. From their early releases, GIS software packages such as ARC/INFO, ILWIS (Integrated Land and Water Information System), IDRISI, TransCAD, and CARIS incorporated location-allocation methods.

OPERATIONS RESEARCH AND DECISION SCIENCE. Geographic optimization problems can be found in the literature on locational analysis, resource management, regionalization and geographic districting, spatial data mining, and spatial decision making processes. Depending on the nature of the problems, some could be solved fairly easily, but many are impossible to solve optimally by numerical approaches. One of the earliest implementations of GIS optimization techniques was the network shortest path algorithm developed in 1959 by Edsger Wybe Dijkstra. The algorithm finds the shortest path between a vertex and every other vertex on a network graph by constructing and searching a shortest path tree. Descendents of this algorithm were later incorporated into Internet-based software or handheld wayfinding devices like Google Maps or GPS navigation systems that were ubiquitously accessible around the turn of the twenty-first century. A raster version of the shortest path algorithm was also implemented by treating grid cells as a set of interconnected vertices and links. The traveling salesman problem (TSP) builds on the shortest path problem to find the shortest path to more than one destination. Though TSP was first formulated in the 1930s as a combinatorial optimization problem, finding an exact optimal solution for problems with a large number of destinations remained computationally challenging into the 2000s. Many geographical optimization problems share the common feature of TSP in that they require a search for configurations (spatial combinations) of discrete spatial entities that satisfy certain optimal objectives. Inevitably, they share the same computational complexity that prevents the use of exact optimization methods (e.g., linear programming) when the size of the problem is large. Heuristic approaches are then used to find near-optimal solutions.

The *p*-median problem, which is a core problem in location-allocation, was studied extensively in the fields of geography, computer science, and operations research from the 1960s well into the 1990s. The problem involves locating *p* facilities such that the total transportation cost for satisfying the spatially located demand is minimized. Similar to TSP, *p*-median problems were usually solved near-optimally by heuristic methods, such as the Teitz and Bart (TAB) heuristics developed in 1968 and the global/regional interchange algorithm (GRIA) developed by Paul J. Densham and Gerard Rushton in 1992 (Church and Sorensen 1994). Both methods were implemented in ARC/INFO for solving location-allocation problems. Though global optimization algorithms such as genetic algorithm, simulated annealing, and TABU search were formulated to solve *p*-median problems in the late 1980s and early 1990s, these methods were not integrated into GIS because of their computational demands and the complexity involved in fine-tuning the algorithms.

The geographic districting problem, also known as the zone-design problem, involves the aggregation of several areal units to form districts (or zones) such that some criterion is optimized, subject to constraints on the topology of the districts (e.g., internal connectivity). The best-known instance of the districting problem is the gerrymandered map of Massachusetts electoral boundaries created in 1812 under then governor Elbridge Gerry. Other applications of geographic districting include the rezoning of school districts or the service boundaries of solid waste management services or fire stations. The *p*-median problem could be treated as a special case of the geographic districting problem where the aggregate distance from the areal units to the geometric centers of zones is minimized. Similar to the *p*-median problem, global optimization algorithms were applied to the districting problem in the 1980s and 1990s. Due to the diverse goals and stakeholders involved in a districting process and the complexity of integrating optimization algorithms into GIS, only tools for interactive districting were developed. These included the ArcGIS Districting Analyst extension and the Maptitude for Redistricting Software developed in the late 1990s.

Geographic optimization problems are primarily multiobjective in nature; that is, more than one criterion needs to be evaluated in the decision process. As a result, GIS decision support tools were combined with multiobjective decision making techniques so that decision makers could be well informed in the intelligence, design, and choice phases of a decision-making process (Jankowski 1995). One of the most recognized attempts to integrate multiobjective land use allocation with GIS is the MOLA module in IDRISI developed by Eastman and others in 1995. MOLA's built-in rules allowed for conflict resolution between competing land uses being allocated to a given location. Multiple objectives could be collapsed into a single objective by a weighted linear combination scheme (a process called "scalarization"). However, such approaches failed to find optimal solutions if the weighting scheme was not appropriately specified. In the early 2000s, many computationally intensive multiobjective formulations of global optimization methods were introduced in geographic optimization problems to find solutions that were Pareto optimal (where no objective can be made better off without another being made worse off).

Geosciences and Remote Sensing

As the computational capabilities of GIS were developing during the 1950s and 1960s, a number of early technical and theoretical developments in engineering and the geosciences were proceeding as well that would later influence GIS analysis capabilities. Several of these developments were aimed at processing and analyzing specific kinds of data for geoscientific patterns, specifically image data, terrain data, and point sample data for characterizing environmental surfaces. Computerizing each type of data created opportunities for analysis of the variability and interactions on terrain surfaces, patterns of heterogeneity and structures in images, and spatial variability in point sample data for the purposes of spatial interpolation. Whereas remotely sensed imaging systems were initially implemented using photographic film, the implementation in the late 1960s and early 1970s of digital imaging systems hastened the development of capabilities to analyze digital images. The developments associated with terrain and image data, in particular, were an outgrowth of advances in digital remote sensing, which was developing concurrently with GIS. The need to estimate values at unsampled locations from point sample data had existed long before the advent of digital computers. Several manual approaches existed for doing so, but digital computers permitted a more rigorous mathematical approach to interpolation than was previously possible.

RASTER ANALYSIS AND DIGITAL IMAGE PROCESSING. During the late 1960s and early 1970s, two areas of work were being undertaken in different fields that were on parallel tracks and would later converge to provide a wide range of tools for analysis of raster GIS data (Faust 1998). The first track was the development of the earliest GIS analysis tools in the CGIS and SYMAP (synagraphic mapping system), followed by the GRID system, at the Harvard Laboratory for Computer Graphics and Spatial Analysis. These tools were generally aimed at the combination and analysis of multiple thematic layers in the service of environmental planning and management. Second, as digitized aerial photography and satellite imagery became available from a wide variety of military sources in the 1960s and civilian sources in the 1970s, development of tools for automated processing of these data became necessary. These tools were aimed at enhancing images to facilitate detection of features, classification of features based on spectral characteristics, and analysis of patterns within images (Duda and Hart 1973).

Tools that reassigned values within a given layer were used to identify features with particular spectral characteristics in images and assign suitability scores to categories within raster GIS data. Tools that allowed the mathematical combination of values contained within multiple layers were used for calculation of spectral band ratios and also for calculation of suitability scores in environmental planning. Tools that calculated a weighted combination of all values within a specified spatial window around each raster cell were called kernels in image processing. Kernels were first used to enhance the spatial characteristics of images and later were called focal operations in GIS and used for analysis of spatial context. The ability of analysts to combine different kernels in various sequences to conduct complex analysis led to the development of cartographic modeling languages that were used in nearly all subsequent raster-based GIS packages. Automation and scripting tools facilitated repeated and more rapid application of complex sequences of raster (and later vector) GIS operations.

TERRAIN ANALYSIS. Although digitizing of terrain data progressed primarily in support of national mapping programs at the U.S. Geological Survey, the availability of terrain data in digital form created a real opportunity to automate the measurement of terrain surface characteristics. During the 1960s and 1970s, these data were most commonly stored in a grid (raster) format, though work was also under way over the next few decades to develop alternatives that might be both more efficient than grids and topologically effective at representing terrain surfaces (Mark 1997). The key alternative structures considered during this period were contours and triangulated irregular networks (TINs), the latter of which were initially developed to assist automation of contour mapping but were used subsequently for other forms of visualization and analysis. Nonetheless, given its simplicity and congruence with the array structure of earlier computer programming languages, the vast majority of analytical and modeling operations and algorithms for terrain surfaces were developed on a grid structure.

Most of the basic analytical tools and algorithms for terrain analysis had been designed and developed in university, government, and private industry labs for use on grids by the end of the 1960s. These included initial software tools for the calculation of basic terrain attributes like slope angle and slope aspect. These were incorporated into early computer mapping packages such as GRID and IMGRID developed in the 1960s at the Harvard Laboratory for Computer Graphics and Spatial Analysis, and raster GIS packages like the Map Analysis Package developed in the 1970s. Throughout the 1970s work focused on the suite of terrain descriptors for use in geomorphology and geobotanical studies, including such quantities as convexity, surface roughness, and relief (Evans 1972). These quantities developed initially for grids were later extended into a broader range of terrain descriptors that could be applied as well to contour and TIN-based surface representations. Many of these terrain descriptors used local statistical descriptions of some sort, defined by a window around each location on a grid. The TIN-based implementations required querying topological information stored for terrain facets represented as triangles, the boundaries of which identify lines of inflection on the surface.

Also during the 1970s and into the 1980s, landscape planners, hydrologists, and other geoscientists were conceiving and implementing applications of terrain data for more specialized analyses such as viewsheds and hydrologically significant features like stream channels and watersheds. These tools would become fairly standard parts of the GIS analytical toolbox by the end of the century, and the programming capacity of many GIS packages facilitated a wide range of geoscientific estimations (e.g., solar radiation) and feature extractions (e.g., ridges). A viewshed (the area seen from a given location) was determined by identifying a line-of-sight from a location radiating out in any or all directions. Extraction of hydrological features required routing of water flow over a surface, filling depressions in which the flow could get erroneously stuck, and some consideration of alteration in the timing and amount of flow for different soils and vegetation on the surface. Once the water-routing problem was solved, flow could either be accumulated downslope to identify channels on the surface or traced backward to identify drainage divides and, therefore, watersheds (Jenson and Domingue 1988). The algorithms that made their way into GIS software like ARC/INFO and ArcView in the 1990s tended to ignore much of the detail in hydrological processes, but customized versions of these tools or specialized software were often available for more process-oriented models.

INTERPOLATION AND ESTIMATION. Given the expense of collecting geographic data in the field, interpolation of measured variables to create continuous surface representations was a mapping technique in use for decades. Implementation of existing interpolation techniques was, therefore, an important early development in GIS technology to support both mapping and spatial analysis. Interpolation took one of two forms. The first was direct estimation of variable values at unmeasured locations based on weighted averaging of values at measured locations. Direct estimation took a range of forms, from use of Thiessen polygons to identify the nearest measured value, to approximate interpolation based on global trend fitting, to averaging of multiple nearby points weighted by distance where weights were estimated point-by-point (inverse-distance method) or as a set to optimized weights (kriging). The latter approach was developed within mining geology to estimate ore concentrations and generalized by Georges Matheron (1962–63), often referred to as the father of geostatistics. The second approach, indirect estimation, involved use of related secondary variables to estimate the values or probabilities of the primary variable. This approach, which made use of regression-type statistical models and later machine learning, was most fully developed and applied within ecology for habitat and population density estimation of biological species and communities.

Direct interpolation techniques were implemented in the earliest computer mapping packages in the 1960s. SYMAP used multiple interpolation methods, with the more complicated methods building on the inverse distance weighting (IDW) approach. SYMAP also made use of multiple approaches to selecting nearby points to be used in estimation (Shepard 1968). The IDW method became the dominant approach to direct interpolation implementation in GIS software for the rest of the decade. While reasonably computationally efficient, the IDW method did not solve all the problems of optimal weight estimation.

The field of geostatistics had produced systems of equations that produced the best linear unbiased estimates of weights for use in direct interpolation in the form of the kriging method. Kriging presented a significant challenge because of the computational power required to solve hundreds or even thousands of simultaneous equations, depending on the number of sample points available and the number of locations to be estimated. Early stand-alone software packages, such as Geo-EAS (Geostatistical Environmental Assessment Software), appeared in the 1980s and 1990s for performing kriging and other forms of geostatistical interpolation. Some of these early packages imposed limits on the grid size and number of sample points that could be used, but as computer power increased these restrictions were lifted and geostatistical tools became a more common part of the GIS toolbox. By the end of the century, a wide range of geostatistical tools that made use of a wide range of data with various distributional characteristics had been developed and were being used for spatial interpolation.

With the wide range of terrain- and map-based measurements available due to the foregoing developments, estimation of values or phenomena at unobserved locations based on correlated variables became a practical approach for spatial analysis and modeling of spatial distributions for many types of natural phenomena. During the 1980s and 1990s, a wide range of statistical and machine learning approaches, including generalized linear and additive modeling, Bayesian statistics, artificial neural networks, and classification and regression trees, were developed to estimate and map distributions. These methods were widely used in ecological mapping by the end of the century (Guisan and Zimmermann 2000). Not all of these techniques had appeared within GIS software, but efforts to link GIS with statistical and other software facilitated the application of these techniques.

Summary

Although many of the analytical and modeling methods that are applied to spatial data were derived from methods developed for nonspatial data, a number of characteristics of spatial data have complicated efforts to extend nonspatial methods. Many spatial analysis and modeling approaches intended to characterize and support understanding of the topological structure, spatial heterogeneity, and spatial dependence inherent in the maps that data analysts were faced with. These characteristics confounded the extension of traditional statistical and computational methods to spatial data by creating more complicated data structures and violating assumptions of stationarity and independence. But opportunities for new analytical and visualization tools were also created, such as new interpolation approaches for estimation. The development of simulation tools has been critical to the extension of statistical techniques to spatial data, but also to the application of dynamic modeling and optimization to spatial problems.

It is clear from the foregoing that approaches to spatial analysis and modeling with GIS have been influenced by developments within a wide range of disciplines, but also that these methods were adapted specifically for work with spatial data. As these various influences have become incorporated into software tools that can be applied to spatial data, they have become part of a broad spatial analysis and modeling toolkit that became available to analysts by the end of the twentieth century. During the latter decades of the century, GIS functionality was available within relatively large desktop software packages like ArcGIS or integrated with database management systems like Oracle Spatial.

The implementation of this functionality in object-oriented programming languages facilitated the implementation of software objects that perform specific functions and that could be integrated with other objects. With the development of Internet technology, these objects could be served from remote servers to desktop or mobile clients. During the first decade of the twenty-first century, these new platforms were creating an environment within which the tools and approaches from a variety of disciplinary perspectives came together to solve a variety of problems in real time and in real geographic contexts, often transparently to the user. This created opportunities for widely disseminating a range of location-based services that draw liberally from multiple intellectual traditions in the analysis of spatial data but also placed a significant burden on analysts as they sought to understand the analytical approaches that were being implemented in the software they were using.

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SEE ALSO: Emergency Planning; Environmental Protection; Exploratory Data Analysis; Hazards and Risk, Mapping of; National Center for Geographic Information and Analysis (U.S.); Standards for Cartographic Information; Statistics and Cartography

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GIS as a Tool for Map Production. When geographic information systems (GIS) were first used to manage spatial data, high-quality cartographic products were not a priority (Tomlinson 1988, 252), despite maps being inherently associated with GIS. By the 1990s, GIS included analysis of data and geographic information management as well as automated mapmaking (Taylor 1991; Pratt 1985). Early GIS specialists viewed maps as the source of data and cartography simply a means of illustrating the results. To many early GIS specialists, cartography was not considered necessary for their analysis of geographic data: the geographic analysis was the important product, and emphasis was not placed on designing high-quality maps. As a consequence, in these early years the mapmaking capabilities of GIS were limited. In 1991, geographer D. R. F. Taylor identified two ways to view GIS and its mapmaking capabilities: GIS could include mapmaking or provide a separate superstructure for computer-assisted cartography (Taylor 1991, 5). Geographer Michael F. Goodchild (1988) described geographic analysis and GIS as developing almost independently of cartography, and noted that this occurred because early GIS users were not guided by knowledge of cartographic traditions.

The limits of technological advances and the disparate backgrounds of the individuals using GIS interfered with integration of the fields of GIS and cartography. Another factor that contributed to this separation was that GIS hinged on the relatively recent invention of computers while cartography had existed for many centuries. Even after computer-assisted cartography systems became available, some cartographers viewed the systems only as a way to produce maps more cheaply and quickly (Taylor 1991, 3), still viewing hand-drawn maps as superior. When computer graphics from both screen displays and printers improved near the end of the twentieth century, cartographers started using computers consistently. During the 1980s, the two fields began to merge, with GIS used for geographic analysis and cartography for data display within the same projects (Goodchild 1988, 315; Keller and Waters 1991, 109). By the end of the century, arguments arose about whether the conflation of cartography and GIS would render cartography obsolete.

The emphasis on geographic analysis is seen in early inventories of GIS functionality in *GIS World*, an early GIS trade magazine. Their first GIS software survey (Anonymous 1988) itemized thirty-nine characteristics offered across thirty-six GIS vendors, with only six particular to map production: raster output maps, vector output maps, on-screen map annotation, and support for pen plotters, inkjet printers, and electrostatic plotters. Similarly, the second survey (GIS World, Inc. 1989, 32–46) itemized over eighty characteristics of sixty-three systems, with the same items listed for display and output and adding support for laser and dot matrix printers. The bulk of other items were specific to geographic analysis, such as nearest neighbor search and terrain slope computation. Two items in the surveys, converting map projections and generating elevation contours, straddled analysis and map production concerns.

At the Auto-Carto 5 conference in 1982, the U.S. Geological Survey (USGS) identified a shift from cartographers using computers for computation to using computers as an aid in map production, the change credited to the decreasing cost of output peripherals (Borgerding, Lortz, and Powell 1983). As early as 1973, the Canada Geographic Information System (CGIS) had produced over 200 resource maps (Taylor 1974, 37–38). Goodchild (1988, esp. 316) argued that with adequate investment, manual mapmaking could be replaced by computer technology. David P. Bickmore at the Experimental Cartographic Unit (ECU) in Great Britain was a strong influence in the change from analog to digital map production. After working on *The Atlas of Britain and Northern Ireland* (1963), produced without computer assistance, Bickmore was criticized for out-of-date content. He subsequently determined that the only way to produce something in a timelier manner would be to use a computer (Rhind 1988, 278–79). As early as 1966, the ECU laid plans for the development of geographic databases and viewed maps as a result of combining data sets. This incentive continued to drive cartographic projects toward GIS until 2000. Geographers Cynthia A. Brewer and Trudy A. Suchan (2001) led a successful effort to publish decennial U.S. census 2000 data distributions using GIS.

With the improved database capabilities of GIS, cartographers discovered they could use GIS as an effective tool in their discipline (Goodchild 1988; Tomlinson 1988; Taylor 1991). One example of cartographic database use was automated name placement. By automatically placing labels for point, line, and polygon features, labeling software allowed faster mapmaking, and it was one of the first popular forms of database use among cartographers. In some of the earliest papers on automated name placement, computer scientists Herbert Freeman and John Ahn (1984) encouraged an expert systems approach, and Steven Zoraster (1986) countered by recommending integer programming. Several types of feature names databases were presented at Auto-Carto 7 in 1985: A Cartographic Expert System (ACES) (Pfefferkorn et al. 1985), Geographic Names Information System (GNIS), and Name Database (NDB). At the same conference, programmer Scott Morehouse (1985) presented current mapping functions of ESRI (Environmental Systems Research Institute) ARC/INFO GIS: drawings based on points, lines, and polygons; automatic text placement; legend generation; and interactive map queries. These are all capabilities found in late twentieth-century GIS.

An early cartographic project using GIS software for production of high-quality cartography was the second volume of the *Historical Atlas of Canada* (1993). Of the fifty-eight plates created for the project, fifty were created using ARC/INFO as well as Interleaf desktop publishing software. The three-volume project had begun in 1979, but GIS-based production was not adopted until 1990, initially to save money because the project had outlasted its funding stream and a software donation was offered. The editor was gratified by the results (fig. 305).

The lack of good output peripherals available for early GIS was the biggest impediment to creating printed maps directly from the software. The main capability of GIS

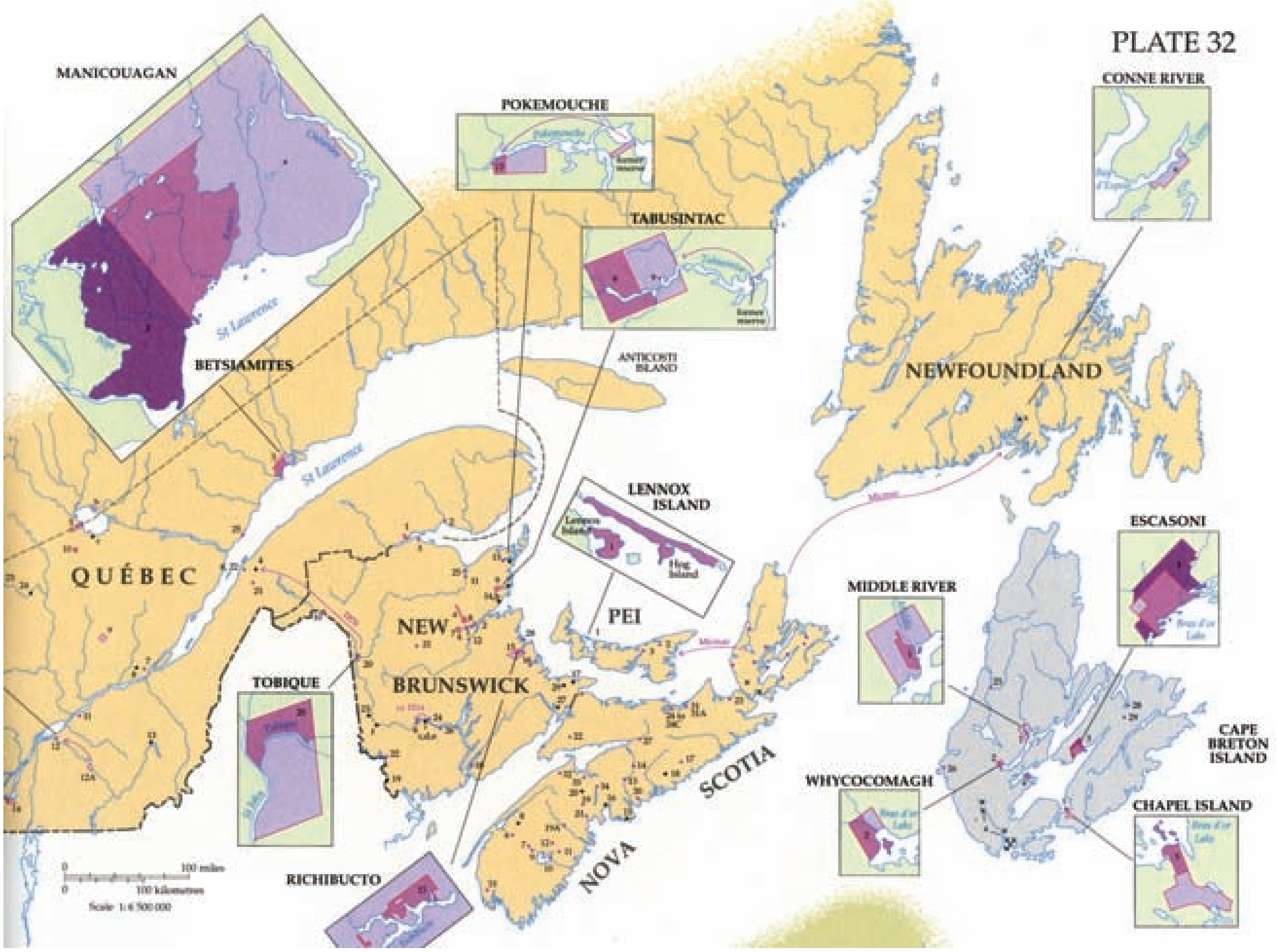

FIG. 305. DETAIL FROM *NATIVE RESERVES OF EASTERN CANADA TO 1900*. Purple areas show reserve territories lost, retained, and gained (from light to dark); gray represents surrendered islands; and point symbols identify reserves of less than 5,000 acres.
Size of the entire original: 34.5 × 51 cm; size of detail: 18.9 × 25.4 cm. From R. Louis Gentilcore, ed., *Historical Atlas of Canada: Volume II, The Land Transformed 1800–1891* (Toronto: University of Toronto Press, 1993), pl. 32. © University of Toronto Press, 1993. Reprinted with permission of the publisher.

was the performance of numerical and statistical analyses (Goodchild 1988, 315) that supported cartography, and these analyses do not require high-quality printing. The U.S. Census Bureau was using computers as early as the 1960s to assign and print class intervals for choropleth maps, but the maps were not computer-generated (Trainor 1990, 28–29). The high cost of computer peripherals in the early years of GIS and the poor graphic quality of these devices were deterrents. In the 1960s, printing graphic images, fonts, and multiple colors were still in the future; the monochrome line printer was the only output device available to mapmakers (Goodchild 1988, 313). Once the pen plotter became available in the 1970s, it gave users a way to create maps that emulated the pen-and-paper character of hand-drawn cartography. Pen plotters were invented in 1959 by Calcomp, which offered a line of single-pen drum plotters as peripherals by 1962. Cartographic uses were introduced in the 1970s, and software was adapted to make the best of this change in technology. Early map prints were not far from what had been created with a line printer, with jagged edges and very simple fonts, neatlines, scales, and legends (figs. 306 and 307). These plots evolved to forms that could represent more complexity. Plotting technologies finally evolved to the point that higher quality maps could be produced using computers (fig. 308).

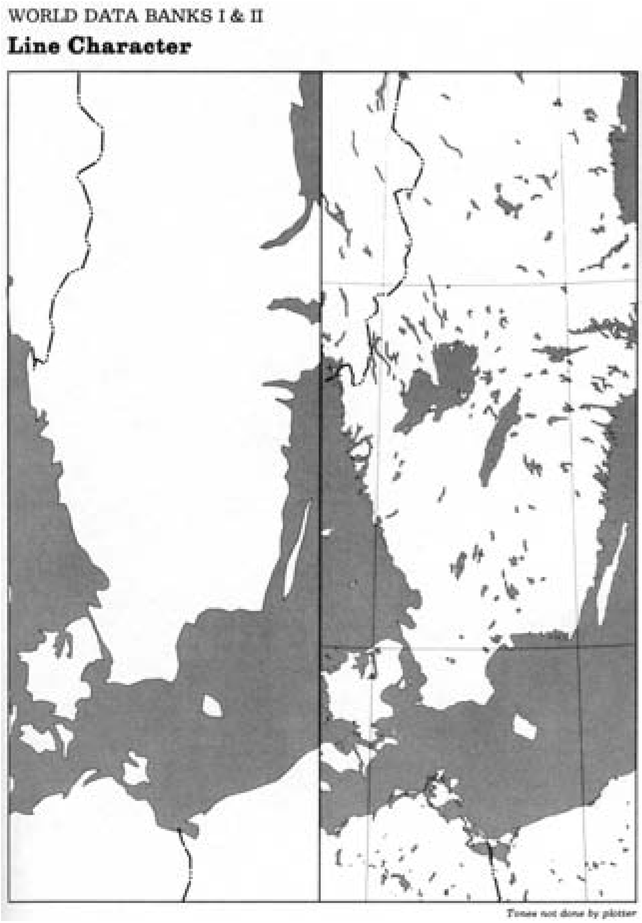

FIG. 306. "WORLD DATA BANKS I & II, LINE CHARACTER."
Size of the original: 15 × 10.4 cm. From Frederick R. Broome et al., "Cartographic Data Bases Panel," in *Proceedings of the International Conference on Automation in Cartography: "Auto-Carto I"* (Falls Church: American Congress on Surveying and Mapping, 1976), 149–63, esp. 155 (fig. 1). Permission courtesy of the Cartography and Geographic Information Society (CaGIS).

Howard T. Fisher, the founder of the Harvard Laboratory for Computer Graphics and Spatial Analysis, wanted to generate whole maps on the computer, without relying on graphic overlays combined using additional processing (Chrisman 2006, 2). The SYMAP program first emerged from the Harvard Lab in the 1960s, but with no memory or backspace option, the line printer severely limited the map output capabilities of the software. Despite the low-quality printing, poor screen displays demanded that analyses occur only after the map was printed (Chrisman 2006, 19–40). Line printer gray tone shading was created by lining up specific letters sequentially, and the letters O, X, A, and V were overprinted to produce near-black areas. SYMAP was successful because it drew attention to "the possibility of digital cartography and paved the way for the more useful graphics technology. . . . It was . . . effective in one particular form of mapping: the rapid production of crude but informative choropleth maps based on constant boundaries" (Goodchild 1988, 313).

Multicolor mapping, beyond hand-coloring a black-and-white print, remained out of reach with early GIS. In 1967 most Harvard Lab scientists sought ways to produce color maps and, programmer Donald F. Cooke worked out a technique to run the paper through the printer three times, changing carbon papers to produce color differences (Chrisman 2006, 155) (fig. 309). Pen plotters offered the option of inserting or selecting from multiple pen colors while the map was drawn, and they were a primary method of color map production into the mid-1990s (Hewlett Packard discontinued its last large-format pen plotter model in 1995, and Calcomp disbanded in 1999). Pen plotter technology in GIS mapping was echoed by a preponderance of line and cross-hatch textures in filled areas and fishnet plots for perspective views of terrain in volumes of *ARC/INFO Maps* from the early 1990s. Several other approaches were taken to create color maps: color film recorders, electrostatic plotters, and finally inkjet and laser printers (Dangermond and Smith 1988). Color film recorders were the first color media to be used with GIS software, but they were expensive and required photographic film processing. Electrostatic plotters like Electroplot

FIG. 307. SYMBOLS AND SAMPLE TYPE.
Size of the original: 5.6 × 5.1 cm (top) and 10 × 8.9 cm (bottom). From Clyde G. Johnson, Allen V. Hershey, and Aubrey L. LeBlanc, "Cartographic Symbology Panel," in *Proceedings of the International Conference on Automation in Cartography: "Auto-Carto I"* (Falls Church: American Congress on Surveying and Mapping, 1976), 215–39, esp. 223 and 224 (figs. 6 and 7). Permission courtesy of the Cartography and Geographic Information Society (CaGIS).

soon followed. By 1987, maps and other graphic products could be directed to what Hugh W. Calkins and Duane F. Marble (1987, 109) considered fast and sophisticated color printers. Laser and inkjet printers were commonplace by the end of the twentieth century, both providing high-quality map printing to a wide range of paper sizes.

Although GIS historically has lacked cartographic elements, computer-assisted cartography systems also relied heavily on geographically referenced data. Computer-assisted cartography systems provided users with improved graphics, editing, and the capability of plotting their data (Tomlinson 1988, 258–59; Coppock 1988). The most popular of these computer-assisted cartography systems were variously called automated cartography, computer-mapping systems, and computer-aided design (CAD). Taylor (1974, 35) defined automated cartography as automation of mapmaking processes. The maps that were produced with automated cartography were intended to resemble existing printed maps. In Canada in the early 1970s, automated cartography software was used to replicate topographic and marine charts. In contrast, Taylor defined computer mapping as map production using the analytical power of computers. The maps produced from computer mapping software were different from those of an automated cartography system in that they were designed to be the rough products from a GIS rather than high-quality cartography for commercial distribution. CAD, which continued to be used for mapping through the 1990s, did not provide users with the database capabilities of GIS, but did provide detailed and accurate graphics (Pratt 1985). David Rhind (1988, 286) argued that, as a spin-off from GIS, computer-assisted cartography systems were unlikely to be viable economically. By the end of the twentieth century the systems had nearly disappeared, but they were considered distinct from GIS at the height of their use.

The early inventories of software functions by *GIS World* also attempted to divide systems into types. The 1989 survey used seven categories: GIS, automated mapping, desktop mapping, facilities management, image processing, computer-assisted design, and computer-assisted engineering, with some companies selecting three or four of these choices to describe their systems. This partitioning seems quite detailed, but market sectors were being established and they could be contentious. For example, *GIS World* (Anonymous 1989, 11) reports that Daratech's study, *GIS Markets and Opportunities*, was criticized for concluding that Intergraph controlled 49.9 percent of the GIS market worldwide because the study defined the subject broadly to include hundreds of automated mapping systems not considered to be "true GIS."

Lesser-known computer-assisted cartography systems also relied on geographically referenced data. Electronic mapping systems (EMS) produced maps used in electronic media such as the electronic atlas and included functionality similar to GIS along with good cartographic display (Taylor 1991, 6). The digital cartographic database described by Calkins and Marble (1987) ran much like GIS in that its associated database contained information about the map and provided greater flexibility

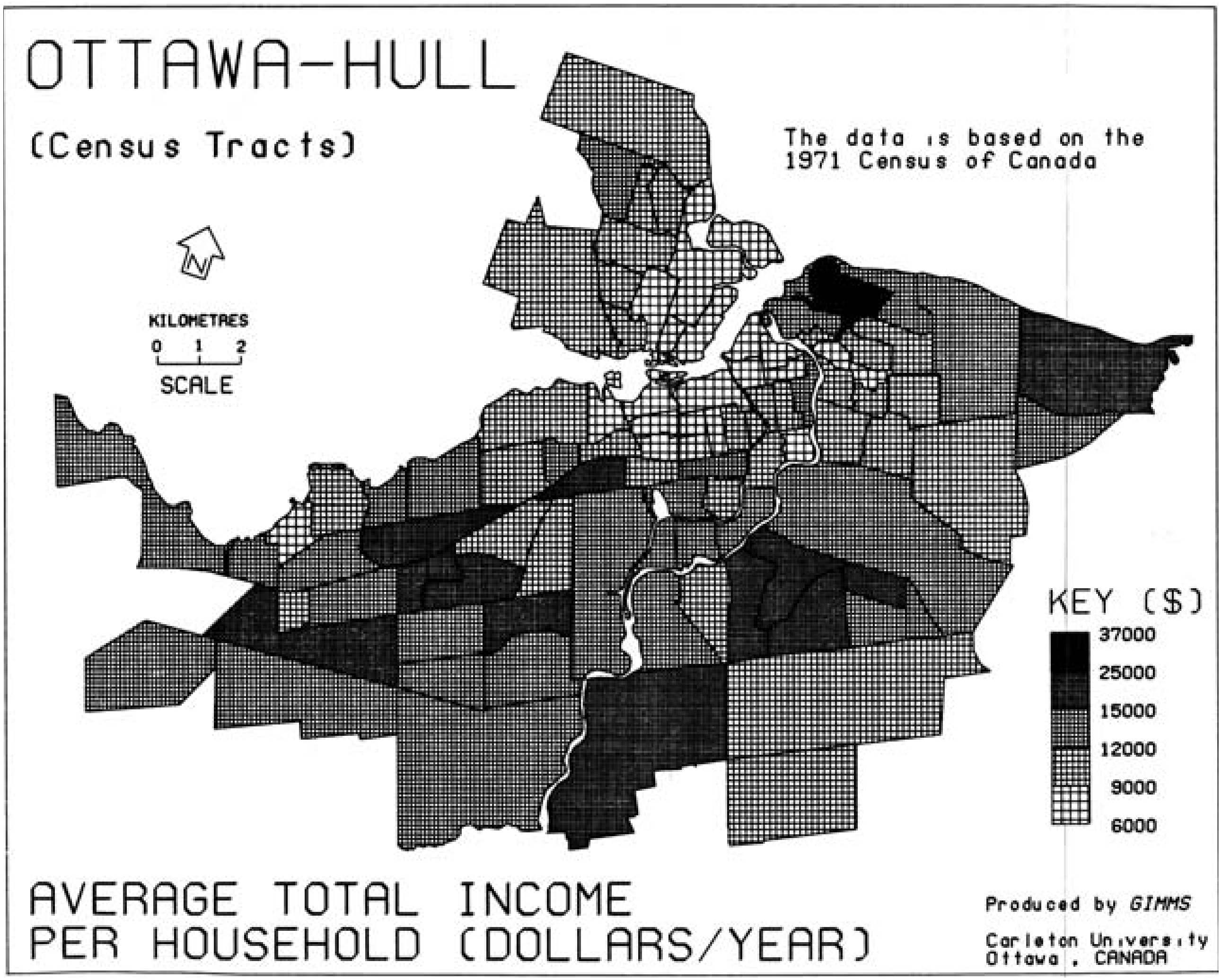

FIG. 308. *OTTAWA-HULL (CENSUS TRACTS).* Size of the original: 17.1 × 22.3 cm. From Thomas C. Waugh and D. R. F. Taylor, "GIMMS/An Example of an Operational System for Computer Cartography," *Canadian Cartographer* 13 (1976):158–66, fig. 1 (between 162 and 163). Permission courtesy of D. R. F. Taylor, Carleton University, Ottawa.

for the cartographic designer. Because many GIS specialists did not have specific cartographic training, several systems were invented with the intention of having the system become the cartographer. One type of such computer-assisted cartographic systems was expert systems or intelligent knowledge-based systems (Robinson and Jackson 1985). The Digital Cartography Program was developed in the mid-1980s at the USGS to produce maps from a GIS to increase production efficiency. In one part of this program, base maps and other digital data were available to produce thematic maps quickly and easily once imported from a GIS (Southard and Anderson 1983).

Finally, the Digital Chart of the World (DCW), a small-scale vector data set developed by ESRI in the early 1990s for the U.S. Defense Mapping Agency, became available on CD-ROM for anyone to use. While not a software program, the DCW (later called VMAP) did offer data digitized from more than 250 Operational Navigation Charts and Jet Navigation Charts from four different countries by the U.S. National Imagery and Mapping Agency (NIMA). The DCW was valuable because it brought a great amount of data together in one place and was relatively easy to access. It also prompted consternation among European partners who accused the United States of data dumping—of freely distributing what had been their intellectual property in a manner that undercut their cost recovery efforts through selling the same data (discussed at the International Cartographic Association 15th Conference, Bournemouth, 1991).

Intermediate computer-assisted map production solu-

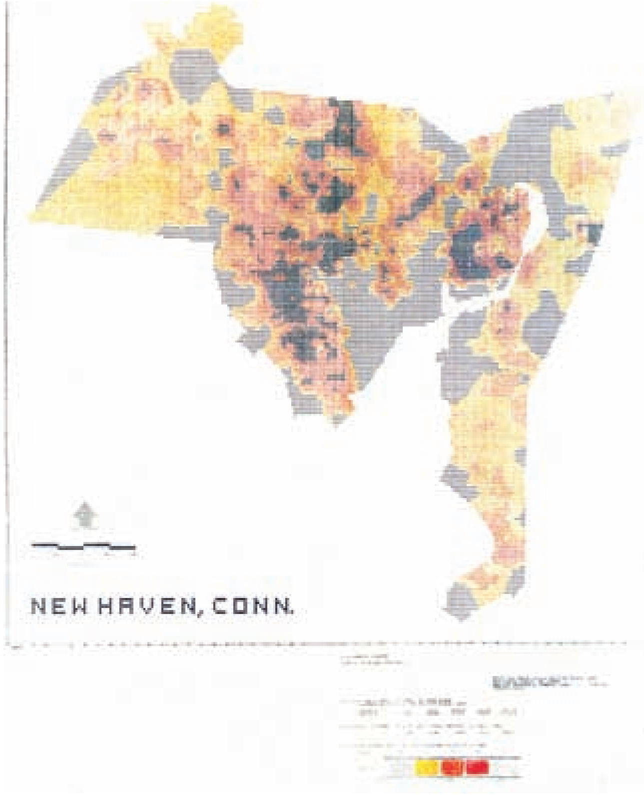

FIG. 309. COLORED SYMAP OUTPUT. New Haven, Connecticut, population density by census blocks from 1967 test census.
Image courtesy of Esri, Redlands. Permission courtesy of URISA, Des Plaines.

tions were also common, such as printing separations by choropleth categories and combining these with traditional manual production methods (see, for example, health atlas production as reviewed in Pickle 2009). Another combination was to use GIS to plot boundary or contour lines and then copy them at reduced scale on photographic negatives to create finer lines. The negatives were then used to expose Peelcoat material and produce open-window negatives for color separated area fills. Judy M. Olson's students at Michigan State University, University of Minnesota, and Boston University experimented with these combinations of automated and traditional methods, producing process-color printed, postcard-sized maps throughout the 1980s.

As graphic design software such as Aldus FreeHand and Adobe Illustrator developed more complete functions for editing lines, areas, and labels in the early 1990s, cartographers took advantage of GIS to prepare selected map elements using existing databases, such as projecting a coastline from digital data, exporting the lines, and continuing production in a graphics software environment that supported PostScript printing. These exported maps from GIS were often mediated through early versions of the Adobe Illustrator format and output with dramatic color differences so they could be separated into particular line styles with more nuanced differences using design tools such as variable line weights and dashing. This meant that unfinished GIS maps were garish before export and completed in a graphics software environment. This combination also allowed the use of service bureaus with imagesetters that produced professional quality film negatives at 12,000 dots per inch and higher. These dot densities are needed to produce halftone screens required for creating a full color gamut from process color ink combinations used in traditional high-quality lithographic printing.

M. J. Blakemore (1985), in his short history of digital mapping from line printer maps to GIS, says that the emergence of digital mapping established a long period of aggravation among cartographic specialists. Byron Moldofsky (personal communication, 9 February 2011) reflects on GIS-based production of plates for volume 2 of the *Historical Atlas of Canada* as an intricate process requiring separate EPS (encapsulated PostScript) files for maps, other graphics, and English and French labeling and text layers, which were sent to a service bureau on floppy disks where they were recombined to make negatives, proofs, and eventually plates. Likewise, Bickmore predicted that just as bad programmers waste computer time, poor information handling would hamper automated cartography if expertise were not improved in this new domain. The cartographic conversations at academic conferences at the end of the century were rife with hand wringing about bad maps wrought with GIS, but there are numerous examples of reasonably professional mapping on a wide range of topics displayed in annual volumes of the *ESRI Map Book* (initially titled *ARC/INFO Maps* in 1984). For example, volume 15, published in 2000, presents 111 map projects, including hillshading and hypsometric tints, proportioned traffic flows, bike routes, 3-D buildings, one- and two-variable choropleth maps, soil and geology classifications, land cover distributions, environmental risks, orthophoto and vector map combinations, cadastral maps, infrastructure detail, and political boundaries, to name a subset. This series also provides ways to look back on GIS mapping: volume 25 of the *ESRI Map Book* (2010) presents four pairs of maps by the same agencies, contrasting rough black-and-white line maps from the first map books with modern full-color high-resolution products to show the evolution of GIS as a tool for map production. The map authors may have been aggravated or wasted their time in the course of map production, but they were certainly doing publishable cartography using GIS by the end of the twentieth century.

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SEE ALSO: Electronic Cartography: (1) Data Capture and Data Conversion, (2) Display Hardware; Experimental Cartography Unit, Royal College of Art (U.K.); Harvard Laboratory for Computer Graphics and Spatial Analysis (U.S.); SYMAP (software)

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Metadata. As "data about data," metadata are the equivalent of a library's card catalog. Metadata allow a producer to advertise data and provide a user with information to make a decision about whether the data are appropriate for an application. Today metadata typically are stored as an XML (extensible markup language) file that is easily found and harvested with standard internet tools.

Metadata include information about data or geospatial services, such as content, source, vintage, spatial scale, accuracy, projection, responsible party, contact phone number, method of collection, and other descriptors. Metadata are critical to document, preserve, and protect spatial data assets. Reliable metadata, structured in a standardized manner, are essential to ensuring that geospatial data are used appropriately and that any resulting analysis is credible.

In order to bring geospatial data producers and consumers together the Federal Geographic Data Committee (FGDC) placed a high priority on creating a useful and rigorous metadata standard. The formalization of this standard began with an executive order by President Bill Clinton in 1994 that formally established the National Spatial Data Infrastructure (NSDI). It referred to "Standardized Documentation of Data" and expressed some urgency: "Beginning 9 months from the date of this order, each agency shall document all new geospatial data it collects or produces, either directly or indirectly, using the standard under development by the FGDC, and make that standardized documentation electronically accessible to the Clearinghouse network" (U.S. President 1994, 17,672).

The FGDC established the first content standard for digital geospatial metadata in 1994 and revised the standard in 1998 (U.S. FGDC 1998). This document describes the data elements and provides details about production. The general information contained in the metadata standard falls into the following categories:

1. identification information—provides the basic information about the data set;
2. data quality information—assesses the quality of the data set;
3. spatial data organization information—represents spatial information in the data set;
4. spatial reference information—describes the reference frame for, and means of encoding, coordinates in the data set;
5. entity and attribute information—provides information about the content of the data set, including the entity types and their attributes and the domains from which attribute values may be assigned;
6. distribution information—provides information about obtaining the data set;
7. multiuse sections—provides templates that allow one to "reuse" metadata elements in various sections of the standard; and
8. extensibility—provides a methodology and process for data producers or the user community to profile and extend the metadata standard beyond the base standard to meet individual organizations and discipline metadata requirements (U.S. FGDC 2005).

In practice the contents of the FGDC metadata standard are created as an XML document that can be generated with a text editor or by completing standardized forms provided by many software systems. It is significant that the 2002 revision of a U.S. Office of Management and Budget circular explicitly lists metadata as a component of the NSDI and requires federal agencies to utilize the FGDC standard (U.S. OMB 2002).

The FGDC has actively promoted the adoption of metadata through all levels of government and has provided limited grants for local and state agencies to develop metadata. Systems such as Geospatial One-Stop and the National Map require FGDC-compliant metadata for any nonfederal organization to include their data. A study suggested that local governments, which often resist national efforts to impose standards, were accepting metadata. In fact, 48 percent of respondents in New Jersey and 60 percent in Minnesota were using a form of metadata (Harvey and Tulloch 2006, 759). All spatial data collected or derived directly or indirectly using federal funds were to have FGDC metadata (U.S. OMB 2002).

The International Organization for Standardization (ISO) developed an international metadata standard, ISO 19115. The FGDC endorsed the switch to the international standard, which will support multilingual data sharing, accommodate high level metadata classifications, and better describe the data especially as they relate to geospatial services (U.S. FGDC 2005).

In summary, both producers and consumers of geographic data have recognized the benefit from "truth in advertising" about geospatial data assets. The development and acceptance of the metadata concept and the official FGDC standard are a major success, and its use should be a standard business practice.

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SEE ALSO: Electronic Cartography: Data Structures and the Storage and Retrieval of Spatial Data; Geocoding; Software: Geographic Information System (GIS) Software; Standards for Cartographic Information

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Geographic Information System Software. See Software: Geographic Information System (GIS) Software

Geographic Names.

SOCIAL AND POLITICAL SIGNIFICANCE OF TOPONYMS
APPLIED TOPONYMY
GAZETTEER
PLACE-NAME STUDIES

Social and Political Significance of Toponyms. The names used to refer to the environment may depend on the language spoken (fig. 310) and on the age, culture, season, and gender of the person speaking. For example, young people in Western societies are likely to use abbreviated versions or acronyms of place-names; aboriginal women in Arnhem Land use sets of names different from those used by men to refer to their environment; in Northern Canada the winter landscape is completely different from the summer landscape and therefore merits a distinct set of geographical names; in the Lower Rhine region during Carnival or Mardi Gras different names are used for the towns; in nomadic areas, the names obtained from the local population might depend on the roaming patterns of different user groups; in northern

FIG. 310. NORWEGIAN, NORTHERN SAAMI, AND KVÆNER PLACE-NAMES FOR THE SAME PLACE IN NORTHERN NORWAY.
Image courtesy of Nils Øivind Helander.

Norway. Norse farmers and Saami (Sami; Lapp) nomads refer differently to aspects of the same environment, as is visible on Norwegian topographic maps, where sometimes name pairs occur (for mountains and slopes only Saami names may be known, while infrastructural works almost always bear Norwegian names); on Java, different sets of names relating to the environment are used when speaking to someone perceived to be on a higher social level than when speaking to someone on a lower social level.

It is not clear when it was first realized that geographical names were also carriers of meaning not in the etymological sense or in the sense of signposts or labels for orientation but in the sense that a geographical feature named in a specific language could be a manifestation of the fact that the area belonged to the people speaking that language. Based on the ideas of nationalism, the thinking was that if people are speaking one language they must belong to one group so their area should be united, and conversely, if a region is to be a part of one nation the names in that region must reflect this belonging, requiring current names to be changed. For example, as a tribute for the help provided by Napoleon III, Savoia and Nizza were transferred to France after the Italian unification. This transfer was followed by the Frenchification of the Italian geographical names in the areas: hence Savoie and Nice.

This practice was followed to the fullest in Europe between 1870 and 1970. Two examples in 1918 were the Italianization of the South Tyrolean place-names by Ettore Tolomei and the reversion to the former Frenchified place-names for the Alsace. Between the two world wars there was the Germanization of place-names with Slavonic roots in Eastern Germany, and after World War II there was the Polonization of German place-names in the parts of pre-1937 Germany occupied by Poland after 1945. Under Nicolae Ceauşescu in Romania, Hungarian and German village names were obliterated by razing the villages and concentrating the rural population in new towns with Romanian names. At the end of the century this practice could still be seen in Kosovo and Bosnia, where toponymic cleansing went hand in hand with ethnic cleansing.

During the twentieth century a change in the political attitudes toward minority populations residing in a nation also can be seen in toponymic changes. Whereas in the nineteenth century, British politicians stated openly in parliament that if the Welsh needed maps with their own place-names, they should produce them themselves (conveniently forgetting that the Welsh were paying taxes and thus had an equal right to the preservation of their cultural heritage), the twentieth century saw the development by the Ordnance Survey of special guidelines for topographers on how to render Gaelic and Welsh names correctly (Harley 1971). In Spain after the victory of General Francisco Franco all manifestations of regionalism were rigidly obliterated. It was only after 1980 that regional autonomy in Catalonia, the Basque Provinces, and Galicia were reinstituted, and place-names reverted from their Castilian version back to their Catalan, Basque, or Galician versions: Gerona became Girona, San Sebastián became Donostia, and La Coruña became A Coruña. In Scandinavia, Norway, Sweden, and Finland worked together in standardizing the rendering of the various Saami languages on their maps. On French topographic maps features might be rendered bilingually, with Catalan or Breton names next to the French versions. In the Netherlands until 1980 topographers translated place-names in the Frisian language minority area into Dutch. This practice was discontinued and monolingual rendering of Frisian place-names became an option. Even the name of the province Frisia was officially codified into Fryslân. In Germany the positive discrimination of Sorbian place-names in Lusatia, understandable when the German Democratic Republic was part of the predominantly Slavonic Soviet Bloc, was continued after reunification (fig. 311). So generally speaking, all through Western Europe geographical names from autochthonous linguistic minority areas increasingly have tended to be recognized and accepted.

A similar twentieth-century change is recognized in the reuse of aboriginal or native names in areas of Australia and the Americas. The sixteenth through nineteenth century expansion of European influence over the Americas and Australia brought with it a submergence of native names. When one compares an overview map of the Midwestern United States from 1784 to one from 1872

FIG. 311. MAP KEY FROM A BILINGUAL TOWN PLAN. From the *Stadtplan Bautzen Budyšin*, a Sorb-speaking area in Lusatia, former East Germany, 1986.
Size of the original map key: 18.2 × 10 cm.

the percentage of native names falls from 80 percent to a mere 10 percent (figs. 312 and 313). Native names, if kept by the settlers, were often modified, distorted, and codified. By the end of the twentieth century there were movements among the descendants of the original populations to restore the original names. This collided with two other forces: (1) to keep things as they are—major cities like Chicago or Ottawa did not change the spelling of their names because of modifications made by the Western European settlers, and (2) a fear that recognition and restoration of a native name might have connotations of native title to the land. The Wik case in Queensland, Australia, serves as a good example (Brennan 1998).

Political "cults of personality" led to toponymic changes in the twentieth century. Communism, and to a lesser degree Nazism, tended to glorify its revolutionary heroes by bestowing their names on existing places. The best-known Communist examples are Leningrad for Sankt-Peterburg and Karl-Marx-Stadt for Chemnitz in Germany. Hundreds of geographical features were (re)named after Joseph Stalin, from Stalingrad (formerly Tsaritsyn, now Volgograd) to Stalin Peak or Pik Stalina (named 1933, changed in 1962 to Communism Peak or Pik Kommunizma and in 1998 to Ismail Samani Peak [in Tajik: Qullai Ismoili Somoni]). Under Nikita Khrushchev, a de-Stalinization campaign changed most of them back. After 1990 almost all Communist-imposed names reverted to their pre-1917 versions, with the exception of Kaliningrad for the former German Königsberg. Mikhail Kalinin, head of state of the Soviet Union 1922–46 also had Kalinin (now reverted to Tver) and a second Kaliningrad, near Moscow (previously Podlipki, but renamed Korolev after a spacecraft engineer), was named after him.

Toponymic change was also used to support war propaganda. One of the results of World War I was that place-names given by German settlers in the United States, Canada, and Australia were changed into English place-names. The example given here is taken from South Australia. The "Nomenclature Committee's Report on Enemy Place Names" (in the *Proceedings of the Parliament of South Australia*, 1916), based on a resolution in the South Australian Assembly, stated that "the names of all towns and districts in South Australia which indicate a foreign enemy origin should be altered." A proposal followed to change sixty-nine place-names of German origin. This was gazetted in 1918. For example, Rhine River North changed to The Somme, Rhine River South to The Marne, Rhine Villa to Cambrai, Kaiserstuhl to Mount Kitchener, and Grunthal to Verdun. Klemzig was changed into Gaza, but later, in 1935, reverted again, as did Hahndorf, which was named Ambleside from 1918–35.

In colonial areas that became independent during the twentieth century there have been movements to rid the land of names that were considered linked to the colonial infrastructure. Africa poses many examples: Lourenço Marques to Maputo, Fort-Lamy to N'Djamena, Salisbury to Harare, Léopoldville to Kinshasa. This also happened in other areas where the majority thought the names used should reflect the majority language groups instead of historical reality: an example was the change of Pretoria to Tshwane. Sometimes the leaders of newly independent states used their own names. Examples were Lake Albert and Lake Edward, which changed into Lake

FIG. 312. DETAIL FROM *A NEW AND CORRECT MAP OF THE UNITED STATES OF NORTH AMERICA*, 1784, BY ABEL BUELL. This portion of the North American Midwest on Buell's map used mostly indigenous names; compare figure 313. Size of the entire original: 127 × 160 cm; size of detail: ca. 42 × 60 cm. British Library, London (Maps *71490.[150]). © The British Library Board, all rights reserved 03/01/15.

Mobutu Sese Seko and Lake Idi Amin Dada (and have since changed back). As discomfort with these leaders followed their loss of power, the previous names seem to have reestablished themselves. Only Lake Victoria apparently survived this decolonization trend. Similarly, in India the major changes of Bombay to Mumbai and Madras to Chennai can be classed as the deposition of colonial names.

At the end of the twentieth century there remain toponymic issues. The Turkish occupation of Northern Cyprus and the ensuing obliteration of the Greek placenames resulted in the United Nations Group of Experts on Geographical Names (UNGEGN) drafting a resolution at the Third UN Conference on the Standardization of Geographical Names in Athens, 1977, that stated, "It is recommended that any changes made by other authorities in the names standardized by a competent national geographical names authority should not be recognized by the United Nations" (Resolution III-16). The name Persian Gulf was almost universally accepted in the seventeenth century. It was named as the Gulf of al-Qatif on some charts until the new economic rise of the Arab states bordering on the Persian Gulf caused them to claim the name Arabian Gulf (this name also has been used as an alternative for the name Red Sea in the past). Iran requested UNGEGN to safeguard its cultural heritage by protecting the Persian names of the islands in the Persian Gulf.

The name for the body of water between Korea and Japan was called Sea of Korea or East Sea in the sixteenth to eighteenth century, but by the end of the nineteenth century the name Sea of Japan was widely used, even before Japan turned Korea into a protectorate in 1905 and in 1910 annexed it. In 1928 Japan had the name Sea of Japan incorporated in the International Hydrographic Organization's *Limits of Oceans and*

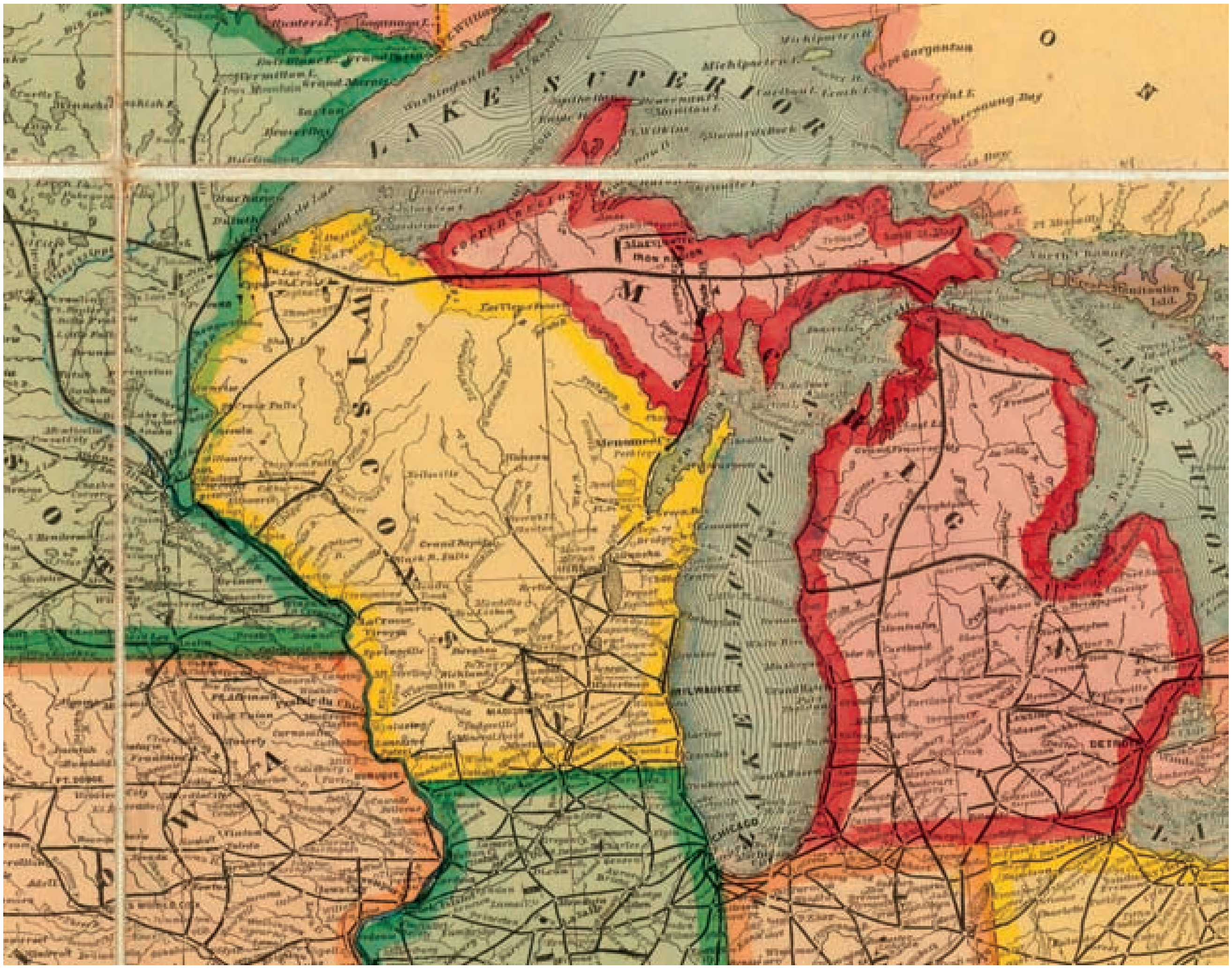

FIG. 313. DETAIL FROM *THE AMERICAN UNION RAILROAD MAP OF THE UNITED STATES, BRITISH POSSESSIONS, WEST INDIES, MEXICO, AND CENTRAL AMERICA*, 1871. The Midwest portion contains mostly European names; compare figure 312. Size of the entire original: 95 × 132 cm; size of detail: ca. 18.5 × 26.7 cm. Image courtesy of the David Rumsey Map Collection.

Seas. Both the Republic of Korea and the Democratic Republic of Korea at the end of the twentieth century claimed that the sea should be given the more neutral name of East Sea. When the southernmost federal state in Yugoslavia was called Macedonia, the Greeks did not object, but when this state became an independent nation in 1991, Greece objected to this name as its use would lay a claim on the adjacent Greek province of Macedonia. Pending this name dispute with Greece, the country was admitted in 1993 to the United Nations under the provisional reference "The Former Yugoslav Republic of Macedonia" (FYROM) (Monmonier 2006, 100–101). Fortunately, the UNGEGN, while never making decisions on individual names, is in place to create and suggest the use of toponymic principles in order to solve such issues. Even so, the naming of a number of countries or bodies of water is still being contested in UNGEGN discussions.

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SEE ALSO: Board on Geographic Names (U.S.); Geopolitics and Cartography; Indigenous Peoples and Western Cartography; Permanent Committee on Geographical Names (U.K.); United Nations

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Applied Toponymy. Geographic names are necessary for spatial reference in an otherwise confusing landscape. Names are applied to landmarks in the development of our sense of place and become the means by which we describe the landscape. Generally, names refer to specific features, and this conveys information about how people categorize spatial phenomena. Geographic names are initially connotative, but in the course of their development and use become denotative—that is, labels that serve as referents to specific landmarks.

In the naming process, those proposing a name are almost always aware of the meaning of the name (connotative) as well as the reasons for its application. However, reasons often are known only locally; with usage and time they may become muddled or forgotten. The name becomes merely a label (denotative) and does not depend on context for functionality. The activities of specific reference and categorization may become quite complex, employing highly variable, personal, and often idiosyncratic methods of perception. Standardization of geographic names is therefore essential for emergency preparedness, regional and local planning, site selection and analysis, environmental problem-solving, cartographic application, and all levels of communication.

Since names identify landmarks, and since maps, whether conventional or digital, abstractly represent aspects and themes of the spatial environment, the use of geographic names is critical in even the most elementary use of any map. Meredith F. “Pete” Burrill (1990), executive secretary emeritus of the U.S. Board on Geographic Names and cofounder of the United Nations Group of Experts on Geographical Names (UNGEGN), often stated that names are the language of maps. The application of geographic names is an integral part of the cartographic process, which is evident in every national mapping program as well as in the numerous specialized and general cartographic applications throughout government and the private sector.

The use of geographic names is not limited to cartography but is inextricably part of other applications ranging from postal and delivery services to boundary definitions to genealogy. Applied toponymy is the recognition and use of geographic names as a specific element necessary to provide solutions to real-world problems. A basic element of applied toponymy is the standardized toponym or geographic name. Major projects, including cartographic ones, often are delayed, and even postponed, until the geographic names are correct.

Applied toponymy is not new, but the term and its recognition conceptually as a means of assisting in solving problems has gained wide attention and recognition only in the last decade of the twentieth century. This is partly a result of the rapid development and increased use of geographic information systems (GIS). As a tool for searching and retrieving information on the Internet and in data mining and linking seemingly disparate topics and categories, the use of geographic names or applied toponymy is essential.

In concert with the development of printing, technical advancements in mapmaking grew steadily from the sixteenth through the nineteenth centuries. Exploration and military campaigns increased and expanded the use of maps. As mapmaking techniques and the use of maps proliferated so did confusion in the use and application of geographic names. There was little or no communication or discussion among explorers, soldiers, and cartographers from one nation to another. Names were assigned as needed, and this led to different geographic names being used for the same feature.

The nineteenth century was a time of rapid development in modes of travel. One of the first organized references to the problem of the use of nonstandard geographic names came at the first meeting of the International Geographical Congress in Antwerp in 1871. Delegates called for the standardization of place-names on maps. In 1875, the Universal Postal Union declared it necessary to establish standard names of countries, cities, and towns for purposes of efficient delivery of the mail. During the 1890s, the first committees were established to standardize the form and orthography of geographic names.

After the American Civil War, there were numerous government-sponsored scientific expeditions to the Western United States. These expeditions yielded new information and fairly accurate maps of some areas. However, each expedition needed names on its maps as referents for features on the landscape, and frequently geographic names were applied without any thought of potential confusion, thereby rendering some maps almost useless. As a remedy, on 4 September 1890 U.S. President Benjamin Harrison issued an executive order creating a committee to establish principles, policies, and procedures for standardizing geographic names. The committee was given the authority to adjudicate controversies, and its decisions were final. This milestone in the history of the standardization of geographic names and applied toponymy was to provide "uniform usage in regard to geographic nomenclature and orthography . . . throughout the Executive Departments of the Government" (Harrison 1890). Canada and the United Kingdom soon followed with similar committees, and by the first decade of the twentieth century the beginnings of the systematic standardization of geographic names had begun. In 1947, the committee was abolished and reestablished (U.S. Congress 1947).

The growing number of names resulting from expansion and settlement during the eighteenth and nineteenth centuries and the growing need and resultant increase in accuracy of record keeping made gazetteers and geographic indexes an expedient means of identifying places, features, and areas. National gazetteers were published in the late nineteenth century and throughout most of the twentieth century, but these often included only cities and large natural features. The goal of completeness, although desired, was generally recognized as impractical, even impossible, given the ever increasing number of names.

The magnitude of the geographic names problem became apparent internationally as the number of issues continued to grow throughout the two world wars of the first half of the twentieth century. The issues were apparent even within countries where attempts at standardization had been established. Cartographers became directly involved in 1909, when the International Cartographic Committee called on its members to address the issue of geographic names on maps. In 1919, the International Hydrographic Conference issued a similar statement regarding chartmaking. By the 1950s, numerous international organizations had issued statements calling for resolution of the growing and somewhat dangerous problem of the lack of standardized name usage. The newly created United Nations began to receive and record various inquiries and suggestions regarding the problem.

On 23 April 1959, the United Nations established a group of experts representing a cross-section of the international community dealing with geographic names to examine the problems and make recommendations. The group (later formally UNGEGN) met in June and July 1960 to consider the technical problems of domestic standardization of geographic names. It is most important to note that the group of experts never considered as an option the establishment of an international body for adjudicating controversies and problems. Such an international body would not be able to deal with the varying requirements of countries. It is the inherent right of individual countries to solve their own toponymic problems. The 1960 meetings recommended the systematic national collection of geographic names, the establishment of office procedures for official treatment of geographic names, and a program of promulgation in each nation.

The meeting also stated the desirability of holding an international conference on the subject. The first United Nations Conference on the Standardization of Geographical Names was held in September 1967 in Geneva. Resolution 4 urged all member nations to establish a national names authority for the purpose of developing a program for standardizing geographic names (United Nations 1968–69, 1:10–11). A permanent group of experts, UNGEGN, was also established, and it played a large role in the conference, preparing a report and recommendations. UNGEGN meets about every two years to examine problems and issues, and an international conference is conducted every five years. From the beginning, aspects of mapping were part of UNGEGN's discussions and deliberations. As a result of these efforts, by century's end more than fifty nations had some means of providing standardized geographic names.

Since the Geneva conference, various resolutions have addressed mapping as it relates to some aspects of applied toponymy. Examples include suggesting that the International Union of Official Travel Agents use standardized names based upon the principles and policies of national committees in its documents and thematic maps. UNGEGN also recommended that each country develop geographic names guidelines for use by map and other editors. Each country was encouraged to provide training in cartographic toponymy at the university or corresponding academic level.

Initially the successes in training were minimal, but in the last quarter of the century some progress was made by several teaching teams spawned from UNGEGN and/or developed separately under the auspices of the Pan American Institute of Geography and History/Instituto Panamericano de Geografía e Historia. Courses differ, but each conveys the principles of standardization and how to administer these policies and procedures. Other topics of applied toponymy training include such items as principles, policies, and procedures for standardization; romanization (systems for rendering names in other writing forms into the Roman alphabet); automation and data exchange; pronunciation; indigenous and minority languages; development of editorial guidelines; and the contentious issue of exonyms (the use of foreign forms, as in Rome instead of Roma or Nueva York instead of New York).

The training sessions have concentrated on developing nations. Toponymic problems and issues plague developing nations and their efficient resolution often removes barriers hindering resolution of other issues. An important development just after the close of the twentieth century was the completion of an online training course offered by the International Cartographic Association as a tool for cartographers.

Most efforts regarding geographic names are handled by a national committee responsible for establishing principles and policies for standardization in their nation (Orth and Payne 1997). However, a small number of nations rely on one governmental agency to supply standardized geographic names. While far from optimum, this latter arrangement is functional in the absence of a truly national committee if all governmental agencies, organizations, and other interested parties agree. Ultimately any successful program needs active participation by all of these groups. In the electronic, digital environment, no single organization, however inclusive its mandate, can meet the increasing data requirements of all users.

There is often a misconception as to what is meant by standardizing geographic names. In many countries, the act of standardization is based almost exclusively on the principle of local use and acceptance. In some countries, such as the United States, there is no attempt to make universal changes based upon rules of grammar, orthography, form, or any other dictate. For example, the same word may be spelled differently when applied to different features in the same area, and there is no attempt to dictate the use of generic terms such as "river," "stream," "creek," or "run" in geographic names. In other countries, these terms may be standardized. In some instances, official languages require certain linguistic and orthographic policies. Other national requirements may include policies applying to the use of minority and indigenous languages. Pronunciation is very important in many nations. The requirements are as varied as the peoples of the world, which is why the United Nations supports and encourages the development of codified policies to solve the problems.

Since the mid-twentieth century, the use of automation provided a more efficient means of processing and analyzing a nation's geographic names. Thus from the mid-1950s through the 1960s, attempts were made to establish automated files of geographic names. For the most part, these files were limited in scope and content.

It became clear that a repository of geographic names containing basic locative and descriptive data about each name was needed at all levels of government and by diverse users in the private sector. In the 1970s, the United States, Canada, and several European countries began designing and implementing automated databases for processing geographic names.

In addition to database design and implementation, data collection was a monumental task. In the United States, the initial phase of data collection was accomplished between 1976 through 1982 when geographic names and locative attributes of features from large-scale topographic maps were recorded, encoded, and entered into the official automated geographic names repository of the United States (Payne 1987). Upon completion of the initial phase, work was begun to supplement the basic inventory with additional names from the products of the various agencies of the U.S. federal government.

It was clear that projected use of names information would require a database as complete as possible for all categories of feature types. It was further recognized that only about 25 percent of the known names were available from products issued by national governments. Thus, in order to meet the goals and requirements of a comprehensive database for the United States, a second phase of extensive names compilation was authorized. A long-term project from 1982 through 2012 examined official state and local maps and documents as well as historical materials to complete the population of the national geographic names database.

The philosophy of designing a geographic names database varies greatly across the globe. In some cases, only existing, published cartographic products are considered. The internal procedures for database maintenance differ from country to country, designed for and dependent on the policies and requirements specific to each nation. Ultimately, with the increasing availability of very large-scale maps, especially electronically on the Internet, and the increasing ability to create interactive thematic maps with user-defined footprints or geometry, a geographic names database compiled from the widest possible array of source materials is necessary.

By 1995, several countries had made their geographic names databases available on the Internet. By the end of the century, geographic names databases using search engines were used by hundreds of thousands of people daily. These databases grow in number, and existing ones are redesigned continuously, enhanced for greater functionality and performance as well as in response to the growing and expanding requirements of the user community. A significant aspect of redesign includes spatially enabling a geographic names database, making the extent of the feature available graphically as well as defined textually, and extending the search capability to the spatial component. This is a major development in the realm of applied toponymy allowing expanded capabilities and applications never before possible.

Cartographers accept that geographic names are an important and inherently different data layer on maps. Geographic names require different procedures and bases of expertise, including history and linguistics. For maps in a national series, especially at a large scale, there must be viable procedures for collecting, verifying, and managing the ever-growing corpus of geographic names. Even so, such a collection will not be sufficient for special and thematic maps created in the large-scale environment of a GIS.

During the last decade of the twentieth century, many countries developed and enhanced National Spatial Data Infrastructures, which include data as well as technology, policies, and standards necessary to support the effort. The purpose is to assure integrity and transportability of spatial data in an electronic environment for analysis and problem solving. In these countries, standardized geographic names are considered in the first level of required categories of data, signifying the importance of geographic names to the cartographic community and to other users in applied toponymy.

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SEE ALSO: Board on Geographic Names (U.S.); Gannett, Henry; Indigenous Peoples and Western Cartography; Permanent Committee on Geographical Names (U.K.); United Nations

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Gazetteer. Following a centuries-old tradition, gazetteers have served cartographers and the general public throughout the twentieth century as a primary source of information on the names and locations of places and features. Early in the 1900s these reference materials were available only in paper copy. Photographic media (microfiche and microfilm) became common later on, and by the end of the century, interactive online gazetteers were in wide use.

In its basic form a gazetteer is either a geographic names index to an atlas or individual maps or is a stand-alone listing of geographic names within a selected region. Entries arranged systematically (usually alphabetically) supplement each name with information on the type of feature and its geographic location. More comprehensive gazetteers might include map references, administrative location, earlier or variant names, place descriptions, pronunciation, elevation, population, glossaries of terms, and other encyclopedic details. Gazetteers have been published under diverse titles as guides, dictionaries, handbooks, place-name or street indexes, registers, thesauruses, or even encyclopedias.

At the turn of the twentieth century, world gazetteers, notably those published by Chambers (5th ed., Munro 1988) and Lippincott (later Columbia Lippincott), provided alphabetical listings of geographic facts that addressed public interest in faraway places. Also, specialized gazetteer compendia were published for smaller regions or for specific purposes, such as post offices or missionary activity. Publishers of railway gazetteers, world or regional fact books, and other compilations requiring frequent updating issued gazetteers at regular intervals, yearly or even monthly.

Cartographers have had a continuing need for authoritative sources for geographic names. Beginning in the early twentieth century, governments or national names authorities of various countries have published gazetteers of standardized names for national and international use. These gazetteers were issued in single or multiple volumes, or as regional series. Because new decisions on names made existing publications obsolete, supplements became a common and useful feature.

Although many countries produced their own national gazetteers, worldwide series of country gazetteers are rare. Since 1955, the United States military mapping establishment (which has reorganized and renamed itself several times) has published country gazetteers (originally in print but later online) showing standard and variant names along with geographic coordinates, feature designations, and the encompassing administrative units. Cartographers have found this series particularly useful for countries for which current and reliable data were otherwise difficult to obtain.

Gazetteer indexes to published atlases and gazetteers published as indexes to names shown on a topographic map series at a specific scale have been indispensable reference tools. Gazetteer atlases, notably the *Canada Gazetteer Atlas* (1980), have won acclaim for supplementing the usual gazetteer information with maps showing populated places and major features. Gazetteer indexes to major world atlases usually include official endonyms (names used within a region) gleaned from the relevant national products, but some, for example, the *Times Atlas of the World*, also include various exonyms (names used by outsiders) in their language of publication.

In the 1950s, cartographers at the newly established

United Nations faced questions about the reliability of geographic names as well as the romanization of names from Russian, Chinese, and other languages that do not use the Roman (Latin) alphabet. The first United Nations Conference on the Standardization of Geographical Names was convened in 1967, and resolutions from this and subsequent conferences provided strong support as well as basic content standards for national gazetteers. In the 1980s countries began to publish their gazetteers electronically as toponymic data files as part of their national spatial data infrastructure, and from the 1990s onward, World Wide Web sites with querying and downloading capabilities provided the opportunities to promote the use of official names in cartographic products.

At the end of the twentieth century, geospatial technology had accelerated the compilation of gazetteer data sets, and the Internet offered numerous opportunities for public access. Many national and world gazetteers were available online, and most offered maps showing a feature's location or areal extent. Among noteworthy new developments in the early twenty-first century, the United Nations Group of Experts on Geographical Names launched a web portal with links to interactive government gazetteers and cartographic databases in many languages and scripts as well as to specialized authoritative gazetteers on undersea and Antarctic features. Multinational digital gazetteers under development for Southeast Asia and the Southwest Pacific were designed to expedite distribution of humanitarian aid, and the EuroGeoNames project showed how national names data sets could be networked across wide regions. Geographic names had become logical entry points into many collections of information, and the Alexandria Digital Library at the University of California, Santa Barbara, led the development of gazetteer content standards for temporal and spatial aspects of a twenty-first-century distributed geolibrary.

HELEN KERFOOT

SEE ALSO: Board on Geographic Names (U.S.); Digital Library; Geographical Mapping; Geopolitics and Cartography; Sources of Cartographic Information

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Place-Name Studies. Well into the twentieth century, the study of place-names, as of names in general, was predominantly, if not exclusively, concerned with etymological matters, its primary aim being the reduction of names to the words they were originally supposed to have been. This quest presupposed a linguistic perspective, and toponymics (the study of place-names), as a branch of onomastics (the study of names), was regarded as an aspect of lexicology (the study of words). Thus the results of toponymic research were often, inappropriately, included in conventional, lexical dictionaries, rather than reserved for geographical dictionaries. It was only when, toward the middle of the century, names starting being investigated for their own sake and when onomastics was liberated from its one-sided dependence on linguistic thinking that the study of place-names began to flourish. This extended the boundaries of place-name study significantly to take its rightful place in cartographic inquiry, both in its treatment of maps as cumulative, stratified palimpsests and in its exploration of the patterned spatial scatter of name types and their components.

This decisive new direction was first signaled in George Rippey Stewart's *Names on the Land* (1945), a pioneer work. Stewart's remarkable vision was the outcome of a happy symbiosis of his creative imagination as a novelist and his pursuit of systematic thought as, for example, in his "Classification of Place Names" (1954). It is not accidental that this article, together with other more limited studies, appeared in one of the early issues of the journal *Names* of the recently founded American Name Society (ANS), which had grown out of the American Dialect Society (ADS). Stewart was an early president of ANS, and it was the creation of this organizational configuration of North American name studies that moved individual name scholars out of their isolation and provided a forum for fruitful cooperation and exchange of ideas. It is not surprising, therefore, that the authors of a new generation of place-name dictionaries, several of them geographers, have all been active and influential members of the ANS over the years.

One of these dictionaries, *Kentucky Place Names* (Rennick 1984), is a model product of the Place Name Survey of the United States (PLANSUS), mainly organized by the ANS on the basis of the establishment of state surveys following centrally determined methodological requirements. In the long run, an undertaking on this scale proved too difficult to set up and maintain, and the question remains whether a political administrative unit, like a state, is the most appropriate or manageable organizational principle, since so much toponymic evidence crosses state boundaries, as demonstrated by the atlas *This Remarkable Continent* (Rooney, Zelinsky, and Louder 1982). The result of another ambitious cooperative venture, the North American Cultural Survey, *Remarkable Continent* contains more than 300 pages and more than 1,300 maps, already in existence at the time of its compilation, including place-name distribution maps. As is to be expected, the editors and other scholars involved in this project were mostly cultural geographers, confirming the conviction that place-name studies benefited greatly from the realization that names are much more than just words with peculiar, additional qualities.

This liberation of place-name studies from purely linguistic, especially etymological, concerns has resulted in the laying bare of a variety of intra-onymic processes: (a) place-names > surnames: Buckley, Gratton, Leeming; (b) surnames > place-names: Endicott, Hudson, Jefferson; (c) place-names > surnames > place-names: Dallas, Houston, Washington; (d) transfers of whole place-names from a homeland: Hamburg, Plymouth, Warsaw; (e) cultural transfers of whole place-names: Homer, Ithaca, Syracuse, Vestal. In all these transformations the names in question were completely unanalyzed semantically and morphologically. A fascinating illustration is names given to units of the Military Tract in upstate New York, as demonstrated in Wilbur Zelinsky's study of classical town names that highlighted sociocultural origins and dissemination, derived from "the notion . . . that the United States is the latter-day embodiment of the virtues and ideals of ancient Greece and Rome" (Zelinsky 1967, 463), at a time when the newly independent country was looking for its postcolonial identity. A related outcome is the realization that the extent of toponymic dialect areas is not necessarily congruent with that of the linguistic dialect areas of their generics. For instance, the term *bayou*, "a sluggish stream" in Louisiana, is more extensive in its lexical usage than as a hydronymic generic (Bayou Beaucoup, Bayou Gauche, Bayou Jaune). Thus it becomes clear that the potential of place-names as factors in region-making cannot be overrated.

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SEE ALSO: Historians and Cartography; Indigenous Peoples and Western Cartography

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Geographical Mapping. Defined simply as a small-scale map of the entire world or a large region, the geographical map has been ubiquitous throughout the twentieth century, when it interconnected with other modes of mapping practice, most notably administrative mapping, thematic mapping, marine charting, overhead imaging, and dynamic cartography. Though far less distinctive than during the European Enlightenment (Edney 1993), geographical maps have provided scientific and scholarly institutions with a generally reliable and often innovative framework for visualizing broad geographic patterns or situations previously represented in a less complete or exact fashion, if at all. The continued vigor of geographical mapping since 1900 reflects a voracious geographical curiosity fueled by expanding technologies for scientific measurement as well as a thirst for order and predictability, particularly in disciplines like meteorology and seismology, concerned with forecasting disaster, but also in more rhetorical or regulatory endeavors like geopolitics, aeronautical charting, and the Law of the Sea. In highlighting arenas of map use that have relied heavily on geographical maps, this entry pays particular attention to applications that emerged or experienced marked expansion during the twentieth century.

An intriguing new arena for geographical mapping was the aeronautical chart, which emerged in the 1920s as a form of topographic map annotated or specially formatted to serve the way-finding needs of aviators. As commercial and military aviation became faster and more common in the 1940s and 1950s, aeronautical charts necessarily covered longer distances at smaller scales and challenged their compilers to integrate a suitable mix of terrain, political, and navigational features (Ehrenberg 2006). In promulgating diverse restrictions on flying, the aeronautical chart produces, reproduces, and regulates navigable airspace and underscores the increased use of maps as tools of government. In addition, the growth of continental and intercontinental air carriers led to small-scale air-route and advertising maps, which helped the traveling public plan an itinerary and select an appropriate carrier.

While the aeronautical chart arose in response to a new, markedly faster mode of transport, journalistic cartography grew well beyond its nineteenth-century roots with the development of more efficient technology for copying images and integrating them into the page layout of a newspaper or magazine. Although many journalistic maps were more topographic than geographical in both scale and content, global conflict and other newsworthy events that were continental or global in scope fostered an increased use of geographical maps in the print and electronic media (Monmonier 1989). Geographical maps with a broad geographic scope, and thus informative to readers across a continent or around the world, dominated the cartographic content of illustrated news stories distributed by feature syndicates and wire services, necessarily focused on broad rather than local markets. Even when a news story highlighted a local disaster or curiosity, a geographical map was often used to locate the site within a broader spatial context.

War and threats of war inspired many geographical maps during World War II and the Cold War that followed, and thus heightened the salience of the long-term relationship between cartography and warfare. Rhetorical maps used to legitimize or refute territorial claims or to frame an invasion or attack as an unavoidable response to an intolerable threat typically required a geographical, rather than topographic, scale as did maps ostensibly intended more for understanding than for persuasion. In many cases, expository maps could be repurposed to support a political agenda. A case in point is the earth-from-space perspective used by journalistic cartographer Richard Edes Harrison to describe the relative proximity of combatants in World War II (Schulten 2001, 214–26) and modified only slightly during the late 1940s and early 1950s to promote air-age globalism, which underscored the need to prepare for an over-the-pole missile attack on the United States by the Soviet Union (Henrikson 1975).

Harrison's global perspective attained greater prominence in a different context in the 1960s and early 1970s, when human spaceflight allowed the Apollo astronauts to photograph the earth from outer space. Denis E. Cosgrove, who examined the cartographic significance of the National Aeronautics and Space Administration's (NASA) Apollo program, identified two iconic photos, taken in 1968 and 1972, on missions 8 and 17. On 24 December 1968, when Apollo 8 was in orbit around the moon, an astronaut took the much-acclaimed "Earthrise" photograph (see fig. 349), arguably a geographical map, which juxtaposed the lunar surface in the foreground with the much smaller, partly illuminated planet in the distance. "Combined with the deathly lunar surface the photograph suggests the complete isolation of terrestrial life in a black, sepulchral universe" (Cosgrove 1994, 275). Although astronauts finally set foot on the moon the following July, the most famous earth-from-space photograph was taken on 7 December 1972, on the way to the moon, by the crew of Apollo 17, the sixth and last mission to land on the lunar surface. Titled the "Whole Earth" by some and the "Blue Marble" by others, the full-disk photograph (see fig. 350) shows the southern jet stream circling a cloud-covered South Pole and the coastlines of Africa, Madagascar, and the Arabian Peninsula as well as portions of Europe and South Asia. According to Cosgrove, both of these images are highly inspirational and can be seen to align with two distinct ideologies: the "one-worldism" of a liberal American Christianity committed to open borders and the "whole-earth" stance of environmental activists.

Rocketry and space photography not only extended the domain of geographical mapping to include maps and atlases of Mercury, Venus, Mars, and various asteroids but also substantially enhanced lunar cartography, with roots in the sixteenth century (Whitaker 1999). Compiled from imagery obtained with fly-by space probes and orbiting sensors, these maps inspired systematic efforts to regulate and inventory the assignment of geographic feature names. On another cartographic frontier, the exploratory mapping and systematic naming of submarine features further blurred the distinction between geographical and topographic mapping (Monmonier 2006, 134–44).

Satellite remote sensing and image processing afforded other earth-from-space views, including the GeoSphere Image constructed by designer Tom Van Sant as a mosaic from a multitude of individual NOAA environmental satellite images and used widely in the early 1990s, most notably as the title page of the 1990 edition of the *National Geographic Atlas of the World*. Van Sant framed his map on a rectangular cylindrical projection with north-south scale reduced in the upper latitudes to partly compensate for areal distortion. He examined months of satellite imagery to select only pixels not compromised by cloud cover and assigned colors chosen, a bit naively, to show how the terrain might look from an altitude of several thousand miles. His exaggerated claims for a "natural representation" on a hypothetical "clear day" was an opportunity for Denis Wood (1992, 48–69) to demonstrate how rhetoric can be deployed to excoriate an ostensibly clever and harmless—though clearly costly—endeavor.

Rhetoric also featured prominently in debates over the Peters projection (see fig. 679), a geometric framework for whole-world geographical maps that was proffered and contested several times from the late 1970s through the late 1990s (Monmonier 2004, 145–71; Wood 1992, 56–61). Supporters claimed it was the only appropriate antidote to the Mercator projection's flagrant inflation of relative size (and hence the relative importance) of the more developed nations of North America and Western Europe, and the consequent visual diminution of Third World nations, largely within 30 degrees of the equator. Opponents denounced the equally flagrant distortion of shape by the Peters map—particularly within 30 degrees of the equator!—and argued that the Mercator map was seldom used to frame whole-world maps. That the debate gained credibility reflected the importance of whole-world geographical maps in the popular print media, where much of the contestation occurred.

Whole-world maps proved particularly valuable in the earth sciences, where perceptive contemplation of continental margins and atmospheric circulation required small-scale representations. Although the suggestive similarity of the eastern edge of South America and the western coastline of Africa had caught the attention of Abraham Ortelius and Antonio Snider-Pellegrini in the sixteenth and nineteenth centuries, respectively, German meteorologist Alfred Wegener is the acknowledged discoverer of continental drift, which he eloquently described in *Die Entstehung der Kontinente und Ozeane* (1915; 2d ed., 1920) with a three-map graphic narrative showing the juxtaposition of continental landmasses roughly 250, 50, and 1 million years ago (Monmonier 1995, 149–69). In the decades that followed, Wegener's model invited controversy and at times ridicule, but his compelling visual argument was vindicated in the 1950s and 1960s by geophysical and hydrographic explorations, which yielded the comparatively detailed thematic maps that helped develop and confirm the hypotheses of plate tectonics and seafloor spreading. Textbooks on physical geography eagerly touted an associated phenomenon, the Pacific Ring of Fire, with small-scale maps relating the pattern of earthquakes and volcanoes on the rim of the Pacific Ocean to continental plate boundaries.

Small-scale maps of weather and climate reflect a strong interaction among geographical and thematic mapping, overhead imaging, and dynamic cartography (Monmonier 1999). Except for local radar maps and focused studies of microclimates and specific storms, atmospheric cartography uses mostly small-scale representations to track and predict the development and movement of comparatively broad geographical features like pressure cells, air masses, frontal boundaries, and jet streams. Computer models are typically continental or hemispheric in scope, and resolution is low because of the sparse monitoring network and the computational demands of representing vertical differences in pressure, heat energy, and moisture while projecting the map forward several days in small increments of time—at century's end the smallest cells in dynamic computational models were several kilometers across.

In the final decades of the twentieth century atmospheric science turned to global models to predict the extent and impacts of climate change under diverse scenarios of anthropogenic warming (Monmonier 2008, 131–46). Controversy over the resulting maps reflected both the inherent uncertainty of computational modeling and the economic consequences of political strategies for reducing concentrations of greenhouse gases known—or merely believed, as so-called skeptics asserted—to cause global warming. Especially problematic were scenarios reflecting the disappearance of ice shelves in Antarctica and Greenland. Topographic as well as geographical maps described both local and broad impacts, and dynamic simulations dramatized consequences by compressing time. Because the direction of climate change was more certain than its timing, maps describing plausible impacts of sea level rise decades or centuries in the future typically focused on elevation, with no specific year-date in either title, key, or caption.

With water covering nearly three-quarters of the earth's surface, geographical maps were especially useful in the latter half of the twentieth century, when international treaties known collectively as the Law of the Sea not only extended territorial waters well away from the shore but allowed maritime nations to claim fishing and subsurface mining rights within so-called Exclusive Economic Zones (EEZs). The typical EEZ extended 200 nautical miles outward from the shoreline, except where EEZs overlapped or an extension of the continental shelf allowed an even broader zone, up to 350 nautical miles wide (Monmonier 2008, 102–13).

Century's end left the geographical map with a significant supporting role in cartographic endeavors more numerous and diverse than those examined here. Nonetheless, the pure geographical map—the small-scale general-purpose reference map—survived in several formats, most notably as wall maps, world and regional reference maps at the front or back of world and national atlases, and the smaller-scale views afforded by dynamic web maps and electronic atlases, including virtual globes with zoom and pan functionality. The latter provided a fitting replacement for the International Map of the World, a complicated endeavor undermined by questionable specifications, most notably its 1:1,000,000 scale, which Arthur H. Robinson (1965, 24) denounced as "too small for one to plot field observations, but . . . sufficiently large to make a general purpose map series quite cumbersome." Zooming and panning freed the geographical map from the tyranny of sheet lines and a rigid level of detail.

MARK MONMONIER

SEE ALSO: Air-Age Globalism; Atlas: World Atlas; Geographic Names: Gazetteer; Projections: (1) World Map Projections, (2) Regional Map Projections; International Map of the World; Wall Map

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Geographical Society of the USSR. See Russkoye geograficheskoye obshchestvo (Russian Geographical Society)

Geographical Survey Institute (Japan). See Kokudo chiriin

Geography and Cartography. The history of geography is one of exploration and mapmaking followed by the development of an academic discipline that took shape mostly in the twentieth century. In the late nineteenth century, the key role that geography and mapping played in colonial trade and imperialism was the basis for the claim that geographical instruction should be a part of school curricula. Newly established geographical societies in Europe and North America argued successfully for the inclusion of geography in the universal school curricula, particularly in Western Europe. Teaching geography in schools required developing programs in universities to train teachers as well as advance scholarship. Geography degree programs and departments in major universities were needed to give the discipline academic credibility, and geographic societies lobbied hard for their establishment.

The academic research directions taken in the late nineteenth century were set by the work of a few influential individuals, especially the German scholars Alexander von Humboldt and Carl Ritter, and French geographer Paul Vidal de la Blache. Humboldt's work was based on field collection of data, particularly from expeditions in Central and South America, and their synthesis through maps, leading to generalizations regarding environmental observations and their links with human activities. Ritter studied the connections between phenomena in places, now called regional geography. This study was based on defining regions, separate areas with distinct assemblages of phenomena, with regional boundaries often drawn on maps. In France, geography was rooted in history and mapping. Vidal de la Blache, who had trained as a geographer, focused on defining on maps and describing regions' relatively small homogeneous areas whose distinctive *genres de vie* (modes of life) resulted from the interactions of people with their environment.

Throughout the twentieth century, the fields of geography and cartography have maintained a close relationship. The linkage was established in North America by the founders of U.S. academic geography, whose approach focused on the map as the tool of the geographer. One of the early leaders in establishing the close link between geography and cartography was J. Paul Goode of the University of Chicago (McMaster and Thrower 1991, 151–52). By 1928 he had established a set of classes at Chicago that focused on what is now called thematic cartography. As early as 1928 Goode had developed a course called Graphics and Cartography for the Geographer that focused on what he called visual education. Seminal cartographers who followed, including Erwin Raisz, Guy-Harold Smith, Arthur H. Robinson, George F. Jenks, and Waldo R. Tobler, each felt that a strong geographical education was essential for the successful cartographer.

By 1938, in the first American textbook on cartography, *General Cartography*, Raisz stated, "Every department of geography in our institutions of higher learning should include a distinct course in cartography, and there should be a literature on the subject adequate and appropriate to the needs of both teachers and students" (viii). A major part of this book emphasized the needs of geographic cartography including distribution maps, economics maps, maps of geography, and government maps. Raisz's claim was that "every map is geographic"

(307). Smith's population and land relief maps of Ohio became references for the emerging field of geographic cartography.

One of the first references to the term "geographic cartography" was by Arthur H. Robinson in the volume *American Geography: Inventory & Prospect* (1954). Robinson pointed out that geographers must have a "working knowledge of cartographic presentation, which includes map projections and mapping of areal relationships, and also an appreciation of how the designs and scales of maps can influence the portrayal of geographical patterns and associations. The term 'geographic cartography' refers to these aspects of cartography" (555). Robinson, who argued that the development of a geographic cartography had been the result of a small number of geographers, thought the focus had been on two scales: the macrogeographers, who worked at small scales, and the microgeographers, who worked at large scales (greater than one inch to the mile).

Both the teaching and research in the field of cartography were mostly done within geography departments by geographic cartographers. At the University of Wisconsin, students working under Robinson studied classification and symbolization, but the geographical problem was always the focus of study. Perhaps the strongest of the geographic cartographers was Jenks, whose own research had initially focused on agricultural patterns. Jenks' courses and students at the University of Kansas were geographically grounded, and he used geographical problems as the base for developing statistical methods. Some of these included mapping agricultural distributions with dot maps and population mapping with the choropleth technique. John Clinton Sherman at the University of Washington likewise brought his geographic background into teaching and research. Jenks, Robinson, and Sherman educated a generation of teachers and scholars who improved our understanding of geographic phenomena through better classification and design methods and new symbolization techniques in thematic cartography.

Education of cartographers during the twentieth century was almost exclusively within departments of geography. Starting in the 1950s, several initiatives focused on the education and training of both academic cartographers and those pursuing careers in the private and governmental sectors. Jenks spent an entire year in the early 1950s traveling around the United States studying most of the major cartographers and publishing houses in order to ascertain the status of cartographic education. He found that cartographic training was universally inadequate, separate departments of cartography were not possible, and that cartographic education was needed by many disciplines. He recommended broadening of the scope and content of present cartography courses, accepting the obligation to train students from all disciplines, opening courses to students in allied fields wishing to pursue cartography, and offering cartographic degrees through interdepartmental committees (Jenks 1953). Later, Robert B. McMaster (1991) documented the development of academic cartography and education and its relationship to geography.

One of the key intersections between cartography and geography occurred during the late 1950s and 1960s when geographers became interested in the application of statistical methods to geographical problems. Out of this interest grew new methods of statistical cartography such as the mapping of residuals. J. R. Mackay taught a seminar in statistical cartography at the University of Washington during the 1960s with topics such as discontinuous, discrete, even, and random distributions; class intervals; and measures of central tendency. Some of the very best quantitative geographers of the twentieth century participated in this seminar, including Brian J. L. Berry, Richard L. Morrill, John D. Nystuen, and Tobler. This strong relationship between cartography and quantitative geography persisted to the end of the century with Robinson, Jenks, Tobler, J. C. Muller, Mark Monmonier, Terry A. Slocum, and others all contributing to the field of statistical cartography. Perhaps the best representation of this intersection was the volume *Spatial Organization: The Geographer's View of the World* (Abler, Adams, and Gould 1971). Throughout this seminal volume, the relationship among spatial theory, geographical problem solving, and mapping is prominent. Related to this, Tobler, the creator of the term analytical cartography, worked at the interface of mapping and geography for much of the second half of the twentieth century. He brought a mathematical cartographic approach to mapping as typified with his focus on transformations (1961). There are many examples of the creative application of Tobler's transformational approach, including the representation of the cost space of postal rates from Seattle.

By the end of the twentieth century the strong relationship between cartography and geography was embedded within geographic information systems (GIS). The development of GIS enabled geographers to solve complex geographical problems through the combination of spatial analysis and increasingly sophisticated cartographic visualization methods. GIS reinforced the importance of a full knowledge of geographical principles and methods to fully understand cartographic representation. Cartography witnessed a resurgence as the importance of map projections, generalization, symbolization, and design were seen as essential.

ROBERT B. MCMASTER

SEE ALSO: Academic Paradigms in Cartography; Scientific Discovery and Cartography; Societies, Geographical

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Geoid. See Figure of the Earth

Geologic Map.

At the outset of the twentieth century geologic maps were still largely prepared and published using methods that would have been familiar to the eighteenth-century innovators who established geology as a science. Although the digital paradigm shift had completely revolutionized the dissemination of knowledge about subsurface phenomena by the year 2000, geologic maps entered the new millennium with a strong imprint of their analog predecessors as well as a digital future impelled by innovative developments in science and technology, particularly in the observation, collection, and application of earth science data and the display of geological knowledge derived therefrom. These enhancements reflect changes in society as well as scientific advances. Two world wars saw intense activity in the application of geologic mapping to discover and delineate energy and mineral resources, and population growth and urban and industrial expansion necessitated a focus on water as both a natural hazard and a scarce, fragile resource. Novel investigative techniques, including remote sensing, provided new perspectives, and the acceptance of plate tectonic theory in the 1960s forced geoscientists to rethink the genesis of rocks and related interpretations. In this milieu of change, geologists and geological cartographers readily adopted and adapted wider developments in cartography and spatial data technology.

A traditional geologic map depicts rock type, classified and colored according to the lithology of the rocks, e.g., sandstone, their age (chronostratigraphy), or their lithology and stratigraphic position (lithostratigraphy) (figs. 314 and 315). Throughout the century a deepening understanding of stratigraphy, made possible through developments in biostratigraphy (in essence using fossils for correlation) and physical and chemical techniques for age-dating, significantly improved the calibration of rocks and allowed the field geologist to produce maps of considerably increased resolution and detail. In addition, a steadily growing number of boreholes drilled for water, civil engineering studies, and mineral explorations added to an evidence base enriched by improved geophysical techniques. This increased information threatened both the appearance and the effectiveness of the geologic map, often regarded as an object of considerable aesthetic beauty but vulnerable to geologist authors eager to include almost everything that they knew of their territory. When a single map was used as both a scientific notebook and a means of communication, the latter often suffered.

Geologic maps had another, related weakness. Unsurpassed as a means of communication among geologists, they are, however beautiful, largely dense and arcane to those outside the profession. Moreover, a fundamental characteristic of geologic maps reflects geology's role as an interpretive discipline—unlike topographic maps, which are rooted in measurement and often touted as objective, geologic maps are based largely on inference. Laypeople rarely recognize geology as a "detective" science and the geologic map as only an approximation of reality based on the evidence available. During the latter half of the twentieth century, geoscientists sought to avoid miscommunication by converting the traditional geologic map, with its basic depiction of rock type and age, into "applied" or "thematic" variants designed to describe more explicitly such phenomena as the stability of the ground or the location and extent of mineral resources. Equally important, the very best of these applied maps also express the geologist's confidence in these interpretations. Explicit recognition of uncertainty made otherwise mysterious correlations and associations accessible to public officials, investors, and other users.

Central to the evolution of geologic maps were the official geological surveys, staffed by professional scientists and technicians and funded by national or provincial governments. By 1900, sixty-five years after the creation of the first national geological survey in Great Britain, geological surveys throughout the world were busily engaged in mapping the rocks of their territories. Although other bodies and individuals, particularly in academe and commerce, also produced geologic maps, official survey organizations produced most of the twentieth century's geologic maps and made key contributions to the development of mapping techniques. Expansion of geologic mapping worldwide reflected differences in economic and social development, and geological surveys evolved differently in different countries, typically progressing from exploration of the territory, through searching for mineral and energy resources, to mitigating hazards and protecting the environment. By 2000 the typical geological survey's mission had grown to include the impacts of climate change on the ground.

In the second half of the century many geological surveys that had expanded their influence to their nation's colonies at the turn of the century began, somewhat paradoxically, to incorporate techniques applied internationally in their domestic mapping campaigns. Geophysics, geochemistry, applied mineralogy, and photogeology (aerial photographic interpretation) became part of the geological survey mainstream, and new variants of geologic map emerged. Around the same time, in the 1950s and 1960s, the stimulus of the search for hydrocarbon resources led to extensive seafloor mapping programs, which necessitated new survey techniques and new types of map.

The two world wars shifted the focus of geologic mapping dramatically, from long-term strategic goals to immediate utility, and this restructuring severely affected systematic mapping programs. Routine geologic mapping intended eventually to provide complete, uniform territorial coverage was largely abandoned as maps and reports on battle zones, energy, and industrial minerals were produced to aid the war effort. Topographic base maps, essential as a framework for geologic mapping, became impossible to obtain as their surveyors were diverted to military priorities, and a paper shortage only compounded the problems. Even so, the disruptions were not wholly unconstructive: the two calamitous wars and their intervening years produced valuable experience as well as a focus on societal relevance, within geological surveys in particular, that would stand them and their users in good stead for the decades that followed. The needs of nations at war brought into sharp focus the dependence of society on the resources and properties of the rocks beneath their feet. If geologic science and mapping had been born of curiosity about our natural history in the eighteenth century, in the first half of the twentieth century it had, beyond doubt, matured into an applied science.

Throughout the century geology as a science enjoyed progressive development as well as a progressive partition into various subdisciplines. Advances were made across subfields, most notably in seismology, hydrogeology, and economic geology, and most advances resulted in new forms of the geologic map. Moreover, the mid-1960s saw the emergence of the single most revolutionary development in understanding the earth since the theory of uniformitarianism and birth of geology: plate tectonics. Since the first two decades of the century, when first Frank B. Taylor and then Alfred Wegener had sought to explain the configuration of the continents, geologists had struggled to establish a coherent model that placed continental drift, seafloor spreading, and seismic and volcanic activity within a consistent context. The theory of plate tectonics provided that unifying concept, which affected all areas of the geosciences, including geologic mapping and its products. Although theory normally follows evidence, rocks and maps of rocks had to be reappraised around the world in light of this groundbreaking discovery.

Because changes in basic techniques for producing geologic maps occurred at different times in different parts of the world, the dates that follow are only approximations. In 1900 copperplate engraving was still a common method of production. This was succeeded around 1920 by lines and letters drawn by hand in ink on paper or thin enamel board; reference copies were hand-colored using watercolor paints. In the 1960s geologic linework was drawn in ink on plastic film, and typed lettering printed on a wax backing was cut out and stuck down in appropriate positions on a separate overlay. The 1970s witnessed the wide adoption of photomechanical reproduction techniques, whereby geologic lines were inscribed on a sheet of thin plastic film called scribecoat by using a graver with a sapphire point to cut out their delineations on the film's photographically opaque coating; the film thus held a negative image of the map's linework. In addition, peelcoats were used to produce printing masks by hand. By the 1980s computer-controlled plotters were producing scribed images and peelcoats for lithographic printing.

In the 1960s and 1970s early experimentation with geological cartographic computing led to equipment and procedures for capturing and displaying geologic data. Innovations in computer graphics technology and geographic information system (GIS) software spawned operational, off-the-shelf systems for map production in the 1980s. The fact that geologic maps were part of an interpretive scientific process, and not merely representations of what could be observed, undoubtedly played a role in an early move away from comparatively primitive computer-aided design platforms toward the direct encoding of scientific features and objects and a more sophisticated use of digital database technology. By the mid-1990s most geological surveys in the developed world had embraced digital technology for the preparation and printing of their geologic maps, and the leaders in the field had also developed corporate databases in which to store geometry and attributes.

The transition to digital methods in the 1990s was not without challenges. Most mapping geologists were initially reluctant to involve themselves in the migration to a digital world, and into the twenty-first century it was a struggle to engage them in developing the scientific protocols, standards, and discipline essential

Wehrgeologische Karte des bosnisch-herzegowinisch-montenegrinischen Grenzgebietes

Bearbeitet von der Abteilung Technische Wehrgeologie der Waffen-SS

Generalkarte von Mitteleuropa
Balkan 1 : 200.000

SARAJEVO

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Zeichenerklärung

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Trinkwasserverhältnisse*

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FIG. 314. *WEHRGEOLOGISCHE KARTE DES BOSNISCH-HERZEGOWINISCH-MONTENEGRINISCHEN GRENZGEBIETES*, 1:200,000, 1942. German army geology map of Bosnia-Herzegovina and Montenegro (*Sarajevo* sheet), produced by Der Abteilung Technische Wehrgeologie der Waffen SS during World War II, showing drinking water conditions. See figure 315.
Size of the original: ca. 81.8 × 52.2 cm.

for efficient computer-based processing. At the same time, cartographers who resented information systems experts and geologists meddling in their domain debunked predictions that the map would become merely an ephemeral product of a database. Computer-aided display and analysis were not the only change that geologists and geological cartographers would have to accept: by the end of the century several geological organizations across the globe had begun to explore digital geological field mapping supported by GPS (Global Positioning System) receivers as well as end-to-end digital workflows and four-dimensional interactive mapping.

FIG. 315. DETAIL FROM *WEHRGEOLOGISCHE KARTE DES BOSNISCH-HERZEGOWINISCH-MONTENEGRINISCHEN GRENZGEBIETES.* The area shown is about sixty-five kilometers northwest of Sarajevo.
Size of detail: ca. 13 × 9.85 cm.

Geology has always been a three-dimensional science—four-dimensional if one includes time. Throughout much of the twentieth century the interpretation and depiction of the geology of our planet was to a large degree as it had been in the nineteenth century, shackled by the limitations of the two dimensions and inflexibility of paper. Throughout the ages every field geologist has held a mental three-dimensional picture of the piece of the earth's crust he or she was mapping, a picture substantially poorer when transcribed into a two-dimensional map or cross-section. By the end of the century the digital revolution had begun to release geology and geologists from these fetters. Colorful maps and cross-sections, once understood only by the cognoscenti, were being replaced by dynamic three- and four-dimensional models and animations. Here, freely available, were new tools and techniques that could not only liberate the doing of the science from its publication and dissemination but also, perhaps more importantly, make clear to decision makers and a wider public the critical relevance of geology to the health and wealth of society. This was an audience that had hitherto perceived geologic maps, if it thought of them at all, as attractive but esoteric documents. As the twenty-first century dawned the digital revolution, supercharged by the Internet, had initiated the most radical change to the dissemination and accessibility of geological knowledge since the creation of the geologic map.

IAN JACKSON

SEE ALSO: Cave Map; Cvijić, Jovan; Scientific Discovery and Cartography

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Geophysics and Cartography. At the start of the twentieth century, geophysics was not a recognized discipline. The word “geophysics,” originally coined in German, had developed some currency during the 1890s, particularly in the United States, but more specific fields such as terrestrial magnetism (geomagnetism), terrestrial gravity, and seismology were more generally recognized. Global and regional magnetic maps—essentially updated and extended versions of Edmond Halley’s 1701 map of magnetic variation throughout the Atlantic Ocean—were routinely constructed and widely available in formats based on isogons (lines of constant magnetic declination) or contoured values of total magnetic intensity. Maps were little used in the other fields. For example, although Robert Mallet had produced a global map of earthquake occurrence as early as 1857, apart from a contribution by Fernand de Montessus de Ballore (1911), no significant new version of this map was published until the work of Beno Gutenberg and Charles Richter (1949).

Geophysics achieved recognition as a primary scientific discipline with the establishment of the International Union of Geodesy and Geophysics (IUGG) under the auspices of the International Research Council in 1919, drawing together various preexisting independent international bodies representing subdisciplines as its sections (from 1930 known as associations). At this point, although regional magnetic surveying had continued to develop, especially in the context of marine navigation, other forms of geophysical investigation were constrained by insensitive or cumbersome instruments. These instruments typically required observatory conditions for successful operation, so consistent measurements of the relevant geophysical parameters were rarely if ever made over a region of the earth. The consequent lack of geographical coverage precluded the production of meaningful maps. Maps were primarily used to identify observing locations.

Early oil explorers recognized the potential for using the torsion balance invented by Baron Loránd Eötvös de Vásárosnamény as a survey tool. The Eötvös torsion balance measures the lateral gradient of the earth’s gravity field, a vector that, in effect, points toward the position of any net excess local subsurface mass. Hydrocarbons tend to gather beneath slowly rising bodies of salt (halite), which are lighter than the sandstone formations within which the salt was initially emplaced. The ductile salt also forms an impervious cap, so salt domes form excellent drilling prospects and, depending on the densities of the salt and sandstone, the torsion balance vector points either toward or away from such structures. In Texas during the 1920s, American geologist Donald C. Barton and colleagues used this instrument to conduct surveys relatively rapidly and to construct local maps of gravity gradient from which exploration prospects could readily be identified (fig. 316).

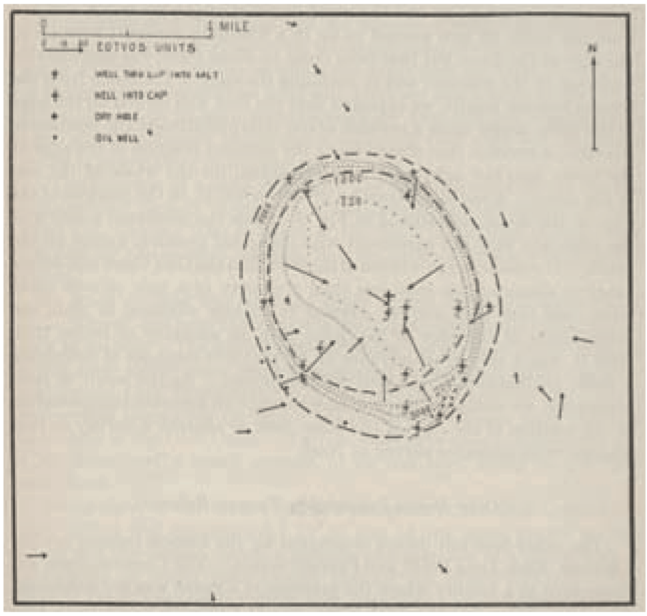

FIG. 316. A GRAVITY GRADIENT MAP OVER A SALT DOME, 1929. The Nash Dome, the first hydrocarbon prospect located with geophysics in the United States, is identified by the distinctive suite of arrows pointing toward the center of dense caprock above the salt dome.

Size of the original: ca. 10.9 × 11.5 cm. From Donald C. Barton, “The Eötvös Torsion Balance Method of Mapping Geologic Structure,” in *Geophysical Prospecting: Papers and Discussions Presented at Meetings Held at New York, February, 1928, and at Boston, August, 1929* (New York: The Institute, 1929), 416–79, esp. 445 (fig. 9). Image courtesy of the Texas A&M University Libraries, College Station.

Accurate relative gravity meters, most notably designed by physicists Lucien LaCoste and Arnold Romberg based on the zero-length spring, were developed during the 1930s. Gravity meters permitted gravity stations to be occupied much more rapidly than with torsion balances, at which point the oil exploration industry moved toward mapping based on total (scalar) field gravity measurements. Seismic reflection and refraction profiling methods were also developed to investigate details of subsurface structure associated with prospects initially identified by surface geological and gravity mapping.

Because gravity changes rapidly with height, raw gravity readings are strongly correlated with topography, so a series of corrections were routinely applied to adjust readings to what would be observed at a suitable datum level, usually mean sea level or (later) the World Geodetic System of 1984 (WGS84). These corrected readings are known as free-air gravity or, if a further correction for the presence of the topographic mass is applied, Bouguer-corrected gravity. The readings, initially charted as posted values, were contoured to produce a map suitable for interpretation. High or low values of Bouguer gravity are due to a mass surplus or deficit beneath, and according to circumstances they might be interpreted either as due to higher or lower densities throughout a region and depth range or to the presence of a specific high- or low-density body. The maps indicated the position of such regions. Where the purpose of the study was resource exploration, Bouguer-corrected gravity was frequently supplemented by subtraction of a known or inferred regional trend so as to emphasize short-wavelength features associated with shallow structures.

During the 1930s and 1940s, the U.S.-based oil exploration industry and the U.S. Geological Survey (USGS) Fuels Branch established standard protocols for gravity surveying. Following World War II, other national mapping agencies began to undertake detailed regional gravity surveys, initially onshore and subsequently offshore. This information was presented in the form of maps of free-air or Bouguer gravity.

The relatively large number of aircraft available following World War II and advances in electronic instrumentation and recording devices made airborne surveys of the strength of the earth's magnetic field not only practicable but essential for navigation over hostile territories. Mapping methods continued to follow the long-standing techniques of constructing profiles, applying corrections, and transferring measurements to posted-value maps, which were then contoured.

Although gravity and magnetic methods in geophysics are frequently lumped together in textbooks, at conferences, and even managerially in many organizations, the techniques and methods of analysis differ quite significantly. Small-scale, crustally induced, geographical variation in magnetic field intensity is typically bipolar in character because—whether the result of remnant or induced magnetization—the effect of a magnetized body is to increase the field strength in one direction and to reduce it in the opposite direction. However, the earth's magnetic field is neither vertically nor horizontally oriented except at the magnetic poles and equator, respectively, so the resulting anomalies are not symmetric—one limb of a magnetic anomaly is larger, often significantly larger, than the other. Through a relatively complex calculation requiring significant computational capability the pattern of anomalies can be transformed to a symmetric situation, yielding a "reduced-to-pole" (or, less often, "reduced-to-equator") representation of the field largely free of the effects of the local orientation of the earth's magnetic field. This process yields significant benefits in interpretation, but the high computational cost meant that it was little used until digital computers became widely available.

Maps produced by geophysicists played a key role in the development of plate tectonics. The similarity of shape between the continental regions on either side of the Atlantic Ocean and the possibility that it represented some sort of separation had been remarked upon since the late sixteenth century. In 1915 meteorologist Alfred Wegener published a lengthy discussion of this idea with some supporting geological and palaeontological evidence and some speculation as to how the phenomenon might have been caused.

Geologists Alexander Du Toit and Arthur Holmes supported and developed these ideas. Du Toit discussed the relationships between the continental masses and recognized that a major ocean—which he named the Tethys—had once been present between the northern and southern continents, but was now largely closed. However, these arguments were largely dismissed by the geophysical community. Throughout the various editions of his seminal work, *The Earth*, and at length in the sixth edition (1976), mathematician Harold Jeffreys argued that the effective viscosity of the interior of the earth determined from tidal observations was too great to permit continental drift, and that if the earth's crust were somehow decoupled from the mantle, the earth's rotation would cause the major continental masses to collect at the equator.

At Cambridge University, Jeffreys and geophysicist Edward "Teddy" Crisp Bullard disagreed strongly regarding the quality of fit between the South Atlantic continents that had been achieved in a reconstruction by Australian geologist S. Warren Carey. Bullard wondered whether some level on the continental slope might be even more representative of the true margin of the continents than the coastline and asked J. E. Everett, a graduate student with a mathematical background, to quantify the degree of fit at various depths. Everett digitized contours from the relevant Admiralty charts and wrote a computer program to perform the rotations on a sphere and to calculate the best fit. Geologist A. G. Smith, a research associate, examined the geological evidence in detail and identified potential matches across the northern Atlantic. The resulting map of the fit across the entire Atlantic, taken at the 500-fathom (914 m) contour, was geologically as well as geometrically convincing, in that similar structures could readily be traced from one side to the other, and the few regions of overlap were clearly associated with relatively recent postpartition geological activity (fig. 317). Presented at an American Geophysical Union (AGU) conference in 1965, alongside palaeomagnetic evidence that the major continents had moved along different paths and magnetic evidence supporting the viability of seafloor spreading as a mechanism, this map persuaded many that the earth's crust was laterally as well as vertically mobile.

The physiographic maps of geologists Bruce C. Heezen

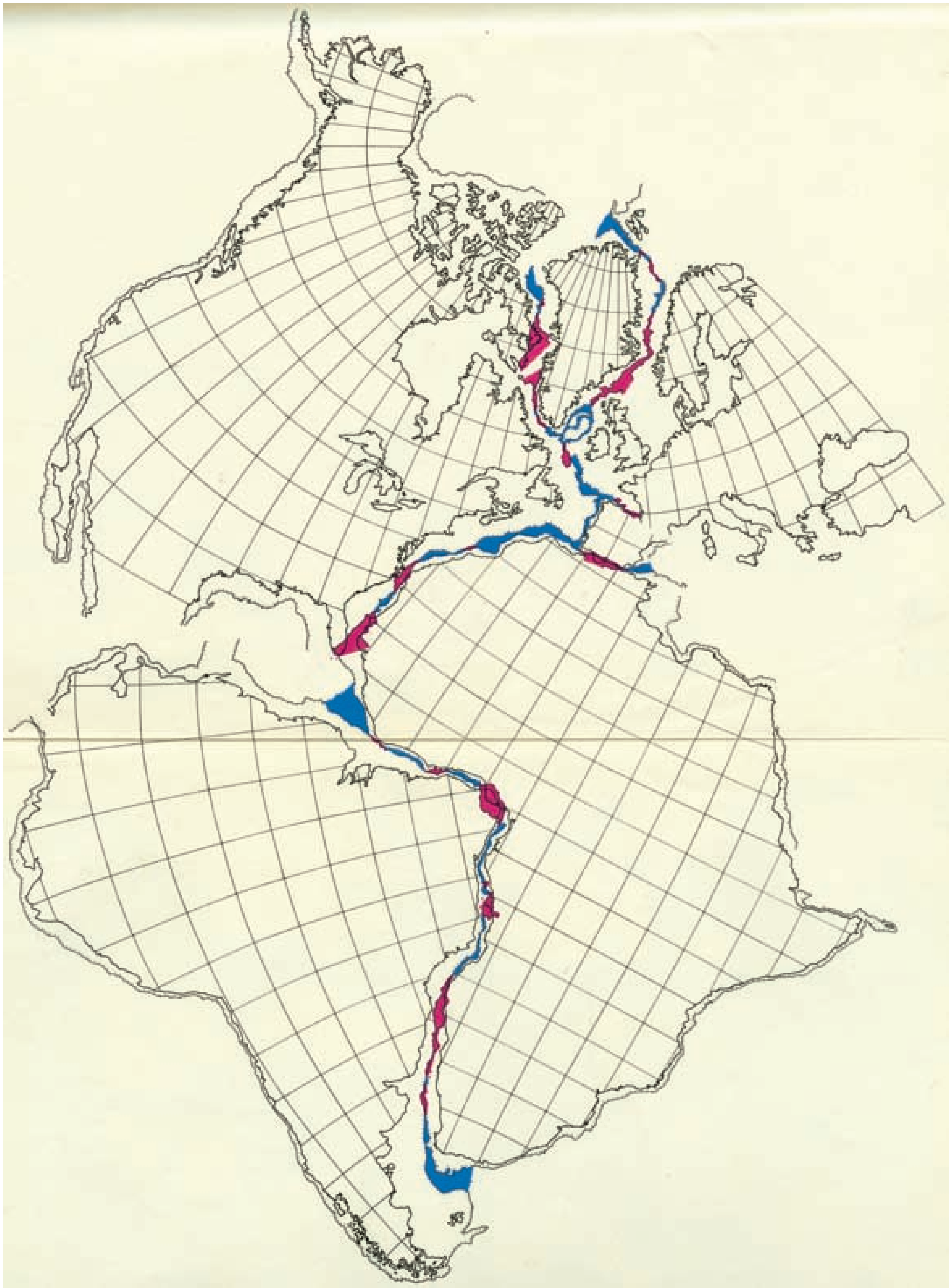

FIG. 317. COMPUTER-GENERATED RECONSTRUCTION OF THE CIRCUM-ATLANTIC CONTINENTS IN 1965. Size of the original: 34.4 × 25.2 cm. From Edward Crisp Bullard, J. E. Everett, and A. G. Smith, "The Fit of the Continents around the Atlantic," in *A Symposium on Continental Drift* (London: Royal Society, 1965), 41–51, map between 48 and 49 (fig. 8). Copyright © 1965, the Royal Society.

and Marie Tharp at the Lamont-Doherty Geological Observatory (LDGO) in New York were similarly influential to the development of plate tectonics. They recognized faults offsetting the midocean ridge in the Southern Atlantic and subsequently the Indian Ocean. The vivid illustration of these features by cartographic artist Heinrich C. Berann made the part these structures play in the development of oceanic plates obvious even to nontechnical eyes. Heezen, Tharp, and Berann's dramatic images of ocean floor topography (see figs. 611 and 888), made widely available through the National Geographic Society from 1966, and posted on the walls of geophysicists' offices and student rooms worldwide, became important vehicles for explaining and popularizing the concepts of plate tectonics, leading to an influx of talented recruits to the science in the late 1960s and 1970s.

Seismological mapping provided further important insight into the kinematics of plate movement. At the University of California, Berkeley, during the 1930s, physicist Perry Byerly had devised a method of analyzing earthquakes by plotting the direction of initial motion (up, down, or unclear) on a projection of the hemisphere beneath the earthquake focus—a map of the earth as viewed at the source of seismic P-waves. As a rule, the first-motion maps of earthquakes can readily be divided into regions of consistently upward (compressional) and downward (dilatational) motion, separated by two lines corresponding to a pair of mutually perpendicular planes at the source (fig. 318). One of these planes corresponds to the causative fault. Other evidence, such as correlation with a major topographic or geological feature or with the geometry of other earthquakes in the region, is required to identify which one. Such correlations are identified by putting small versions of the global first-motion maps onto the regional map.

The establishment of the WWSSN—World-Wide Standardized Seismograph Network (originally WWNSS—World-Wide Network of Standard Seismograph Stations) under the auspices of the United States' VELA Uniform project from the early 1960s meant that for

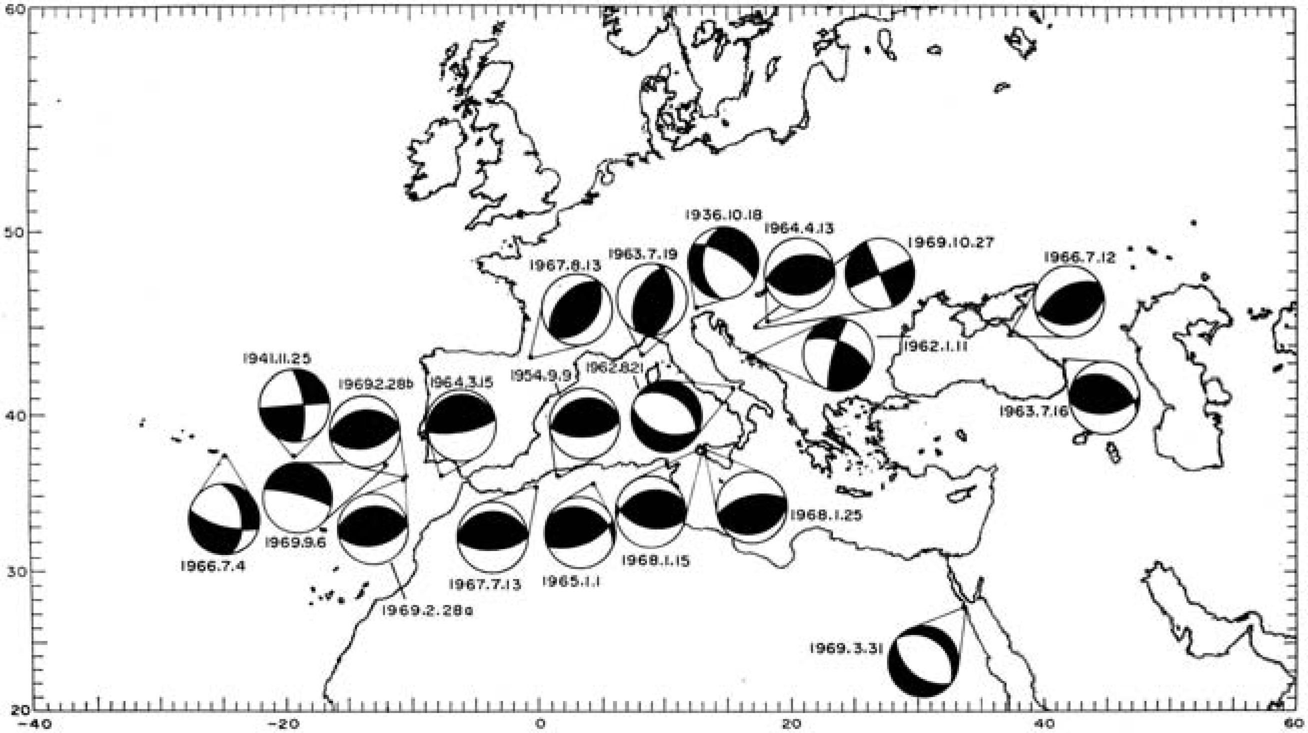

FIG. 318. MAP OF EARTHQUAKE FIRST-MOTION SOLUTIONS THROUGHOUT THE WESTERN AND CENTRAL MEDITERRANEAN. Each of the "beach balls" is itself a map of the earth, divided into regions within which the initial motion of the earthquake is observed as compression (dark) or dilatation (light). The figure demonstrates, for example, that the Algerian region is dominated by east-west-oriented compressional thrust motion, whereas the very different mechanism in eastern Italy indicates that tension and normal faulting is present.

Size of the original: 12.1 × 21.5 cm. From D. P. McKenzie, "Active Tectonics of the Mediterranean Region," *Geophysical Journal of the Royal Astronomical Society* 30 (1972): 109–85, esp. 126 (fig. 9). Copyright © 1972 Blackwell Scientific Publications. Reproduced with permission of Blackwell Publishing Ltd.

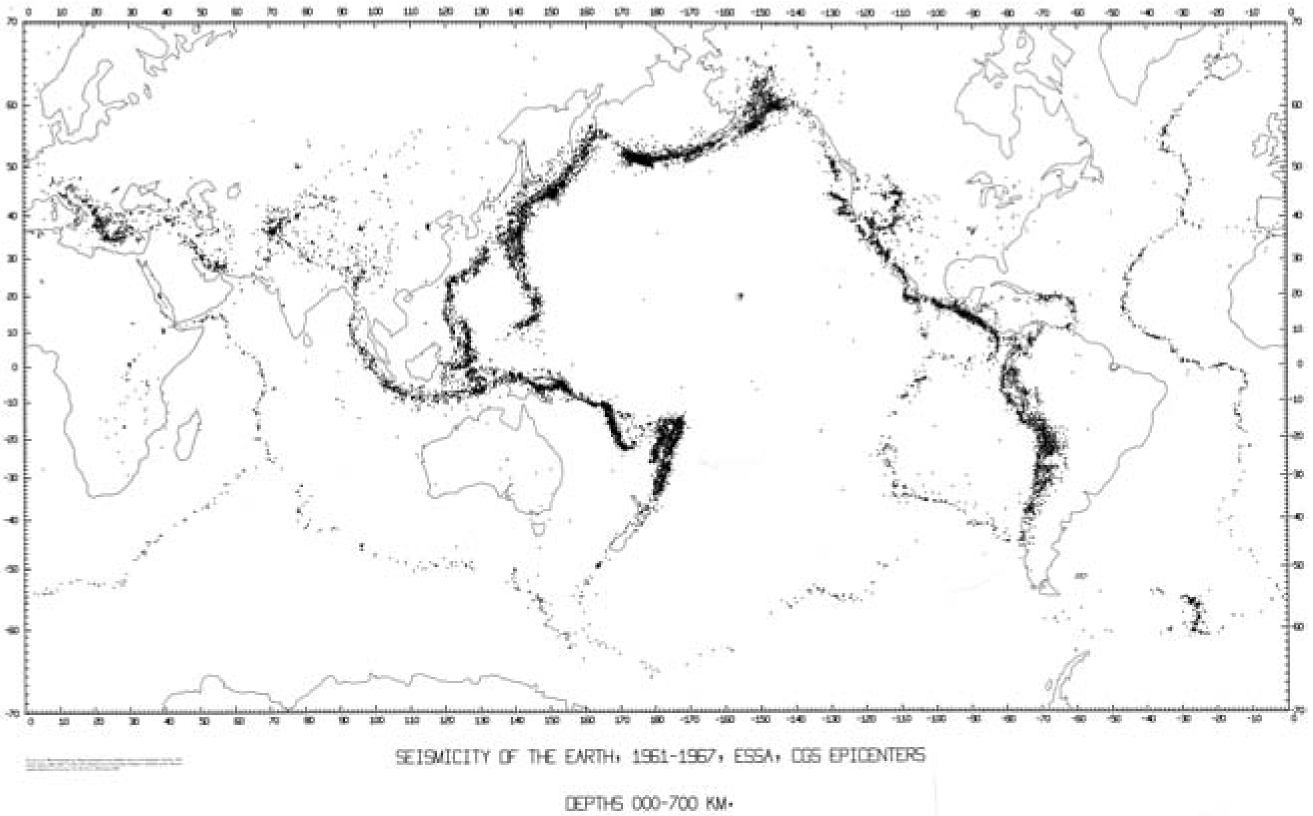

FIG. 319. *SEISMICITY OF THE EARTH, 1961–1967*. The global map of earthquakes detected in 1961–67, following the development of the World Wide Standard Seismograph Network, clearly demonstrated how the earth's crust is divided into a number of distinct plates. Examination of similar maps prepared for various ranges of earthquake depth showed that, at certain points such as beneath Japan and South America, these plates are bent into the body of the earth and are being drawn into it.

Size of the original: 64.7 × 103.8 cm. From Muawia Barazangi and James Dorman, "World Seismicity Maps Compiled from ESSA, Coast and Geodetic Survey, Epicenter Data, 1961–1967," *Bulletin of the Seismological Society of America* 59 (1969): 369–80, pl. 1. Permission courtesy of the Seismological Society of America, Albany, California.

the first time, reliable, accurately timed readings including seismogram polarity were available with worldwide coverage. Seismologist L. R. Sykes, also at LDGO, used WWSSN seismograms to locate and map earthquakes very accurately and confirmed that these were occurring at offsets on the Mid-Atlantic Ridge (fig. 319). He also demonstrated that the mechanisms of these earthquakes were entirely consistent with the transform-fault model of geophysicist J. Tuzo Wilson, a key consequence of the plate tectonic concept.

Computers were readily adopted by geophysicists as routine tools both for scientific analysis and for acquiring and processing large quantities of data. At one point it was claimed that more than half of all the computer cycles available worldwide were employed in processing seismic reflection data for the oil and gas industry. The ever-improving graphical display capabilities of these systems encouraged geophysical analysts to look for new ways to present and understand the spatial variation of the properties they were measuring, as well as the complex relationships between those properties.

The ability to digitally manipulate spatial data was exploited by the gravity and magnetic communities in several very different ways. Whereas contour maps had previously been constructed by hand as overlays on posted values of original measurements reduced through manual calculations, it became possible to emphasize and analyze features of interest through a wide variety of digital manipulations and to display the results promptly. Long-wavelength variations in the earth's field could be suppressed so as to emphasize shallow structures associated with oilfield prospects, or emphasized to identify features in the deeper crust and upper mantle associated with tectonic activity.

In practice, such manipulations are most readily accomplished by substituting the original scattered network of observations with interpolated values on a square or rectangular grid. With values in grid form, it is a near-trivial matter to use a computer to calculate a range of derivatives using specific features of the data set that are enhanced or suppressed to aid visualization. Although typically involving rather greater computational effort and complexity, derivative grids can also be computed for any model of subsurface density. The residual differences between a model and the actual data can be displayed and examined, and can be used to measure and potentially improve the degree to which the model accounts for the observed data.

Two theoretical papers by geophysicists George Backus and J. Freeman Gilbert (1968; 1970) put forward ideas that proved pivotal to the analysis of geophysical data and led to an independent and widely applied discipline known as geophysical inverse theory. Backus and Gilbert noted that there were several ways in which data acquired on the earth's surface might fail to reveal details of the earth's interior. Errors in the data due to limited resolution of the instruments used will lead to imprecision and lack of resolution of specific parameters within the model, but beyond that, the mere fact that properties must be inferred from remote measurements means that, in practice, the true properties at any point of the interior of the earth can never be determined exactly, and that specific features or regions of the earth's interior may not even be open to examination using surface measurements. Geophysicists therefore recognized that the estimates of the properties of the earth that they investigate represent averages of finite precision taken over significant volumes. In some branches of geophysics, the resolution kernels associated with a set of measurements and models can be of critical importance, and in such cases, this information is often presented in the form of maps alongside those of the primary data and models.

Gravity analysis can illustrate how inverse theory is applied. Because the gravitational fields due to different masses combine through simple linear addition, any distribution of mass or density that gives rise to no net observable field throughout the region of observation can be added to a suitable model, and the result will satisfy the observations as well as the original. Examples of such no-net-field models are readily constructed. There are therefore an infinite number of models of the distribution of mass or density in the earth that will account for any set of observations of gravity.

The wealth and complexity of possibilities that can be derived from geophysical measurements, especially regional gravity and magnetic surveys, led to considerable innovation in their presentation on digital maps. Contours, colors, and shading were all extensively used (fig. 320). In order to present different aspects of data, models, or of their interaction, multiple parameters were displayed simultaneously on the same map with a view to illustrating or enhancing correlations. These computer programs were, in effect, early geographical information systems. In contrast with this sophisticated approach, in 1988, Paul Wessel and Walter H. F. Smith, both at the Scripps Institute of Oceanography at the time, released GMT (Generic Mapping Tools), a suite of simple mapping tools for Unix-style operating systems which quickly found favor throughout the geophysical community and became a de facto public-domain standard for rapid construction of maps and related images.

Seismologists working with global (typically earthquake-derived) data made use of these cartographic techniques for displaying results from innovations such as tomographic models of the earth's subsurface. However, for much of the twentieth century, exploration seismology was constrained by practical considerations to undertaking linear surveys and, in consequence, to data interpretation based on vertical cross-sections. Although highly complex and sophisticated data processing methods were devised, and vast quantities of data were acquired, geographically oriented data presentations typically took the form of location maps or fence diagrams.

The development of true 3-D exploration technology during the 1980s led to enormous changes. Onshore exploration is always slow, as the power of seismic sources is often limited by practical considerations, and geophone arrays have to be reconfigured manually for each new geometry. Nevertheless, small-scale 3-D surveys during the 1970s had demonstrated that valuable additional information could be derived from complex geometries. The construction during the 1980s of vessels capable of towing large, complex arrays of seismic sources and multiple parallel arrays of hydrophone receivers made marine 3-D seismic profiling a feasible prospect. Multiple coordinated source and receiver vessels became capable of deploying tens of thousands of receivers extending over several square kilometers of the sea surface. As these move, seismic waves are generated from various points in the source array, transmitted into the seabed, and the responses are received with a wide range of geometries.

The resulting waveforms are processed to produce 3-D models of various subsurface parameters to depths of several kilometers, usually represented as a system of 3-D grids with a resolution of tens of meters. Within these models, important boundaries, typically indicating changes in rock type, can be identified and their geom-

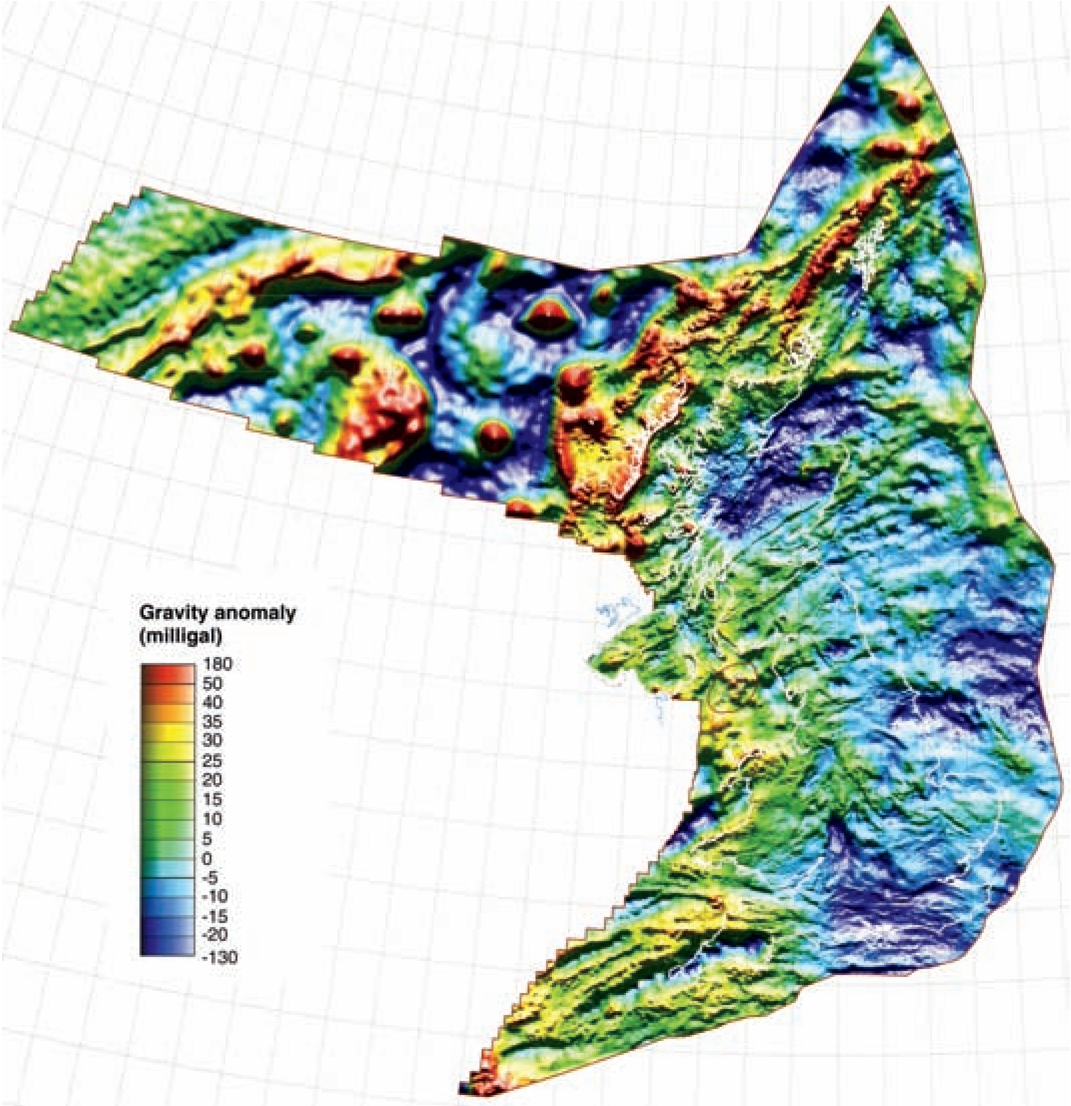

FIG. 320. SHADED RELIEF BOUGUER GRAVITY MAP OF THE UNITED KINGDOM REGION. The shading permits short-wavelength structural features such as faults to be readily identified, while the color system indicates their relationship to the overall pattern of variation in subsurface density. The United Kingdom is outlined in white.

Size of the original: 25.5 × 17.4 cm. From Ian Jackson, ed., *Britain Beneath Our Feet: An Atlas of Digital Information on Britain's Land Quality, Underground Hazards, Resources, and Geology* (Keyworth, Nottinghamshire: British Geological Survey, 2004), 19. CP14/017 British Geological Survey © NERC. All rights reserved.

etries as well as their properties imaged. The availability of these models led to much wider use of maps in the seismic exploration industry and to innovation in terms of both the features presented and the display format (fig. 321). In consequence, the geophysical exploration industry became a major user of geographic information systems (GIS) and a driver of GIS technology from the 1980s onward.

The International Geophysical Year (1957–58 and extended to thirty months), although focused on polar and upper-atmospheric research, attracted much interest in all aspects of the subject, not least because of the important role played by the first artificial satellites in that program and the rivalry that developed between the various major nations involved in space science as a result. Later, the GEOS-3 and Seasat satellites that operated between 1975 and 1978, and for just 105 days during 1978, respectively, both carried laser altimeters to determine the height of the ocean surface. Although the primary purpose of this instrument was oceanographic research—to examine the effect of tides, currents, and storm surges—geodesists including Richard H. Rapp of

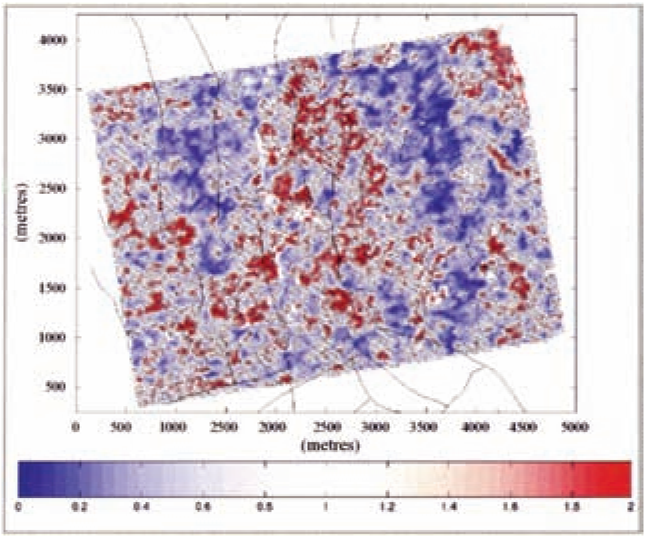

FIG. 321. FRACTURE ORIENTATIONS AND MAGNITUDE OF SEISMIC ANISOTROPY. Careful analysis of 3-D seismic data permits physical properties at depth in the earth to be mapped precisely and in detail. Here, the orientations of fractures in a section of the Valhall chalk reservoir are indicated, along with (in color) the magnitude of the seismic anisotropy, from which the fracture information was derived.
Size of the original: 7.2 × 8.7 cm. From Stephen A. Hall, J-Michael Kendall, and Olav I. Barkved, "Fractured Reservoir Characterization Using P-Wave AVOA Analysis of 3D OBC Data," *Leading Edge* 21 (2002): 777–81, esp. 780 (fig. 7).

Ohio State University noted that because the sea surface follows the shape of the geoid, variations in geoid topography are due to the distribution of mass or density (Rapp 1979). Sea-surface altimetry can therefore be used to construct maps of the long-wavelength variation in gravity over ocean regions and, after allowing for variation due to ocean depth, of variation in sub-seabed density.

The U.S. National Aeronautics and Space Administration (NASA) launched Geosat in 1986, which operated initially in a Geodetic Mission mode and then in Exact Repeat Mission mode until 1990. Geosat data and results were restricted until the European ERS-1 satellite, carrying a more advanced laser altimeter, was launched in 1995. Declassification of the Geosat data permitted geophysicists David T. Sandwell and Walter H. F. Smith of the Scripps Institute of Oceanography to release their model of gravity throughout the earth's ocean basins and subsequently a detailed, comprehensive model of the topography of the ocean floor reminiscent of the 1960s images of Heezen, Tharp, and Berann. The ERS-1 and TOPEX/Poseidon satellites, operating until 2000 and from 1992 to 2006, respectively, added further information to this data set.

For a six-month period from late 1979, a high-resolution vector magnetometer satellite, Magsat, operated in a low orbit and produced a global data set suitable for small-scale mapping applications, within which anomalies due to variations in the earth's crust are visible. A further high-resolution vector magnetometer satellite, Ørsted, was launched by Denmark in 1999 and operated successfully well into the twenty-first century.

Other satellite systems, not all launched specifically for geophysical purposes, have proved valuable sources of geophysical data. For example, beginning in the mid-1960s, the Defense Meteorological Satellite Program (DMSP) operated a series of satellites in sun-synchronous, near-polar orbits. In addition to their primary instruments for observing cloud cover and transmission characteristics, many of these satellites carried magnetic and ion sensors. Data from these sensors provide a lengthy history of the earth's magnetic field and electrical currents at an altitude of about 850 kilometers, which have been used in studies of the earth's ionosphere and its behavior, as well as a variety of solar-terrestrial phenomena.

During the early 1990s, teams at NASA's Jet Propulsion Laboratory devised ways to combine synthetic aperture radar (SAR) images of a region taken at different times interferometrically, allowing them to detect millimeter changes in topography. The InSAR technique allows deformation of the earth's surface to be observed and monitored directly over a wide area. Such deformation may be due to earthquakes, subsidence, or human activity such as fluid extraction. Geophysicist Didier Massonnet and colleagues applied the InSAR technique to the magnitude 7.3 earthquake that occurred near Landers, California, in 1992 (fig. 322). It was subsequently recognized that coherent reflections from relatively small individual features including structures such as buildings, preinstalled retro-reflectors, or even natural features could also be tracked, allowing very detailed studies of local motion to be conducted and motion maps created.

RUSS EVANS

SEE ALSO: Astrophysics and Cartography; Figure of the Earth; International Geographical Union; International Geographical Year; Molodenskiy, M(ikhail) S(ergeyevich); Scientific Discovery and Cartography; Tharp, Marie

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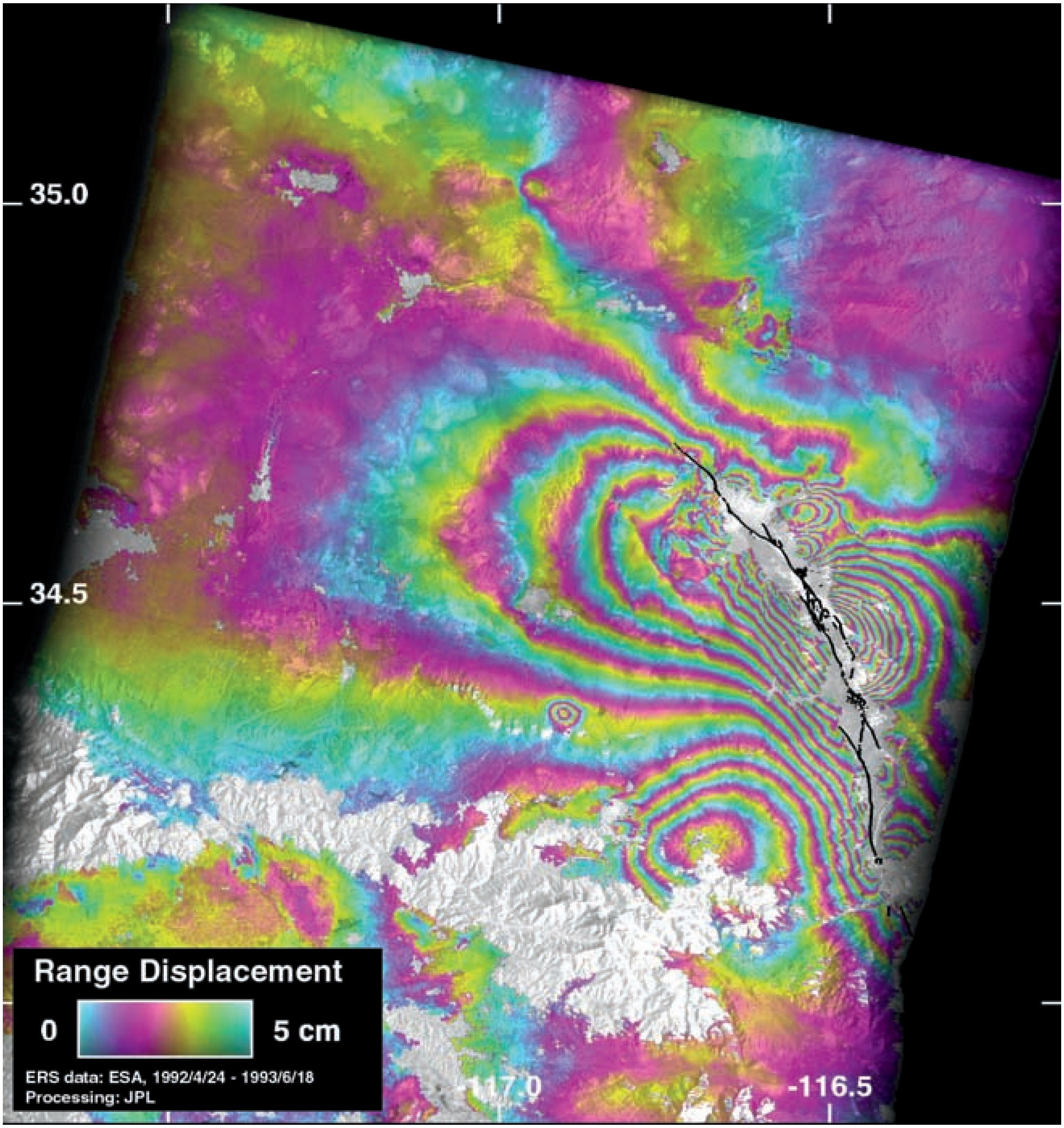

FIG. 322. INTERFEROMETRIC MAP OF DEFORMATION DUE TO THE LANDERS, CALIFORNIA, EARTHQUAKE, 1992. Interferometric analysis of synthetic aperture radar images before and after the Landers earthquake of 1992 showed the deformation of the earth's surface that occurred, not only on the fault itself but throughout the region affected. Data were acquired by European Remote Sensing satellite (ERS-2) on 24 April 1992 and 18 June 1993.
Image courtesy of the Jet Propulsion Laboratory, Pasadena.

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Geopolitics and Cartography. Geopolitics is a form of geographic inquiry that contains a program for political action. It prioritizes the national interest and is premised on the idea that the geographic environment has a determining influence on humans. It analyzes power relations between states by focusing on geographic constraints and opportunities for human action. The goal is to maximize the power of one's own state in the quest for global dominance. Although the environmental determinist roots of this type of thinking can be traced back as far as Aristotle, it did not emerge as an established school of thought until the beginning of the twentieth century, a few years after Swedish political scientist Rudolf Kjellén coined the term *geopolitisk* in 1899 (Holdar 1992).

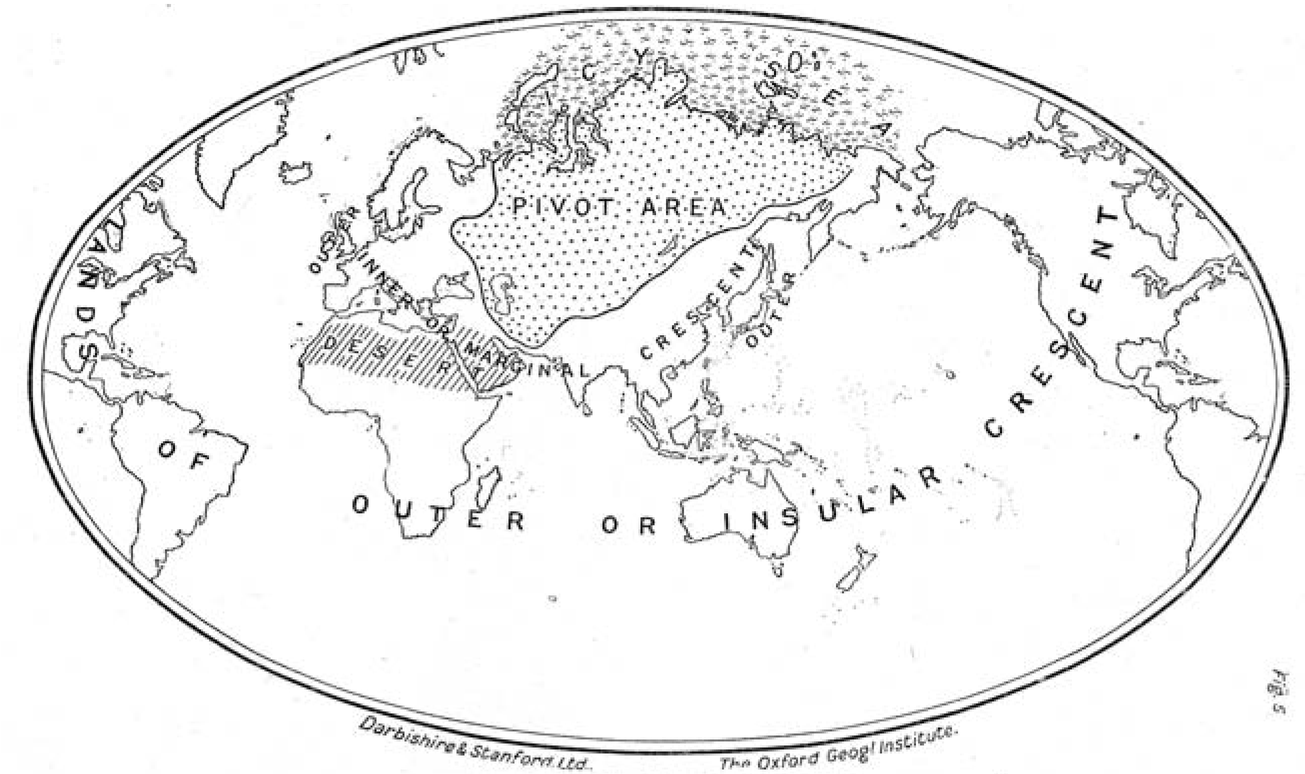
Maps are ideally suited for geopolitical inquiry. First, they make it easy to silence alternative explanations or unwelcome details. Geopolitical representations, sometimes called territorial codes or geographs, provide frames that offer structured explanations of how to interpret the world. Maps help in the constructions of such frames because their symbols impose hierarchies and order. Second, the causal link between environmental condition and human action that geopolitics strives to prove can be suggested in a convincing manner simply by showing spatial covariation of two phenomena. The anthropometric maps of Ellsworth Huntington are good examples (Livingstone 1994, 141–44). Finally, maps have a cloak of scientific respectability and authority due to their association with positivist objectivity and precision as well as with state power (Harley 1988). Geopolitical reasoning needs such legitimation to convince those in power to put concepts in action.

Geopolitics emerged during the intensified competition among states at the end of the nineteenth century. Three factors were key: the general realization that the world was finite, the declining importance of religious explanations, and rapid technological change. The famous scramble for Africa at the Berlin Conference of 1885 drove home the point that the world was finite and that rivalries could no longer be diffused by the discovery of new lands. This new conception of global space set the stage for change, while new nineteenth-century philosophies of evolution and positivism provided the driving ideology and challenged conventional explanations based on an uncritical faith in God. It also added the dire warning of a future struggle grounded in Herbert Spencer's notion of survival of the fittest. Technological change and rapid capitalist industrialization created new means to conquer space, which destabilized the existing balance of power among states. Railroads allowed the faster and more efficient land transportation of not only goods but also massive armies, and steamships offered similar advances for the projection of power across the oceans.

Maps were inherently useful for the development and propagation of early geopolitical concepts. Halford John Mackinder traced the historical ebb and flow of imperial expansion on world maps and identified the key place for global dominance: the heartland. The drainage of rivers to the Arctic underscored the inaccessibility of sea power into this citadel of land power (fig. 323). A. T. Mahan illustrated the control of the Gulf of Mexico and the Caribbean through a triangle that linked the major maritime choke points with the proposed canal across the Central American isthmus (fig. 324). By contrast, Friedrich Ratzel's (1897) concept of the state as an organism, the earliest theoretical conceptualization of the need for state expansion, did not feature such signature maps.

While maps generally accompanied geopolitical texts, especially those directed at a broad audience—for example, Mahan published in the popular magazines *Harper's* and *Atlantic Monthly*—the full potential of cartographic representations for geopolitical concepts was realized only toward the end of World War I. One factor was that geopolitical reasoning acquired a greater urgency in the turmoil of war and especially in the postwar redrawing of the world political map. The second factor was the perceived effectiveness of British wartime propaganda maps spurred by publications such as Campbell Stuart's *Secrets of Crewe House* (1920), which provided detailed explanations of the British propaganda campaign. The two came together for the first time in postwar Germany in a network of geographers and nationalists seeking an effective way to justify a revision of the new boundaries stipulated by the Treaty of Versailles.

Frustrated by the loss of German might, convinced of foreign treachery, and intrigued by British propaganda, German geographer Karl Haushofer and several noteworthy academic collaborators developed a school of thought that came to be known as *Geopolitik*. They communicated through neoconservative publications and institutions such as *Die Grenzboten* and the



THE NATURAL SEATS OF POWER.

Pivot area—wholly continental. Outer crescent—wholly oceanic. Inner crescent—partly continental, partly oceanic.

FIG. 323. HALFORD JOHN MACKINDER'S GEOGRAPHIC PIVOT OF HISTORY.
Size of the original: 12 × 18 cm. From Halford John Mackinder, "The Geographical Pivot of History," *Geographical Journal* 23 (1904): 421–44, map on 435 (fig. 5).

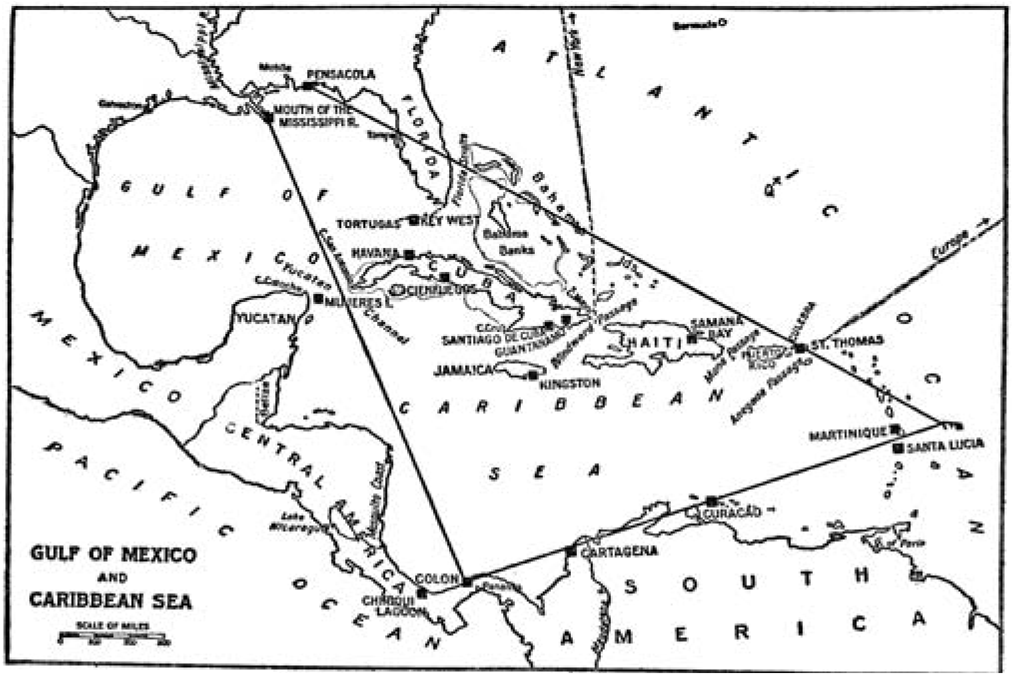


FIG. 324. A. T. MAHAN'S STRATEGIC ASSESSMENT OF THE GULF OF MEXICO AND THE CARIBBEAN.
Size of the original: 8.9 × 13.2 cm. From A. T. Mahan, *Mahan on Naval Warfare: Selections from the Writings of Rear Admiral Alfred T. Mahan*, ed. Allan F. Westcott (Boston: Little, Brown, 1918), 101.

Deutscher Klub in Berlin as well as through secret conferences of academics, politicians, and representatives of the government (Herb 1997, 76–84). Starting in 1924, their central forum became the newly founded journal *Zeitschrift für Geopolitik*.

Followers of this new school of thought believed that *Geopolitik* should offer (1) a better understanding of the geographical constraints on politics and on state power, (2) a thorough study of Germany's fair and correct national territory and its rightful place in world politics, and (3) a convincing presentation of these geographical constraints to educate German politicians and the German people about how to bring about change and restore Germany's status as a world power. Maps were singled out as the most effective means for this purpose, and Haushofer sounded the call for developing a new genre of maps in the early 1920s.

Designed to appeal to the emotions and to exploit psychological principles, these new maps were called "suggestive." Haushofer explained that Germans had not made such maps before because it was not in their national character. "In contrast to the German cartographic representations, the English—because both were a product of the national character, and namely a particularly distinctive one—typified much more and created a more suggestive map image that emphasized the essential and preferably suppressed things that were coincidental or extraordinary; precisely the way England molded its people: individually certainly less attractive and complete, often also less insightful and deep, but more useful for a large and collective purpose: man and map!—life-form on earth and its image" (Haushofer 1922, 17). Even so, Haushofer cautioned that maps could not depict outright lies, which would be easily detected. The key was to omit unwanted detail and to leave out things that did not support the argument. He was convinced that such maps were still truthful and legitimate tools.

Haushofer's suggestion fell on fertile ground. Over the next few years geopolitical maps were widely disseminated through flyers, textbooks, slide lectures, newspapers, journals, books, and even atlases. Dominant themes were the depiction of enemy aspirations (fig. 325), military vulnerability (figs. 326 and 327, and see also fig. 613), different conceptions of national territory (fig. 328), and the spread of German culture (fig. 329). Dissemination of maps was aided by the increased use of illustrations in publications in the early twentieth century and especially by liaisons among publishers and pan-German organizations, such as Volk und Reich, Deutscher Schutzbund, and Verein für das Deutschtum im Ausland (Herb 1997, 88–94).

There was remarkable design conformity in suggestive maps in their bold black-and-white contrast and heavy use of geometric shapes, such as circles, triangles, and especially arrows. The latter was the ideal symbol to express the dynamic character of geopolitical conceptions. Suggestive maps also had clear links to innovations in German graphic design at this time. Arnold Hillen Ziegfeld (1935) advocated the term *Kartographik* for this new type of map in analogy to the new field of *Gebrauchsgraphik* (commercial art). Edoardo Boria (2008, 301–2) argues that geopolitical cartography of the period might even have been influenced by the Italian futurist movement and Otto Neurath's work on visualization.

FIG. 325. GERMAN SUGGESTIVE MAP DEPICTING PLANS BY THE CZECH NATIONALIST HANUŠ KUFFNER FOR THE DISMEMBERMENT OF GERMANY. The categories in the legend are, from the top: (1) the Czech bastion (after Kuffner: mutilated Czech lands), (2) the Czech glacis lands (after Kuffner: the essential extension of the Czech state), and (3) the Czech approaches in the north and south. The map also appeared in other publications.
Size of the original: 11 × 11.8 cm. From Rupert von Schumacher and Hans Hummel, *Vom Kriege zwischen den Kriegen: Die Politik des Völkerkampfes* (Stuttgart: Union Deutsche Verlagsgesellschaft, 1937), 41.

By the early 1930s, suggestive maps were so widely used that Rupert von Schumacher (1934; 1935) felt compelled to develop a theory of design and a grammar of geopolitical symbology. He offered a framework for designing geopolitical maps for two different audiences—scientifically trained readers more tolerant of complexity, and the general public—and presented a catalog of 130 symbols classified under eleven subject headings for topics such as attack, encirclement, and blockade (Schumacher 1935, 256–65). Tellingly, arrows were visually blatant and constituted over one-third of the symbols. The effect of the new design theory is difficult to gauge. It was developed after several key cartog-

FIG. 326. THREAT TO THE GERMAN EAST AND SOUTH-EAST.
Size of the original: 12.9 × 10.5 cm. From Max Hildebert Boehm, *Die deutschen Grenzlande*, 2d ed. (Berlin: Reimar Hobbing, 1930), 309.

FIG. 327. GERMANY THREATENED BY HEAVILY ARMED NEIGHBORS. The title of the map reads: "Who is disarming?"
Size of the original: 7.6 × 10.8 cm. From Albert Ströhle, *Von Versailles bis zur Gegenwart: Der Friedensvertrag und seine Auswirkungen* (Berlin: Zentralverlag, 1931), 113.

raphers, notably Friedrich Lange, Kurt Trampler, Dora Nadge, and especially Ziegfeld, had already developed a unique style and made names for themselves (Herb 1997, 93–94). The theory was as much a survey of past achievements as a new set of rules.

Even though suggestive geopolitical maps were part of a successful strategy to convince the German population of the rightfulness of territorial expansion, Nazi officials were little involved. First, there were conceptual differences between the National Socialist focus on race and the *Geopolitik* emphasis on space (Bassin 1987). Second, the network of *Geopolitik* mapmakers contributed to the National Socialist cause on its own, without significant direct involvement in party or official government endeavors. The Nazis even refrained from employing the most important suggestive cartographer, Ziegfeld, for their wartime map propaganda but recruited him for his experience in having run a publishing firm earlier in his career (Herb 1997, 159–60). This lack of collaboration is further apparent in the Nazi atlas *The War in Maps* (Wirsing 1941), which deviated from the general design practice of geopolitical maps and violated several of the rules of suggestive cartography such as excessive color variation, crude and badly placed lettering, and the use of what Schumacher (1935, 265) had labeled "nonsensical" symbols (Herb 1989, 300).

The success of geopolitical cartography did not go unnoticed in other states. The 1930s maps of the Italian cartographer Mario Morandi, who worked for the journal *Geopolitica*, featured strikingly similar designs of arrows and bold black-and-white contrasts (invoking good and evil). Yet, Italian geopolitical cartography also had distinct features, such as intricate and complex legends and multiple inserts (fig. 330) and the production of atlases for use in schools (Boria 2008). Portugal's geopolitical maps also were part of the genre (Cairo Carou 2006). By contrast, in the United States geopolitical maps were quickly, albeit falsely, equated with Nazi imperialism and discredited as lies and propaganda (Speier 1941; Strausz-Hupé 1942; Quam 1943). This assessment stuck: in addition to heralding a dismissal of geopolitical concepts as well as a decline in political geography as a whole, it also created the false dichotomy of objective scientific maps and propaganda maps, now recognized as fallacious (Crampton and Krygier 2005). The end result was that any map with a captivating message became suspect.

Geopolitical cartography might have gained greater respect in the United States, where, toward the end of the war, a general recognition of the usefulness of maps for education led to important innovations in geopolitical maps. Walt Disney developed sophisticated animated maps for the film *Victory Through Air Power* (United Artists, 1943) to effectively present Alexander P. De Seversky's (1942) new geopolitical concept, air power,

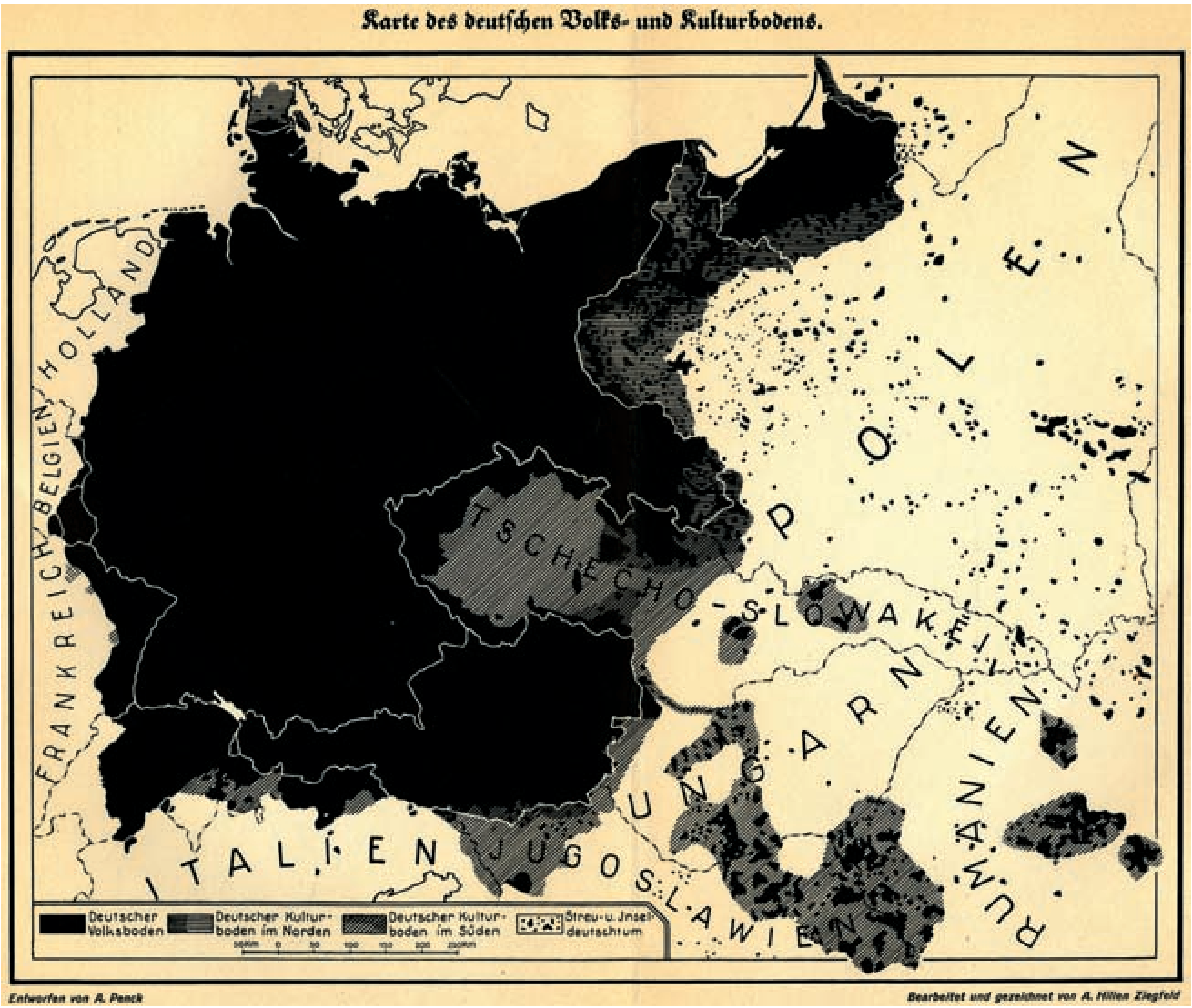


FIG. 328. A NEW CONCEPTION OF NATIONAL TERRITORY THAT MAXIMIZES GERMAN CLAIMS THROUGH THE DESIGNATION OF GERMAN CULTURAL SOIL (*KULTURBODEN*).

Size of the original: 20.6 × 25.8 cm. From Albrecht Penck, "Deutscher Volks- und Kulturboden," in *Bücher des Deutschtums*, vol. 1, *Volk unter Völkern*, ed. Karl C. von Loesch (Breslau: Ferdinand Hirt, 1925), 62–73; map between 72–73.

with arrows sweeping halfway across the globe to strike the industrial center deep in enemy territory. However intriguing, these animated maps disappeared shortly after the war.

Ironically, De Seversky's new geopolitical concept also contained the seeds for the demise of geopolitics. In the air age, with long-distance bombers and nuclear missiles, not even the forbidding terrain and climate of the Artic could constrain military air strikes. Power projection was no longer determined by the configuration of the land but simply by the abstract geometric properties of distance and direction. De Seversky's further development of his concept in the immediate postwar era clearly reveals this: it identified an abstract geometric area of decision circumscribed by the circular reaches of Soviet and U.S. airpower across the North Pole (fig. 331). His map was cast on an azimuthal projection similar to those used by Richard Edes Harrison to vividly describe the global nature of the war against Fascism. But in the 1950s, when De Seversky made his map, the enemy was Communism.

Geopolitics reemerged in the late 1970s, when nuclear parity had made traditional geographic considerations acute for military engagements in different regions and the popularization of geopolitics by Henry Kissinger eclipsed the Nazi stigma (Hepple 1986). Even so, the revitalized geopolitical cartography was comparatively cautious. New conceptions, such as the innovative geopolitics of Yves Lacoste and *Hérodote*, and Colin S. Gray's (1977) update of Mackinder's heartland thesis,

FIG. 329. NATURAL BOUNDARIES AND THE LIMITS OF GERMAN CULTURE IN EASTERN EUROPE.
Size of the original: 16 × 12.6 cm. From Hermann Lautensach, "Geopolitik und staatsbürgerliche Bildung," *Zeitschrift für Geopolitik* 1 (1924): 467–76, map on 472.

which posited that Soviet nuclear submarines could exclude American warships from much of the world, were cautious and rather pedestrian in their use of maps (for example, Foucher 1983, 124–25).

A true revival for geopolitical maps came with the publication of a new generation of geopolitical atlases in the 1980s. Spurred by widespread interest in geopolitics across the political spectrum—in addition to the left geopolitics journal *Hérodote*, which had provided an outlet for Marxist geographers since 1976, a new geopolitics journal on the right, *Géopolitique*, was published starting in 1983 by the pro-NATO Institut International de Géopolitique in Paris—atlases during the first decade took on a decidedly realist approach that exposed nuclear threats and east-west and north-south divisions. The most innovative of these early atlases was Gérard Chaliand and Jean-Pierre Rageau's *Atlas stratégique* (1983), which used a variety of projections, addressed different scales, and even included the spatial perceptions of major global players.

After the end of the Cold War, the orientation of geopolitical atlases became multipolar as new agendas, such as the environment, health, and sexual identity, came to the fore. Yet most atlases remained wedded to the basic tenets of a realist tradition; some were even aggressively neoconservative (Vandeburie 2006). In recent years, the focus has been broadened with a forceful presence of the critically left *L'atlas*: *Le monde diplomatique*, which has been translated into several languages (Gresh et al. 2006).

This more recent prominence of geopolitical atlases must be placed in historical context. While geopolitical maps have a long history that traces back to the end of the nineteenth century and were widely accepted by the end of the twentieth century, they came into their own as a unique genre only during the heyday of German Geopolitik, between the end of World War I and the end of World War II. Claude Raffestin (2000, 11) even went so far as to argue that "all geopolitical cartography has more or less—and often more rather than less—imitated German geopolitical cartography." Deconstructing numerous examples of German maps in light of Schumacher's graphic grammar and Haushofer's conceptual statements, he posited that geopolitical maps are "uchronic" because they seek "to 'smooth' and 'homogenise' all the deposits of history" and "utopian" because they are "not interested in places in terms of their content but instead, as positions, shapes and surfaces." Their goal is to depict the geometry of power by the "application of vector calculus" to politics (Raffestin 2000, 24, 26).

However compelling, Raffestin's argument is limited by its disregard of late-twentieth-century conceptualizations in critical cartography, such as those of Denis Wood (1992). Raffestin's reliance on the standard communications model permitted him to expose the design tricks of German geopolitical maps as well as the intentions behind their creation but prevented him from fully engaging with the larger cultural context of geopolitical cartography. Maps are not mere models of reality that convey unambiguous messages but can be seen as social constructions whose imagery can be interpreted in various and even contradictory ways. Geopolitical maps have to be investigated in the context of human experience and action, not based on their "look or form" (Crampton and Krygier 2005, 17).

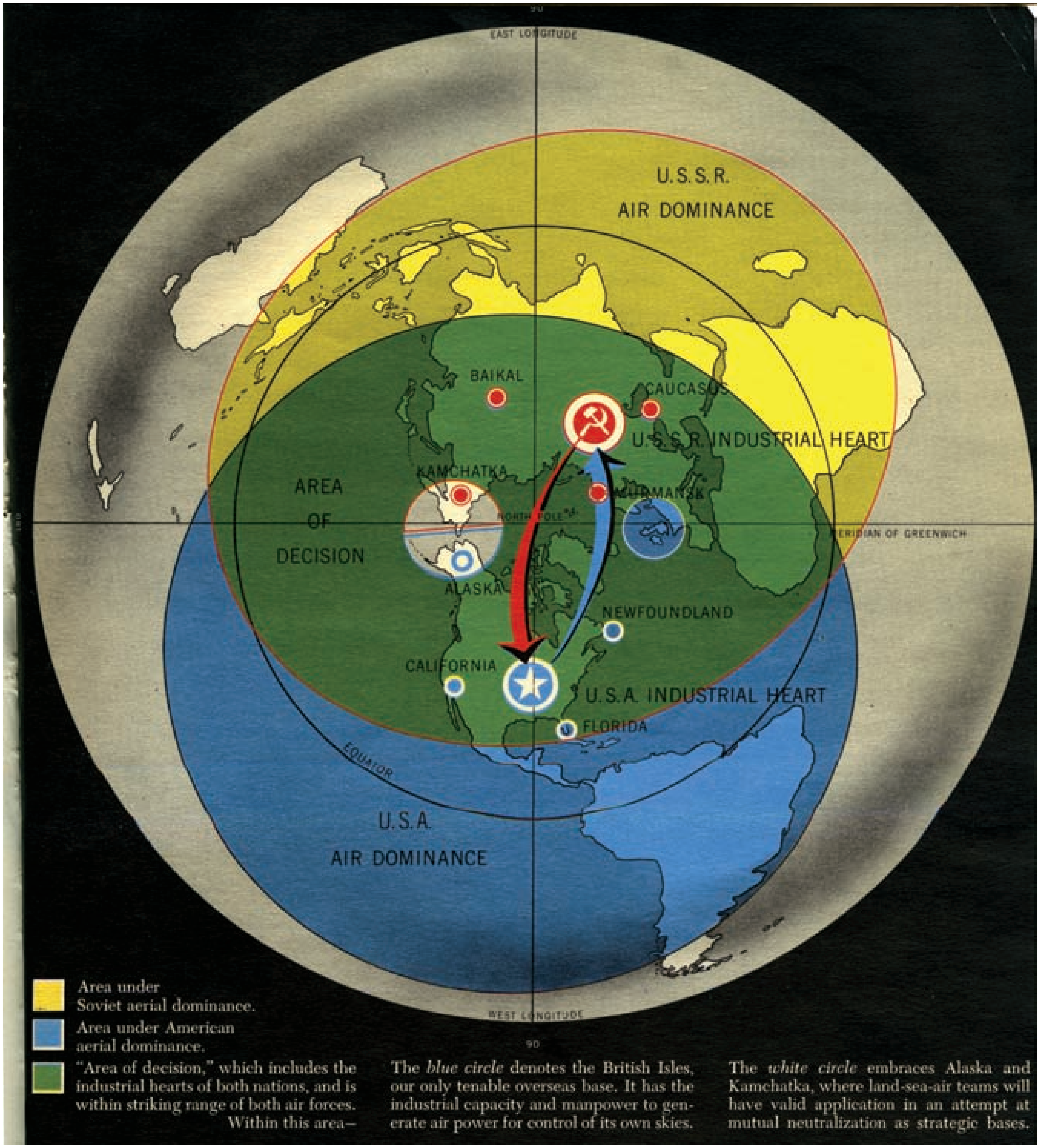
Geopolitical maps are embedded in the cultural context in which they are created. Mapmakers and their audiences operate within a commonly shared value system, and the political program the maps contain builds on already existing aspirations for change. In interwar Germany, these shared values were the belief in the injustice of the Versailles Treaty and the consequent need to revise the borders—values that were shared across the political spectrum. Viewing maps as social constructions reveals that it was not the superior design of suggestive maps that made them effective tools of persuasion, but

FIG. 330. MAP WITH MULTIPLE INSETS. *Sintesi Geopolitiche—N. 6: Il Mar Nero* by Mario Morandi. Size of the original: ca. 21.2 × 13.8 cm. From *Geopolitica* 1, nos. 7–8 (July/August) 1939, 416–17.

that the maps resonated with widely held beliefs in society. Since these beliefs also existed among the Left, it is no surprise that there were even left-wing suggestive maps in interwar Germany (fig. 332).

At the close of the twentieth century geopolitical cartography was marked by atlases with widely differing political viewpoints, from the Far Left to the Far Right. This diversity suggests that democratic societies are perhaps the best guarantee that narrow conceptions will not become dominant tools of persuasion. The fact that geopolitical maps in the early twenty-first century mostly appear as collections in the form of atlases should be considered a positive development: engaging with multiple topics and dimensions makes it more difficult to reduce arguments to simplistic statements. By contrast, the online journal *Heartland: Eurasian Review of Geopolitics* claimed on its web page, in 2008, that geopolitical maps merely illustrate "specific cases, not theories." The future of geopolitical cartography is open. Advances in digital technology, which foster an easier manipulation of data and the incorporation of different media, not only present the danger of technologically dazzling maps that are falsely imbued with added authority but also offer an opportunity for public participation and a democratization of the mapping process.

GUNTRAM H. HERB



🟨 Area under Soviet aerial dominance.

🟦 Area under American aerial dominance.

🟩 "Area of decision," which includes the industrial hearts of both nations, and is within striking range of both air forces. Within this area—

The *blue circle* denotes the British Isles, our only tenable overseas base. It has the industrial capacity and manpower to generate air power for control of its own skies.

The *white circle* embraces Alaska and Kamchatka, where land-sea-air teams will have valid application in an attempt at mutual neutralization as strategic bases.

FIG. 331. ALEXANDER P. DE SEVERSKY'S AIRMAN'S VIEW.
Size of the original: 22.4 × 20.3 cm. From Alexander P. De Seversky, *Air Power: Key to Survival* (New York: Simon and Schuster, 1950), map between 110–11.

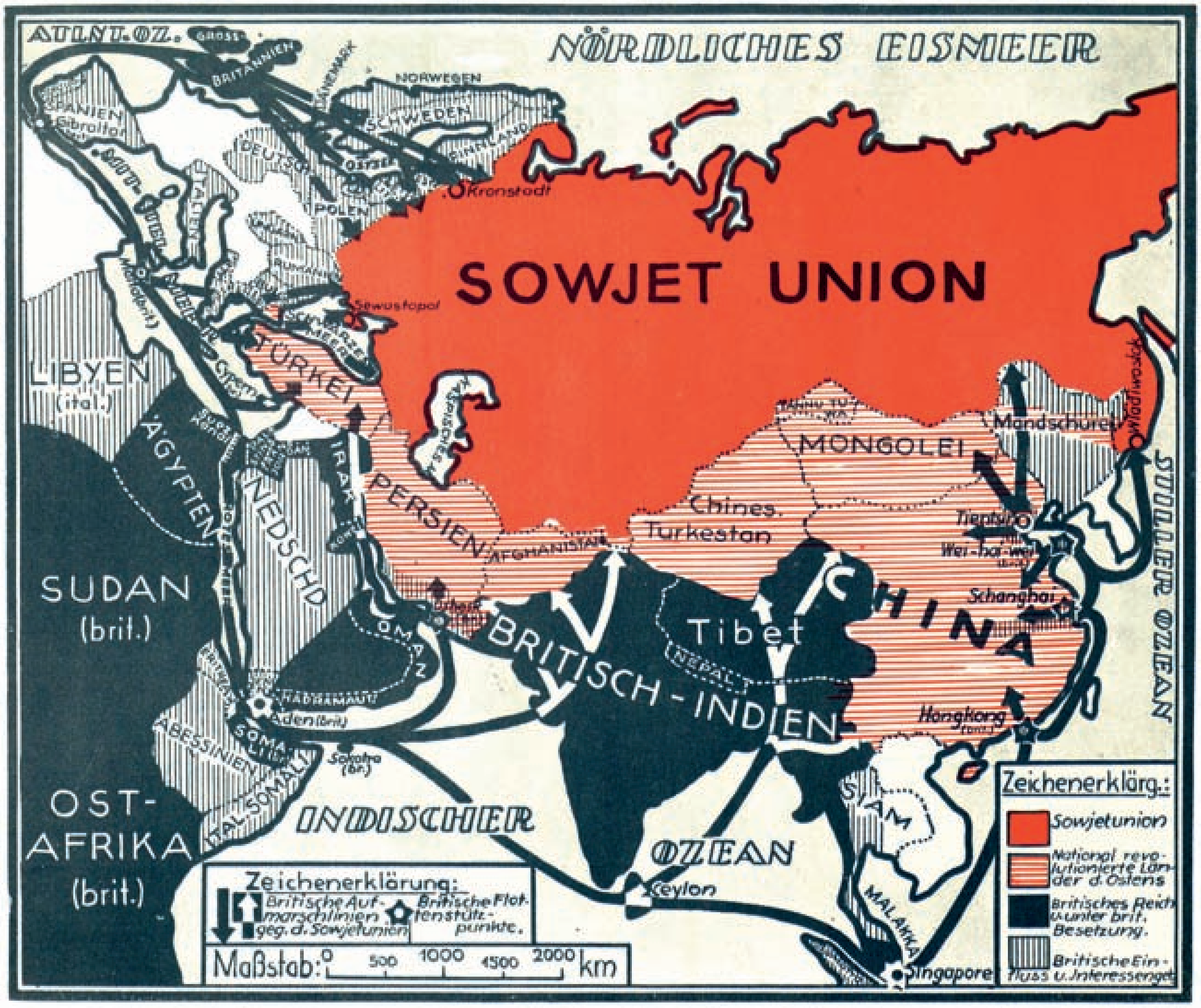


FIG. 332. THE GERMANS IN CENTRAL EUROPE. Size of the original: 21.9 × 26.1 cm. From Sándor Radó, *Atlas für Politik, Wirtschaft, Arbeiterbewegung: I. Der Imperialismus* (Vienna: Verlag für Literatur und Politik, 1930; reprinted Gotha: Haack, 1980), 91. © Ernst Klett Verlag GmbH, Zweigniederlassung Gotha.

SEE ALSO: Air-Age Globalism; Cartographic Duplicity in the German Democratic Republic; Cold War; Colonial and Imperial Cartography; Geographic Names: Social and Political Significance of Toponyms; Harrison, Richard Edes; Nation-State Formation and Cartography; Russia and the Soviet Union, Fragmentation of

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GEOSPACE Beckel Satellitenbilddaten GmbH (Austria). GEOSPACE Beckel Satellitenbilddaten GmbH is a private Austrian research, publishing, and service company. It was founded in 1984 in Bad Ischl, Austria, by Lothar Beckel, an Austrian geographer who had used aerial photographs since 1967 for his geographical research. Beginning in 1972, when the first Earth Resources Technology Satellite, ERTS 1 (later renamed Landsat 1) was launched by NASA (National Aeronautics and Space Administration), Beckel was also involved scientifically in the evaluation and application of EOSAT (Earth Observation Satellite Company) image data. In 1994 GEOSPACE relocated to Salzburg.

Established during the beginning phase of commercialization of satellite data, GEOSPACE became the Austrian distributor for Spot Image (France) and EOSAT (United States). Its role was to develop the Austrian remote sensing market, to provide information and data to potential national users, and to evaluate data for government administration, industry, and education. GEOSPACE became involved in applied research using remote sensing data from satellite images and GIS (geographic information systems). GEOSPACE also became one of the national players in earth observation, participating in many national research projects frequently carried out in cooperation with national research institutions. It also took part in various Framework Programme projects of the European Union, cooperating with international organizations and universities. It worked closely with the ESA (European Space Agency) and with NASA. Those connections continued into the twenty-first century.

In the decade after 2000, GEOSPACE was working on data acquisition by satellite imagery for the support of relief activity during floods and for studying dynamic phenomena like precipitation in the tropics and its relationship with vegetative land cover. GEOSPACE undertook conversion of data from land observation satellite systems—SPOT (Satellite Pour l’Observation de la Terre), Landsat, IRS (Indian Remote Sensing Satellite), ERS-1/ERS-2 (European Remote Sensing satellite), Radarsat, NOAA (National Oceanic and Atmospheric Administration), Meteosat—to images and cartographic products in near-natural color. Satellite data were classified for applications in a number of fields, including plant sciences, hydrospheric and earth sciences, land use, and land cover. Particular areas of activity were satellite image mapping, environment, alpine security, forestry and agriculture, health, cultural heritage, and education.

GEOSPACE made its products available in both printed and digital formats. Its publishing line grew to include satellite image maps (e.g., of Lower Austria, Styria, the Alps, Switzerland), satellite image books and atlases of various countries, and digital atlases on CD-ROM and DVD. Examples include *Die Erde neu entdeckt: Farbige Satelliten-Fotos* (1975), *Österreich im Satellitenbild* (1976), *Österreich-Satelliten-Bild-Atlas* (1988, updated ed. 2004), *Österreich: Ein Porträt in Luft- und Satellitenbildern* (1996), and the *European Space Agency School Atlas* (2007). Satellite image atlases on CD-ROM offered the possibility of generating three-dimensional views of landscape in true time and of navigating through different landscapes. A special GEOSPACE product was a satellite aeronautical chart of Germany (six sheets, 1:500,000); additional products included city guidebooks of Vienna, Linz, Graz, and Salzburg. Altogether more than 150 publications and studies offer proof of the continuing accomplishments of GEOSPACE.

INGRID KRETSCHMER

SEE ALSO: Remote Sensing: Remote Sensing as a Cartographic Enterprise

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Gerrymandering. See Electoral Map

Glavnoye upravleniye geodezii i kartografii (Chief Administration of Geodesy and Cartography; Russia). Throughout the history of the development of geodesy and cartography in Russia, all work to provide primary geodetic and cartographic base information was managed by state agencies. Although the state geodetic service was not established until 15 March 1919 by decree of the Sovet narodnykh kommissarov, or Council of People's Commissars, preliminary discussions had begun in Russian intellectual circles and especially in the Imperatorskoye Russkoye geograficheskoye obshchestvo in the 1880s. In 1916, at the general meeting of the Imperatorskoye Rossiyskaya Akademiya nauk, academician Vladimir I. Vernadskiy summed up previous discussions and laid the scientific foundations and main guidelines for the state geodetic service (Postnikov 1988).

From the beginning, the activities of the Vyssheye geodezicheskoye upravleniye (VGU; see table 18 for the organization's name changes) were connected with those of the Voyenno-topograficheskaya sluzhba (the military topographic service). The geodetic and cartographic activities of both agencies were coordinated by the permanent council board of the military topographical branch of the Red Army's general headquarters, which was established by a 30 May 1925 decree of the Soviet Council of People's Commissars and the Voyenno-revolyutsionnyi sovet. On 21 April 1940 special guidelines were approved to coordinate topographical, geodetic, and cartographic activities conducted by the Glavnoye upravleniye geodezii i kartografii (GUGK) and the ministry of defense and navy. Those guidelines empowered the GUGK to map all the territories of the Soviet Union except for areas within ten kilometers of naval bases, military installations of the coast guard, state borders, and "the Special Regions" under the jurisdiction of the ministry of defense. The latter had to be surveyed by military topographers and navy hydrographers. First-order triangulation, first- and second-order leveling, and first-order astronomical observations became the responsibility of the civil geodetic service, with the ministry of defense controlling all the GUGK's activities that had military importance. All military and civil surveys and mapping had to conform to the general rules and programs developed by the GUGK and be coordinated with the ministry of defense. Subsequently, instructions and accuracy standards were developed to provide uniform topographic materials and maps. In 1951 a special meeting of high officials from the civil and military topographical agencies finally codified these standards and instructions.

The VGU did not start active work until as late as 1922 or 1923. The agency's evolution reflected the power struggles between the different Bolshevik factions and leaders of the period. In 1922 there was even an attempt to disband the young agency altogether (Komedchikov 2000, 5–8). The attempt failed and the special scientific-technical council of the VGU under Feodosiy Nikolayevich Krasovskiy generated new theoretical and methodological foundations for topography and geodesy in the country. At first, due to the Civil War

TABLE 18. As the names of the Glavnoye upravleniye geodezii i kartografii (GUGK) changed during the twentieth century, so did its form and functions

1919–23	Vyssheye geodezicheskoye upravleniye (VGU) (Higher Geodetic Administration)
1926–28	Geodezicheskiy komitet (Geodetic Committee)
1928–30	Glavnyi geodezicheskii komitet (Chief Geodetic Committee)
1930–32	Glavnoye geodezicheskoye upravleniye (Chief Geodetic Administration)
1933–35	Glavnoye geologo-gidro-geodezicheskoye upravleniye (Chief Geological-Hydrological-Geodetic Administration)
1935–38	Glavnoye upravleniye gosudarstvennoy s"ëmki i kartografii (GUGSK) (Chief Administration of State Survey and Cartography)
1938–91	Glavnoye upravleniye geodezii i kartografii (GUGK) (Chief Administration of Geodesy and Cartography)
1991–92	Komitet geodezii i kartografii (Glavkartografiya) (Committee for Geodesy and Cartography)
1992–2004	Federal'naya sluzhba geodezii i kartografii Rossii (Roskartografiya) (Federal Service for Geodesy and Cartography of Russia)
29 July 2004–	Roskartografiya (Department of Geodesy and Cartography of the Russian Ministry of Transport and Construction)

and other needs of the Bolsheviks, the VGU was unable to organize any new surveys of Russian territory and compile the necessary topographical maps. As a result, Soviet cartographers had to depend on prerevolutionary cartographic materials. They continued to reprint the most important military topographical maps (with scales of 1, 2, 5, and 10 versts [1 verst = 1.07 kilometers] to one inch) and military communication maps using old printing plates.

After the official change to the metric system, the VGU began to compile new topographical maps in the metric system, using old sources but changing the map symbols. In the nineteenth century, printed maps with scales larger than 1:420,000 covered only a minor part of the European Russian territory. To make matters worse, the results of some of the surveys of the time were not published. The administrators at the Soviet cartographic service decided to finish those works and publish them using new symbols and the metric system. The so-called General Mende's surveys were the most imposing unfinished Russian cartographic project of the nineteenth century. The surveys, which began in 1848 under the supervision of Lieutenant General Aleksandr I. Mende, represented the first coordinated efforts by the country's main topographical and geodetic services to create a universal topographical map meeting the needs of a broad range of users. The majority of the maps and detailed geographical descriptions drawn up as part of that program remain at the Russian state archives, Rossiyskiye gosudarstvennyye arkhivy, in manuscript form (Postnikov 1989, 150–55). By 1926 Soviet cartographers had published some 790 sheets of topographical maps at the scale of 1:100,000 using Mende's manuscript materials and a few new surveys. In 1929–30, in order to facilitate the introduction of new technology in geodesy, air survey, and cartography, the Soviet state geodetic survey initiated active contacts with the U.S. Coast and Geodetic Survey and with such private American firms as Brock & Weymouth in Philadelphia.

By the late 1930s, it became obvious that the topographic surveying and mapping of the country was far from fulfilling the demands of the developing economy. Two categories of large-scale mapping were envisaged under a 1938 plan. The first category included not only European Russia, but also the parts of the Soviet Union under the exclusive control of the Gulag (the main administration of prisoners' camps). Depending on the significance of a given region, the mapping was to be performed at the scale of 1:10,000, 1:50,000, 1:100,000, 1:200,000, or 1:500,000. By 1941 only a few regions had been surveyed in accordance with the project. Nevertheless, Soviet cartographers achieved some real successes. Detailed and up-to-date atlases such as the five-volume atlas of industry, *Atlas promyshlennosti SSSR* (1928–31), the *Atlas Moskovskoy oblasti* (1933), the *Atlas Leningradskoy oblasti i Karel'skoy ASSR* (1934), and the two volumes of the *Bol'shoy sovetskiy atlas mira (BSAM)* (1937–40) were produced and their value acknowledged at the Exposition Internationale des Arts et Techniques dans la Vie Moderne in Paris in 1937, where the *BSAM* was awarded the Grand Prix.

World War II had taught the Soviet leadership a lesson concerning basic large-scale cartography. Learning from that lesson, Joseph Stalin decreed that the first priority for the military and civil state topographical services after the war was a survey of the entire territory of the Soviet Union in preparation for a 1:100,000-scale topographic map. That project, completed in 1954, was grandiose. The map was based on air surveys performed in the remote regions of Siberia and the Russian Far East, using relatively sparse points of astronomic geodetic control. The network of those control points was adjusted by phototriangulation. The national topographic map project had nothing to do with providing ordinary consumers with quality large-scale maps. A map at the scale of 1:100,000 fell into the category of secret materials and could not be used even as a source for any general-purpose map.

Large-scale maps for ordinary consumers had to be compiled using the 1:2,500,000-scale map of the Soviet Union, with relevant parts enlarged to the needed scale. In that way tourist maps and maps of administrative units (such as regional and oblast maps), usually compiled at the sale of 1:600,000, showed only the most general data for main towns, villages, and roads. Even special road maps and atlases for tourists contained no information as to whether the roads were paved with macadam or were stone or dirt.

Limitations on Soviet cartography were relaxed only after *perestroika*. In 1989 the Voyenno-topograficheskaya sluzhba of the General Staff and the GUGK began to publish dependable maps for sale to ordinary consumers and for use in business, industry, and agriculture. The maps were at the scale of 1:200,000 and smaller. They were based on topographic maps stripped of military and other information deemed confidential (Lyutyy and Komedchikov 1999, 21).

During its nearly ninety years of activity the GUGK has provided the country with a high-precision geodetic control network in a uniform coordinate system. The net includes some 370,000 control points evenly distributed over the country's territory. A high-precision leveling network was developed for continental Russia, providing it with heights in the Baltic System. The first-class gravimetric network with a density of one measurement per 100,000 square kilometers was created. In the early twenty-first century it was being developed and updated for the whole country. By then Russia had been fully covered with topographic maps at scales from 1:25,000 to 1:1,000,000, while 1:10,000-scale maps were available for 25 percent of Russian territory. The GUGK mapped all towns, settlements, and industrial areas at scales of 1:5,000 to 1:2,000 and sometimes larger.

By the end of the century the right of the state to manage geodesy and cartography and to name geographical features had been fixed in the constitution of the Russian Federation. The legal foundations of geodetic and mapping activities were set forth in the Federal Act on geodesy and cartography. The responsibilities of Roskartografiya were as follows: coordination of geodetic and cartographic activities of the subjects of the Russian Federation with a view to pursue a single technical policy and avoid duplication in geodetic and mapping works financed by the federal budget, the budgets of the subjects of the Russian Federation, and local budgets. It was also responsible for the organization and execution of geodetic and cartographic works of federal and departmental significance, geodetic and cartographic works ordered by the state authorities of the Russian Federation, self-management bodies, and private individuals.

Roskartografiya had grown by the early twenty-first century to include twenty aerial-survey geodetic establishments (AGE), three topographic mine-surveying establishments, six geoinformational centers (two of which were a part of aerial geodetic establishments), three mapmaking facilities, the cartographic production association Kartografiya, two optico-mechanical plants (one of which was a part of an AGE), the Tsentral'nyy nauchno-issledovatel'skiy institut geodezii, aeros"yëmki i kartografii (TsNIIGAiK), the Gostsentr Priroda, nineteen territorial departments (which are responsible for inspections) for state geodetic supervision, the Tsentral'nyi kartografo-geodezicheskiy fond, the Gosudarstvennyi kartograficheskii i geodezicheskii tsentr, and four secondary specialized educational establishments (colleges). Departments of Roskartografiya were located in various cities and regions of the Russian Federation, and their production capacities were distributed territorially, each aerial geodetic establishment servicing a certain locality in the Russian Federation within which it worked and was responsible for the level of topographic and geodetic information. Geoinformational centers were situated in each region. Roskartografiya had become the principal executive authority in the field of geodesy and cartography and geographical names.

ALEXEY V. POSTNIKOV

SEE ALSO: Geodetic Surveying: (1) Europe, (2) Russia and the Soviet Union; Moskovskiy institut inzhenerov geodezii, aerofotos"yëmki i kartografii (Moscow Institute of Geodetic Engineering, Aerial Photography, and Cartography; Russia); Topographic Mapping: Russia and the Soviet Union

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Global Positioning System (GPS). The Navstar Global Positioning System (GPS) is a multipurpose satellite system developed by the U.S. Department of Defense in the early 1970s. It was primarily designed to provide all-weather real-time spatial coordinates anywhere on (or near) the earth for use in navigation. These coordinates are typically accurate to about ten meters, but with enhancement can be accurate to less than a millimeter. Other countries have pursued similar systems—the Soviet Union's GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema) was also developed during the 1970s, while the European Union's Galileo and China's Compass systems are both scheduled for the 2010s—but Navstar GPS has been by far the most prominent, and for most nonspecialists "GPS" is simply a generic name for a device that provides precise geographic location.

GPS is of central importance to the history of geographic knowledge in the late twentieth century, and the pace of the GPS revolution has been staggering. When the United States used GPS during the Persian Gulf War in early 1991—its first major test—receivers numbered in the thousands, equipment was in short supply, and its military applications made newspaper headlines. By 2010 there were roughly one billion GPS receivers in use around the globe, and only a tiny fraction of these were deployed by the American military. The diffusion of GPS technology thus brought many of the themes of postwar cartography into the everyday lives of commuters, scientists, farmers, and even teenagers: the ubiquity of maps and map knowledge, the transition from static paper maps to dynamic electronic mapping, and the ambiguous status of dual-use military/civilian technology.

Since the impact of GPS on property surveying and personal navigation is addressed in other entries, the goal here is to evaluate the wider cultural-political importance of GPS as a ubiquitous spatial technology. After first explaining the design and subsequent evolution of the system, the rest of this entry analyzes the various uses of GPS since it first began functioning in the mid-1980s. There are two ideas to be addressed in particular: first is the common assumption that GPS is an inescapably military system; second is the countervailing idea that GPS is a neutral technology with no inherent politics. Both these approaches, however, overlook key features of its history. GPS does indeed enable certain kinds of interventions and not others, but its politics are defined less by the military/civilian divide than by a certain approach to local knowledge.

Designing a Universal System

Construction of Navstar GPS was initially approved by the U.S. Department of Defense in late 1973. The overarching goal was to replace the variety of electronic navigation systems then in use—most of which could be used only in specific areas for specific tasks—with a single, global system. The more immediate goal was to supersede the first-generation satellite navigation system known as Transit, which had been designed by the U.S. Navy in the late 1950s for targeting submarine-fired nuclear missiles. Transit was perfectly adequate for this task, and was widely used for geodesy and civil-marine navigation as well, but coordinates could be calculated only once every few hours, and results were strictly two-dimensional and unreliable on fast-moving vessels (Williams 1992, 238–39; Parkinson et al. 1995). By the mid-1960s both the U.S. Air Force and the Navy were pursuing second-generation projects that could give continuous three-dimensional positioning. GPS combined these various proposals into a joint project that would satisfy all military requirements at once.

The basic idea behind GPS was relatively straightforward. A successful GPS fix relies on precise distance measurements between a receiver and multiple satellites. These measurements are made using signals continually broadcast from each satellite that give its precise location and the time when the signal was sent. Since the signal travels at roughly the speed of light, computing distance just requires knowing how long the signal took to reach the earth. What this means, however, is that all GPS clocks must be synchronized to within a few nanoseconds, since a time error of just 1 millisecond would mean a coordinate error of nearly 300 kilometers. Every GPS satellite is thus equipped with an atomic clock accurate to about three seconds over a million years. Because the clocks in most receivers are not nearly this accurate, usually four satellites are used to solve for four unknown values—three for distance and one to synchronize receiver time with satellite time. Precise timekeeping is so important that in many contexts the entire GPS system can be reduced simply to "clocks in space" (Pace et al. 1995, 204).

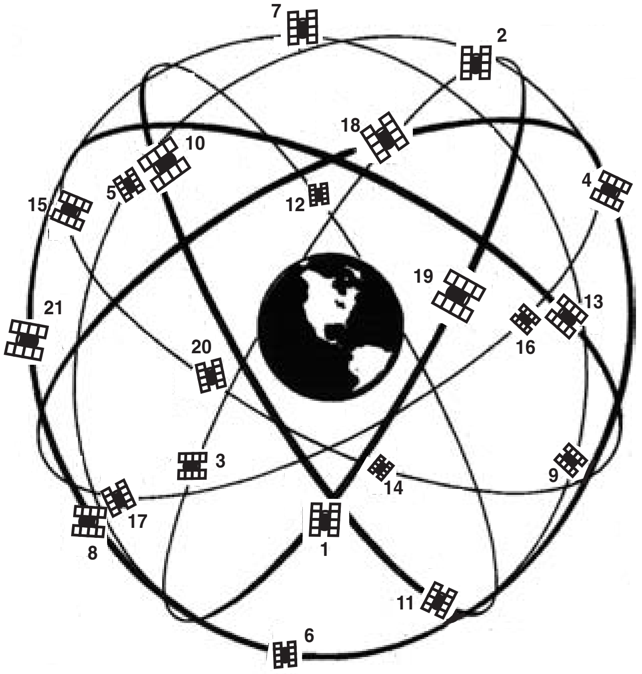

FIG. 333. BASIC DESIGN DIAGRAM OF THE GPS CONSTELLATION. This mid-1980s configuration shows eighteen primary satellites and three spares, but the final constellation has included as many as thirty-two operational satellites.
After R. L. Beard, J. Murray, and J. D. White, "GPS Clock Technology and the Navy PTTI Programs at the U.S. Naval Research Laboratory," in *Proceedings of the Eighteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting* (N.p., 1986), 37–53, esp. 50 (fig. 1).

For engineering purposes, GPS was divided into three segments: the satellites themselves, control stations to monitor the satellites, and user equipment. The first—the space segment—was designed as a constellation of nearly identical satellites in very similar orbits. The governing requirement for the arrangement of satellites was to have at least four visible in the sky everywhere on earth at all times. Figure 333 shows the basic design of the constellation as of the mid-1980s: the satellites are in medium earth orbit about 20,000 kilometers above the earth, completing one orbit roughly every twelve hours. Each is about the size and weight of a car (fig. 334) and powered primarily by solar panels. The satellites have a finite lifespan, and new satellites must be launched periodically to replace those that fail.

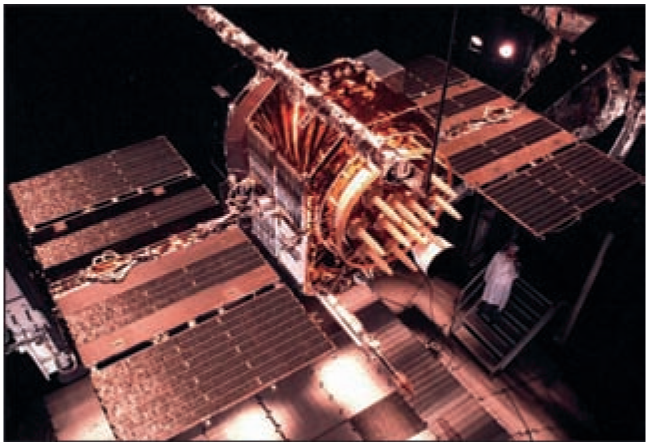

FIG. 334. TESTING A BLOCK II GPS SATELLITE, 1985. The size of the satellite is indicated by the person standing lower right.
Image courtesy of the Arnold Engineering Development Center, Arnold Air Force Base.

The control segment is composed of a number of fixed receiver stations that track the satellites as they pass overhead. These stations are crucial for ensuring the reliability of GPS coordinates, since the accurate broadcast of each satellite's location requires predicting how its orbit will be affected by factors like high-altitude gases and the earth's gravity field, and these predictions are not always correct. Actual measured satellite paths are thus continually processed to give new orbit-prediction data, which are subsequently uploaded to each satellite along with ongoing clock synchronization. In the Cold War–era 1970s, the main consideration for siting ground stations was that together they should provide as much tracking coverage as possible while still being located on U.S. military bases (fig. 335).

Finally, the user equipment segment was designed to include a great variety of receivers, from multiantenna sets built into aircraft to portable receivers powered by batteries. The most important engineering distinction was between military and civilian equipment. Civilian uses were taken into account from the beginning (and were crucial for maintaining adequate funding from the U.S. Congress), but the military wanted to be able to deny GPS to unfriendly forces if necessary and to restrict the use of GPS for high-accuracy targeting. GPS satellites were thus designed to transmit signals on two frequencies at once, one of which is encrypted for military use. Not only could the civilian signal be turned off in wartime, but access to both signals also enables direct correction of the effects of the earth's ionosphere, thereby giving authorized users an accuracy advantage.

Given how closely these parts are interrelated, it is difficult to identify any single feature that sets GPS apart from earlier systems, and apportioning credit for its design has been controversial. The main contest has been between two leaders of proto-GPS projects from the 1960s. The leader of the Navy's Timation project, Roger L. Easton, has argued that "the GPS invention" was using space-based atomic clocks to measure distance (Easton 2005). In contrast, the director of the Air Force's Project 621B, Bradford W. Parkinson, who subsequently went on to lead GPS in the 1970s, has instead identified the GPS signal structure—an early use of a code division multiple access (CDMA) signal—as the "keystone technology" (Parkinson and Powers 2010, 31). Not surprisingly, these are exactly the technologies that had been pursued by the Navy and the Air Force, respectively. Easton and Parkinson have both been awarded medals as the "inventor" or "father" of GPS, but the intractability of their dispute over its key innovation suggests that assigning a definite inventor is not a useful exercise. GPS was a synthetic project both technologically and bureaucratically, and GPS-like ideas can be found in both satellite and terrestrial precedents as early as World War II. The creation of GPS, like most complex technical systems, was more a question of engineering and project management than groundbreaking novelty.

Since the initial design of the system in the early 1970s, most of its basic features have changed only slightly. GPS satellites, for example, have been made more robust, and the constellation has been tweaked in response to budget fluctuations. Similarly, beginning in 2005 several new ground stations, generally sited on non-U.S. land, were added to the tracking network to allow constant monitoring by at least three receivers simultaneously. GPS signals have likewise been modified as policies for civilian and military capabilities have changed. After discovering that early civilian receivers were more accurate than expected, the military began intentionally degrading the civilian signal. But this practice—known as Selective Availability—was discontinued in 2000, and later satellites were designed to broadcast using additional frequencies to improve both civilian and military accuracy alike (Lazar 2002).

The combined effect of these changes, however, has been relatively minor compared to the impact of the radical miniaturization and falling price of user equipment. Figure 336, for example, shows the change in the size of portable military receivers between 1978 and 2004. Not only did they become smaller and lighter, but the later equipment also began displaying electronic maps rather than just raw coordinates. Civilian receivers likewise transformed from specialist instruments to mass-market commodities complete with small color map display screens and up-to-date digital maps. The

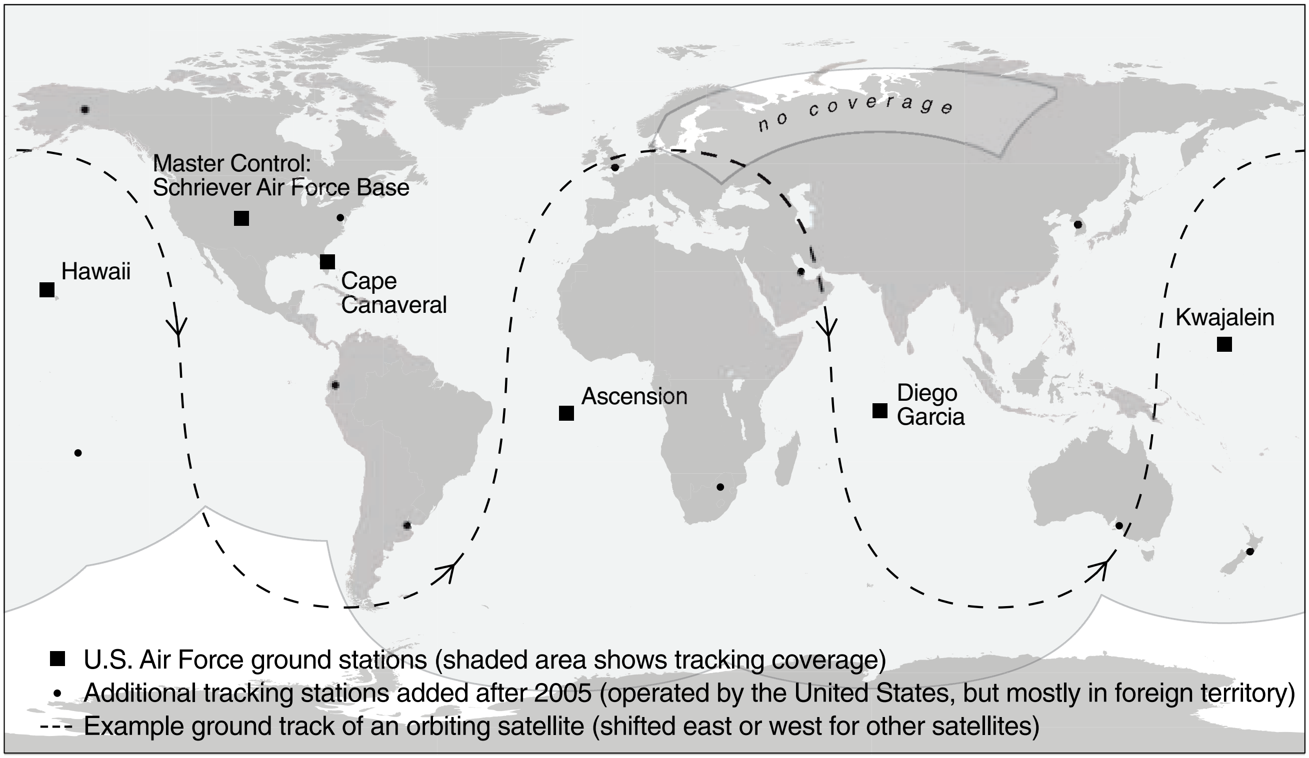

FIG. 335. MAP OF GPS TRACKING STATIONS. Uniform global GPS coordinates still rely on the particular political-physical geography of the earth, since satellites must be continually monitored from a network of ground stations. Image courtesy of William J. Rankin.

FIG. 336. GPS RECEIVERS IN THE FIELD, CA. 1978. In 1973 the designers of GPS had hoped to eventually produce a portable military receiver weighing less than twelve pounds (5.5 kg). The Manpack of 1978 (left) weighed 14 kilograms, while the Defense Advanced GPS Receiver (DAGR) of 2004 (right) weighed about 400 grams and fit comfortably in the hand. Left, from Lazar 2002, 45; permission courtesy of the Aerospace Corporation, Los Angeles. Right, image courtesy of the National Museum of American History, Smithsonian Institution, Washington, D.C.

FIG. 337. FIRST GPS WRISTWATCH, PRO TREK. Sold by Casio in 1999 for $895; ten years later GPS watches were no larger than their non-GPS counterparts and cost just over $100.
Size of the watch body: 6.5 × 6.5 cm.

cost of an entry-level receiver fell from $1,000 to $100 between 1992 and 1997, and the smallest receiver in the early 2000s was the size of a wristwatch (fig. 337). Even the most optimistic predictions in the 1980s for the diffusion of GPS turned out to be far too conservative (Kumar and Moore 2002, 69, 79).

This ubiquity has had a profound effect on the way GPS has been understood. Rather than being seen just as a positioning and navigation technology, beginning in the mid-1990s GPS began to be described as new kind of public utility, alongside electricity, gas, and water (Pace et al. 1995, 184). The product to be delivered was location, and the marginal cost was essentially zero. One of the most common analogies was between GPS and the Internet, as both were sponsored by the U.S. military and eventually transformed into open platforms (Aporta and Higgs 2005). The basic idea here was that forecasting GPS's future uses—or even providing a comprehensive list of current ones—became essentially impossible. More conceptually, however, the larger implication was that GPS should not be seen as simply a tool for making geographic space legible. Rather, GPS became a replacement for traditional space (and time) altogether. Both the spaces of day-to-day experience and the spaces constructed by representational maps were superseded by a space that was more immediately calculable, less historical, and almost perfectly uniform (Kurgan 1994; Rankin 2011).

The Uses (and Abuses) of GPS

The history of GPS after it first became operational is largely a history of how it has been used. The major trends are relatively clear: civilian applications quickly outnumbered military uses, and GPS became tightly integrated into other systems of communication and geographic management. Evaluating the impact of these trends, however, is less straightforward, as the social consequences of GPS have been wide-ranging, often unanticipated, and at times contradictory. The recent history of GPS thus raises questions relevant to any history of infrastructure: With the transformation of GPS into a multiuse utility, what is gained and what is lost? Who wins and who loses? Two issues are especially important here: the relationship between civilian GPS and its military origins and the politics of action at a distance.

Two of the most significant early uses of GPS were in cartography and war. The surveying industry began to adopt GPS in the mid-1980s while the constellation was still incomplete. Its effect was profound. GPS not only solidified the decades-long transition from traditional astronomical and angular methods to black-box electronic equipment, but it further untethered surveying from the geography of national states. The widespread use of the GPS world datum (WGS84) enabled everything from cross-border engineering projects to reliable measurement in international waters, and it became a de facto standard for global geographic information systems (GIS) platforms. More broadly, GPS signaled a shift in the very nature of mapping. As the tools of mapping merged with the tools of navigation, it became increasingly difficult to distinguish mapmaking from map use. The famous tales by Lewis Carroll and Jorge Luis Borges about maps on the same scale as the territory thus apply quite well to GPS, since using GPS for fishing management, offshore drilling, or coordinating archaeological sites is effectively mapping at a scale of 1:1. GPS is used both to make a record of important points and to return to them; traditional mapping problems of selection and representation need not arise at all (Rankin 2011, 440–51).

The impact of GPS on military strategy was no less decisive. During the Persian Gulf War, GPS lowered the cost of precision bombing and enabled large-scale troop coordination in the featureless Iraqi desert, both of which gave the U.S. a substantial advantage. After the war GPS quickly became a core component of a "precision revolution" in American strategy that prioritized smaller, more mobile, and more technologically advanced forces. GPS also changed the geography of war, since GPS-guided missiles and bombers can be launched thousands of miles from their target. The dream—unrealized, to be sure—is to remove soldiers from the battlefield altogether (Rip and Hasik 2002).

The multiplication of civilian GPS applications in the 1990s and 2000s largely followed these precedents of automation and tighter geographic coordination, but the mass commercialization of GPS also raised entirely new issues. Most of the best-known uses of GPS had been under development since the early 1980s, such as automobile and aircraft navigation, close control of farm equipment for precision agriculture, or the direct measurement of tectonic plate drift. The use of GPS for time synchronization—in cell phone networks, power grids, or even municipal stoplights—also extended earlier techniques. But in the late 1990s several applications began to proliferate that had not been anticipated and did not sit easily within traditional descriptions of GPS as a positioning, navigation, and timing (PNT) system. Foremost among these was the use of GPS for tracking (of wildlife, criminals, children, or cargo) and amateur mapping by artists and activists. These applications have provoked the most debates about the nature of GPS, raising questions of civil liberties, privacy, and the democratization of cartography.

There have been primarily two ways that scholars have interpreted the spread of civilian GPS. First is a pessimistic assumption that GPS is an inherently military technology and that its widespread use represents the militarization of civil society. The strongest versions of this argument claim that GPS (along with its cousin, GIS) has created a cultural obsession with precision so pervasive that techniques of military targeting end up blending seamlessly into practices like targeted marketing. Not only has GPS turned American consumers into "militarized subjects" (Kaplan 2006, 708), but the integration of GPS into everything from cell phones to traditional hunting practices will "deliver American militarized realities" abroad as well (Mark H. Palmer and Robert Rundstrom in Aporta and Higgs 2005, 748). A less forceful version of this interpretation also drove much of the debate in the early 2000s about competition between GPS and the European Union's civilian (and partly commercial) Galileo system. Many observers, from American pundits to foreign heads of state, distrusted claims that a system maintained by the U.S. military would remain reliably accessible, despite high-level assurances (Han 2008).

The second interpretation—often explicitly opposed to the first—instead posits GPS, and technology in general, as an inherently neutral tool that can be used either for good or for evil, regardless of its origins. Optimistic scholars tend to emphasize the usefulness of GPS for things like tracking endangered species, clearing landmines, or the rapid mapping of Haiti after the 2010 earthquake (fig. 338). Optimists also stress that although GPS can be used for top-down surveillance by police or employers, it can also be used for bottom-up "sousveillance" to hold governments accountable, such as when marginalized citizens use GPS for reporting broken street lights in New Jersey or mapping informal settlements in Kenya. Even advanced missile guidance has its good side, since surgical strikes on infrastructure obviate the senseless killing of area bombing (Klinkenberg 2007).

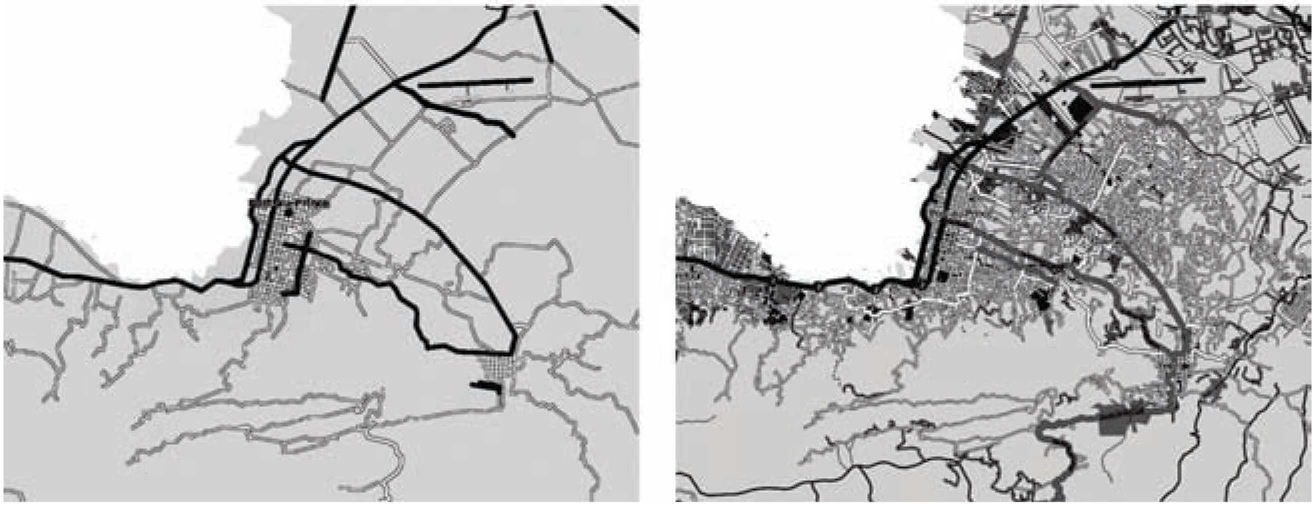

FIG. 338. RAPID HUMANITARIAN RESPONSE USING GPS. Coverage of Port-au-Prince, Haiti, by the collaborative project OpenStreetMap before (left) and two days after (right) the 2010 earthquake.

Image courtesy of William J. Rankin.

Belief in technological neutrality also undergirds certain kinds of pessimism as well. Jerome E. Dobson and Peter F. Fisher, for example, have issued strong warnings about the coming mass-surveillance society and the potential for a new "geoslavery" enabled by coercive GPS tracking. For them, the worry is not the military, or even GPS itself, but its exploitation by unscrupulous corporations and individuals; arguing that technology is neutral is important rhetorically for defending GPS against these abuses (Dobson and Fisher 2007; Herbert 2006).

There are good reasons to challenge military essentialism. Claiming that technology is inherently neutral, however, is no less problematic. Certainly, the assumption that military-sponsored technology can only further militarist goals is empirically unfounded. Yet it is also true that every technology is inevitably designed for certain tasks and not others and therefore is prejudiced with specific capabilities and constraints. Technological systems are also always being modified to further privilege some uses over others. Military pessimists tend to simplify this history to confirm their suspicions; technological neutralists, however, tend to overlook it altogether. Neutralism can also be rather fatalist. Saying that technology inevitably has both positive and negative social effects can easily imply that any attempt to steer the course of technological progress will prove futile.

For GPS, both its initial design and its ongoing evolution suggest that a different interpretation is necessary. First, GPS was explicitly designed so that it could serve more than just military interests. One of the basic military requirements in the late 1960s was that it use only one-way broadcast from satellites to users rather than two-way communication. The latter would have been technologically simpler, but any ground transmission could be used by the enemy for tracking and targeting. For this reason, civilian agencies—especially the Federal Aviation Administration and the National Aeronautics and Space Administration (NASA)—initially expressed little interest in GPS and instead proposed systems that would broadcast users' locations back to a satellite to enable active air traffic control or ship monitoring. These systems also would have only supported a limited number of receivers at once (Stansell 1971, 107). In other words, it was precisely the involvement of the military—and its lack of neutrality—that made GPS an open system that could support unlimited nonmilitary users, with features like privacy and anonymity prioritized over tracking and surveillance.

Second, by the early 2000s the military had decisively lost much of its control over GPS, after a long struggle with civilian agencies and corporations. Not only had President Bill Clinton annulled the military's Selective Availability policy, but the governance of GPS was changed so that top-level responsibility was shared between the Departments of Defense and Transportation. Even more important was the civilian development of local and regional augmentation systems to increase accuracy and reliability (fig. 339). These systems had effectively thwarted Selective Availability in the 1990s, and because they were used for life-critical applications like harbor and air navigation, they likewise drastically reduced the military's ability to disable the civilian signal in wartime (Pace et al. 1995, 20–27). The very existence of these ongoing technological and policy changes make it difficult to see GPS as neutral, and again military interests tended to align with individual privacy, since similar augmentation systems have enabled some of the most Orwellian GPS applications, such as indoor tracking (Trimble 2003).

If GPS is neither inherently militaristic nor inherently neutral, what is it? The answer need not be so grandiose. The key conceptual feature of GPS is that it replaces lumpy, historical, human space with a globally uniform mathematical system. By extension, the central political fact about GPS is that it substitutes a locally available grid of geographic coordinates for other kinds of local knowledge and encourages intervention without local commitment. This intervention can be initiated from afar—precision bombing, humanitarian relief, GPS tracking—or it can be projected outward, as with activist mapping. In all cases, however, the goal is to encourage action and to bridge the political divide between center and periphery. This has been the goal of most official mapping from the sixteenth century forward, but the relationships GPS constructs are much less mediated, since GPS is not a technology of representation. GPS can also be wielded by almost anyone, not just institutions with massive resources. The relevant political distinction is therefore not between state and nonstate, military and civilian, or even good and bad, but between local and nonlocal decision making. And thus with GPS the basic political question, as ever, is not what or how, but by whom.

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SEE ALSO: Cold War; Cruise Missile; Geodesy: Satellite Geodesy; Hydrographic Techniques: Global Positioning System in Hydrographic Mapping; Property Mapping Practices: Global Positioning System and Property Surveying; Warfare and Cartography; Wayfinding and Travel Maps: In-Vehicle Navigation System

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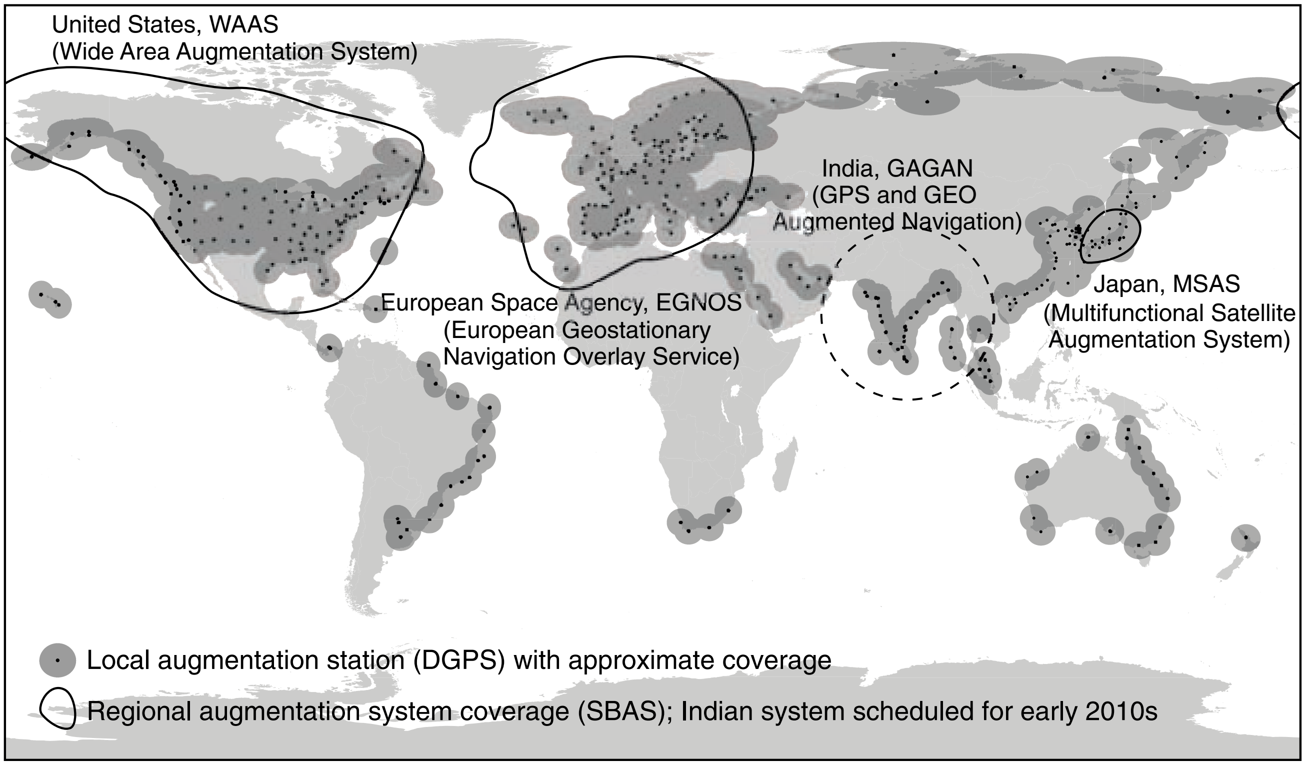

FIG. 339. MAP OF REGIONAL AND LOCAL AUGMENTATION SYSTEMS; COVERAGE AS OF 2010. In response to military degradation of civilian GPS signals, competing government agencies and companies (especially the U.S. Coast Guard, NASA, Federal Aviation Authority, Fugro, and John Deere) began providing Differential GPS (DGPS) and Satellite-Based Augmentation System (SBAS) services in the 1990s; these systems increase accuracy by monitoring raw GPS signals and broadcasting real-time corrections.
Image courtesy of William J. Rankin.

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Globe.

CULTURAL AND SOCIAL SIGNIFICANCE OF GLOBES
MANUFACTURE OF GLOBES
VIEWS OF EARTH FROM SPACE

Cultural and Social Significance of Globes. Globes representing the earth, the sky, and the moon have played significant roles in the context of society and culture in the twentieth century. This entry makes a strict distinction between globe instruments, intended as problem-solving devices, and terrestrial and celestial spheres, intended for representation. It covers only rack-mounted globes, which usually feature a graticule or map image, as well as their two-dimensional and three-dimensional reproductions.

In addition to their role as scientific instruments and teachings aids, terrestrial and celestial globes have long been important as symbols and signs. In pictures as well as three-dimensional spherical models, globes have been an integral part of the allegorical language of Western culture: the terrestrial globe as a symbol of the earthly and the ephemeral and the celestial globe as a symbol of the cosmos, the infinite universe, the eternal, and the divine. In these roles, globes have not only symbolized the power, status, and wealth of sovereigns and world leaders but also represented the knowledge and professionalism of geographers, cartographers, mapmakers, astronomers, navigators, explorers, and world travelers.

In the twentieth century, geopolitics and economic globalization further enhanced the significance of terrestrial globes. While the traditional symbolism of globes was apparent throughout the century, the sociocultural context was in flux. As the importance of globes as scientific instruments declined, their symbolic meaning changed as well, particularly for terrestrial globes (including reproductions and replicas), as the globe became largely a sign of global activity, open-mindedness, or interest in science and education. And around midcentury a new meaning emerged when the terrestrial globe became a symbol of world peace.

Because of a dearth of relevant scholarly studies, insights into the cultural and social significance of globes must rely heavily on indirect or less formal sources, including scholarly research on globes as commercial products, analyses of globe producers' advertisements and promotional literature, and essays on globes displayed publicly in lobbies, plazas, and other public settings. In addition to studies of the role and meaning of two-dimensional and three-dimensional reproductions and replicas of globes in diverse contexts, further evidence for the social importance of globes can be found in dictionaries and encyclopedias. Indeed, the words "globe" and "global" embody much of the cultural significance of globes in the twentieth century.

The importance of globes in the sociocultural context of the twentieth century is closely associated with their visibility—in particular, as representational objects linked in the public's imagination to important personalities and institutions—as well as with the globe's importance as a commercial product. After all, the greater the number of globes produced and disseminated, the greater their role in culture and society, and the greater the impact of reproductions and replicas of globes as symbols and signs.

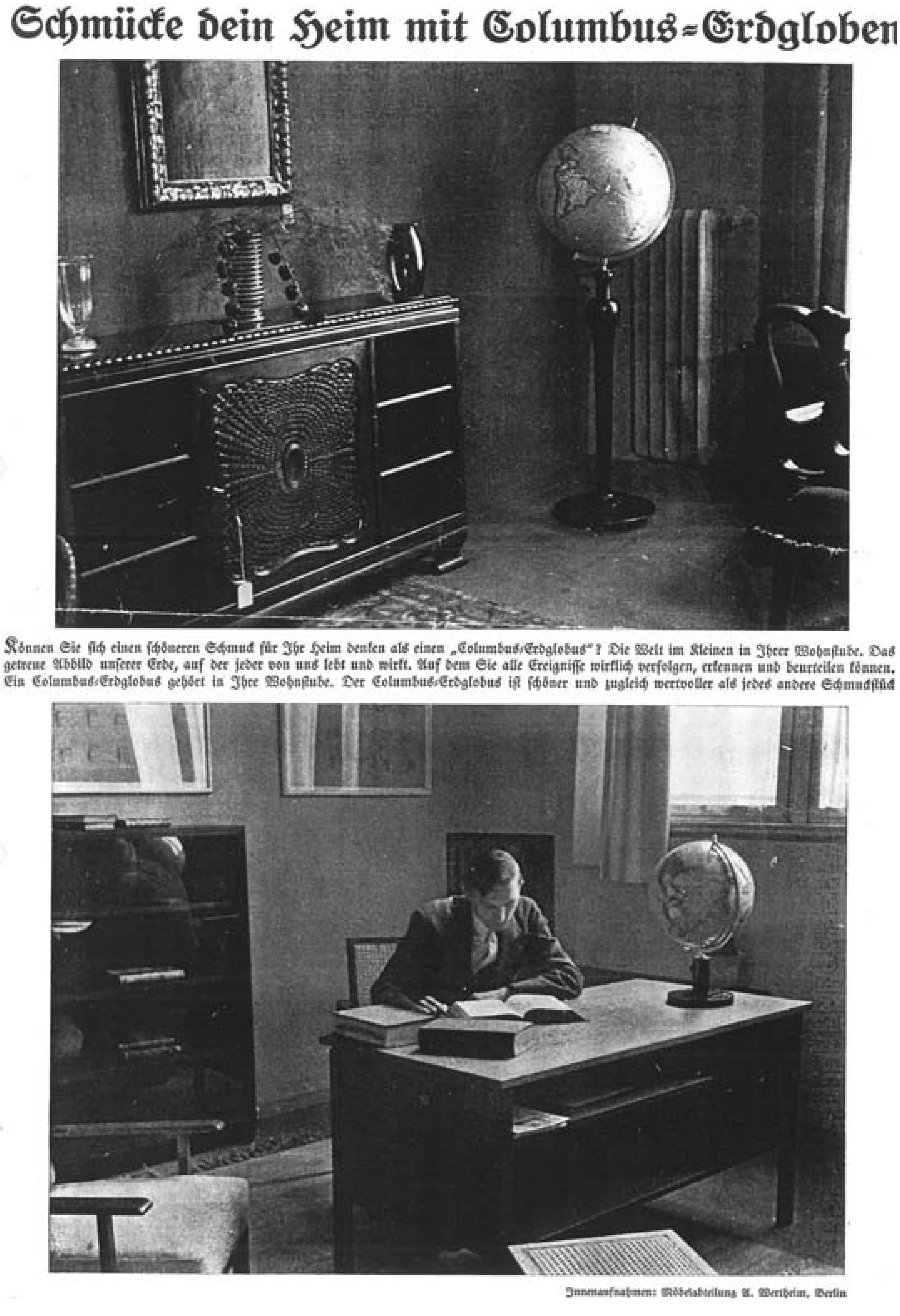
In the late nineteenth and early twentieth centuries, globe instruments, especially terrestrial globes, were primarily used as teaching tools in schools and as decorative accessories in private and semiprivate living and work areas (fig. 340). Indeed, in schools and colleges as well as in better-educated middle-class households, the globe was as commonplace as an encyclopedia or a world atlas. During that period, globes were also used as furnishings in dollhouses, and manufacturers who offered a wide range of globe products expressly advertised their smallest versions as "dollhouse globes."

During the first half of the century a huge number of globe instruments, especially terrestrial globes, were manufactured in Europe and the United States. Producers in the United States successfully counteracted the standardized and inexpressive map images of these mass-produced instruments by making a variety of versions, differentiated by mounts ranging from the simple to the highly elaborate.

Terrestrial globes attained their greatest importance in society and geopolitics in the 1930s with the development, production, and marketing of the elaborately designed *Großglobus für Staats- und Wirtschaftsführer* (large globe for state and business leaders), produced in different representative mount variations by the Berlin-based Columbus-Verlag Paul Oestergaard. These globes were as large as 106 centimeters in diameter and attained a total height of 165 or 175 centimeters, depending on the size of the mount.

During the second half of the century, the importance of globes as educational tools declined and by century's end was almost negligible. This decline—understandable insofar as the globe was now perceived as an expensive, bulky version of a minimally detailed small-scale world map—had a direct impact on the role of globes as successful commercial products. As a result, a marked reduction in the number of globes produced went hand in hand with the consolidation of manufacturing firms, and the relevance of globes (including reproductions and replicas) as symbols and signs in the societal context diminished as well. Even so, electronic technology introduced other scientific tools and media, such as cartographic animations and the interactive virtual globe, which had symbolic meaning and perpetuated the notion of the globe as a sociocultural concept. Despite this diminished sociocultural importance, two-dimensional images of globes had become increasingly prominent on posters, stamps, poster stamps, bookplates, coins, banknotes, securities, and corporate logos, while three-dimensional reconstructions served a symbolic function, particularly in public places.

During the second half of the nineteenth century and the first half of the twentieth century, huge globes were mounted atop or adjacent to important buildings such as railway stations, post offices, telegraph offices, hotels, department stores, travel agencies, newspaper publishers, and chambers of industry and commerce.



Schmücke dein Heim mit Columbus-Erdgloben

Können Sie ſich einen ſchöneren Schmuck für Ihr Heim denken als einen „Columbus-Erdglobus“? Die Welt im Kleinen in Ihrer Wohnſtube. Das getreue Abbild unſerer Erde, auf der jeder von uns lebt und wirkt. Auf dem Sie alle Ereigniſſe wirklich verfolgen, erkennen und beurteilen können. Ein Columbus-Erdglobus gehört in Ihre Wohnſtube. Der Columbus-Erdglobus iſt ſchöner und zugleich wertvoller als jedes andere Schmuckſtück

Innenaufnahmen: Möbelabteilung A. Wertheim, Berlin

FIG. 340. *DECORATE YOUR HOME WITH COLUMBUS TERRESTRIAL GLOBES*, CA. 1935. Advertisement in a brochure of the Berlin-based Columbus-Verlag Paul Oestergaard for globes as home and office furniture. Top: rack-mounted globe, 50-centimeter diameter; bottom: table globe, 34-centimeter diameter. From *Jubiläumskatalog* (Berlin: Columbus-Verlag, 1934), 14. Image courtesy of Jan Mokre. Permission courtesy of Columbus Verlag Paul Oestergaard, Krauchenwies.

FIG. 341. LE GRAND GLOBE CÉLESTE AT THE EXPOSITION UNIVERSELLE IN PARIS, 1900. The huge celestial globe had a diameter of 46 meters and rested on a construction of four masonry piers. Inside it was a second celestial globe with a diameter of 36 meters, and within that globe was a terrestrial globe with a diameter of 8 meters. Visitors could pay an additional fee and, using a spiral staircase in the terrestrial globe, climb up to the North Pole and look at the sky, which was painted on the inside of the second celestial globe.
Image courtesy of the Brooklyn Museum Archives, Goodyear Archival Collection.

Additionally, globes were added as three-dimensional elements to sculptures, monuments, and tombs, particularly those commemorating cartographers, astronomers, navigators, and world travelers.

Huge globes were often erected at world exhibitions and other venues where size was an emblem of achievement. The 1900 Paris Exposition Universelle featured a 140-foot-diameter celestial globe accessible from the inside (fig. 341), and the 1964–65 New York World's Fair at Flushing Meadows Park included a twelve-story steel terrestrial globe. In the United States in particular, large globes have been placed in the lobbies of prestigious newspaper offices and prominent railway stations and airports. Babson College (renamed from Babson Institute in 1969), a business-oriented college in Wellesley, Massachusetts, is known locally for its 28-foot-diameter outdoor globe, built in the mid-1950s by founder Roger Ward Babson. The structure had deteriorated by the late 1980s, but when administrators announced plans to tear it down, outraged alumni raised funds for its restoration, completed in 1993 (fig. 342). In 1998 the DeLorme Company unveiled a 41.5-foot-diameter indoor globe adjacent to its factory and map store in Yarmouth, Maine. Nicknamed Eartha, the *Guinness Book of Records* (2001) proclaimed the DeLorme globe as the world's biggest revolving globe. Despite the globe's decreased presence in homes and classrooms, these examples as well as the recurrent use of globes in advertising highlight the continued cultural importance of globes the twentieth century.

Three distinctly twentieth-century phenomena ran counter to the declining cultural and social significance of the globe. First, prominent people from diverse sectors of society were photographed with globes. There exist, for example, several portraits of U.S. President Theodore Roosevelt during his presidential terms (1901–9) with a large terrestrial globe (almost 80 cm diameter), perhaps taken in view of his active foreign policies (fig. 343). Second, globes appeared in feature films and television dramas as furnishings in middle-class homes much more commonly than in reality, even at the end of the century. The traditional popularity of globes as symbols of learning and affluence survived in the fantasies of mass media set designers. Third, lunar globes achieved a brief prominence from the early 1960s through the early 1970s, when the United States and the Soviet Union faced off in an epic race to the moon. Within a short time, manufacturers were producing large quantities of lunar globes—scientific and commercial—as well as similarly shaped tin toys, souvenirs, money boxes, and other knickknacks. These attracted great interest: for the first time, the cartographic representation of the backside of the moon was possible, and the landing sites of planned and successful space expeditions were represented on lunar globes. Official photographs from the National Aeronautics and Space Administration (NASA) often juxtaposed American astronauts and lunar globes (fig. 344).

Virtual globes based on digital data and programming emerged in the final decade of the twentieth century following the development of the digital world atlas, itself a reflection of slightly earlier advances in interactive graphics and personal computing as well as the development of massive worldwide data sets, including environmental and historical data. The user could rotate a two-dimen-

FIG. 342. THE BABSON WORLD GLOBE. George C. Izenour designed the enormous globe, with a diameter of 28 feet. The idea came from Roger Ward Babson's grandson, Roger Webber. It was erected on the campus of the Babson Institute and dedicated in 1955. The sphere, which rotates using a motor, is made of steel with enameled steel panels fastened on it; they represent the earth's surface in twenty different colors. Photograph 2005.

Image courtesy of Babson College, Babson Park.

sional image of a globe to any position and then zoom in so that the horizon was no longer visible, while the projected globe became merely a projected map.

Despite the diminished importance of contemporary globes, old globes enjoyed increased interest as collector's items, as reflected in sales and auction catalogs, their presence in major public and private collections, and an increase in scientific studies on globes. Particularly significant was the emergence of a scholarly institution focused on globes. The International Coronelli Society for the Study of Globes, founded in Vienna in 1952, has fostered the scientific study of globes as a distinct cartographic expression, and its journal *Der Globusfreund: Wissenschaftliche Zeitschrift für Globenkunde*, initiated the same year, provided an outlet for scholarly papers on globes, their producers, and their significance. An English-language version, *Globe Studies: The Journal of the International Coronelli Society*, began in 2002.

JAN MOKRE

SEE ALSO: Colonial and Imperial Cartography; Projections: Cultural and Social Significance of Map Projections; Visualization and Maps

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FIG. 343. THEODORE ROOSEVELT, FULL-LENGTH PORTRAIT, WITH LARGE GLOBE IN THE BACKGROUND, AT THE WHITE HOUSE IN 1903.
Image courtesy of the Library of Congress, Prints and Photographs Division, Washington, D.C.

FIG. 344. ASTRONAUT JOHN W. YOUNG WITH A LUNAR GLOBE, 1971. Young, a participant in the U.S. space missions Gemini, Apollo, and the first space shuttle, was the ninth man to walk on the moon as commander of Apollo 16 in 1972.
Image courtesy of NASA/Johnson Space Center.

2d ed., ed. William Cartwright, Michael P. Peterson, and Georg F. Gartner, 255–66. Berlin: Springer.

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Manufacture of Globes. During the twentieth century, globemakers in Europe and the United States produced conventional terrestrial and celestial globes as well as replicas of Mars, Venus, Mercury, and Earth's moon. This entry focuses on the serial, or mass-market, production of globes that adhere to a discernible scientific standard. It thus ignores metal toys or globe puzzles as well as single-piece globes crafted individually for a specific client or special purpose.

At the beginning of the twentieth century, globes were produced by gluing together two hollow papier-mâché hemispheres. A gypsum-like paste was applied to the surface of the sphere and sanded down after drying. Then a world map, which was reproduced lithographically and typically consisted of twelve spherical bi-angles and two polar caps, was glued or laminated onto the sphere. Subsequently, the globe was covered with a protective coating and equipped with an axis.

Because globes had already lost their standing as scientific instruments by the middle of the nineteenth century, manufacturers did not bother to fully outfit globes with a horizontal circle, meridian circle, altitude quadrant, hour hand, and compass. Instead, they mounted the globe on a simple frame, typically consisting of a base plate and a center column. In many cases, the globe was fitted with a metal meridian circle that featured degree counts or with a half meridian circle.

Beginning in the 1910s, the manufacture of hollow hemispheres was shifted to hydraulic presses, which produced very smooth surfaces and made the gypsum layer obsolete. The world map was now directly laminated onto a cardboard sphere. Gradually, more modern and efficient industrial reproduction methods replaced lithographic map printing.

In the 1930s, some manufacturers in the United States implemented a mechanical, hydro-press method for producing cardboard globes. This method glued maps with a special projection screen for the northern and southern hemispheres onto cardboard disks, which were then cut out mechanically to create surfaces shaped like pinwheels, with sharply angled isosceles triangles meeting at the center (North or South Pole). These cardboard disks were then molded in a press, under intense heat and pressure, to produce hollow hydro-pressed hemispheres. The northern and southern hemispheres were then clipped at the edges, glued together to form a sphere, coated with a protective coating, and mounted on a frame.

In the 1920s globe manufacturers introduced translucent globes illuminated by electricity. The world map was printed on transparent paper and glued or laminated onto a hand-blown, hollow glass sphere into which a light bulb was fitted. This type of globe production experienced a revolutionary improvement in the 1950s, when the globe map was printed on both sides using a complex procedure. Depending on whether or not the globe was illuminated, it showed either a physical or a political map.

From the 1950s onward globes were more commonly produced using plastic rather than glass, and by the end of the century plastic had largely displaced cardboard as the basic material for mass-produced globes. Three different production methods were used for plastic globes. The simplest method followed the traditional approach of gluing segments of a map printed on paper or plastic film onto a hollow plastic sphere. The second method required special map projections for the Northern and Southern Hemispheres; the maps were printed on circular pieces of plastic film, which were subjected to a thermoplastic process that combined thermoforming with injection molding and simultaneously produced Northern and Southern Hemispheres, which were then joined into complete a sphere (fig. 345). A third production method entailed mechanically mounting films with cartographic images onto previously molded hollow plastic spheres. In addition to the traditional format, plastic globes were manufactured as illuminated globes, sometimes with changing images.

Relief globes were also manufactured in the twentieth century. Initially they were crafted by hand, the traditional method, by modeling the terrain in a gypsum-like paste on the outside of a cardboard sphere with the vertical dimension typically exaggerated, sometimes for dramatic effect. From the 1940s onward, machine-shaped terrain segments were commonly glued onto a plastic sphere. In the second half of the twentieth century, earth-relief globes were produced using mechanically pressed hemispheres made of cardboard as well as plastic. The first mass-produced earth-relief globe featuring both terrain and seabed profiles in three dimensions was introduced in 1990.

Magnetic levitation globes were introduced in the late 1980s. In this special design, a combination of permanent magnets and computer-controlled electromagnetic levitation keeps the globe in balance and rotates it about the axis. These globes represent the final stage of development of analog globes.

A completely new development emerged toward the end of the twentieth century. Virtual globes based on digital data and computer software can be displayed on flat or spherical screens, reproduced as holograms, or accessed interactively online. These three-dimensional models of the planet can show not only static or animated representations of current patterns, such as surface weather, but also historical events, such as explorations, warfare, and boundary changes. When equipped with zoom-in and pan functions, virtual globes afford a seamless integration of the globe with intermediate- and large-scale maps.

FIG. 345. GLOBE PRODUCTION AT COLUMBUS-VERLAG. Globe hemispheres are produced by a combination of thermoforming and injection molding. Hemisphere being removed from the machine (left) and stacked (right).

Image courtesy of Columbus-Verlag, Krauchenwies.

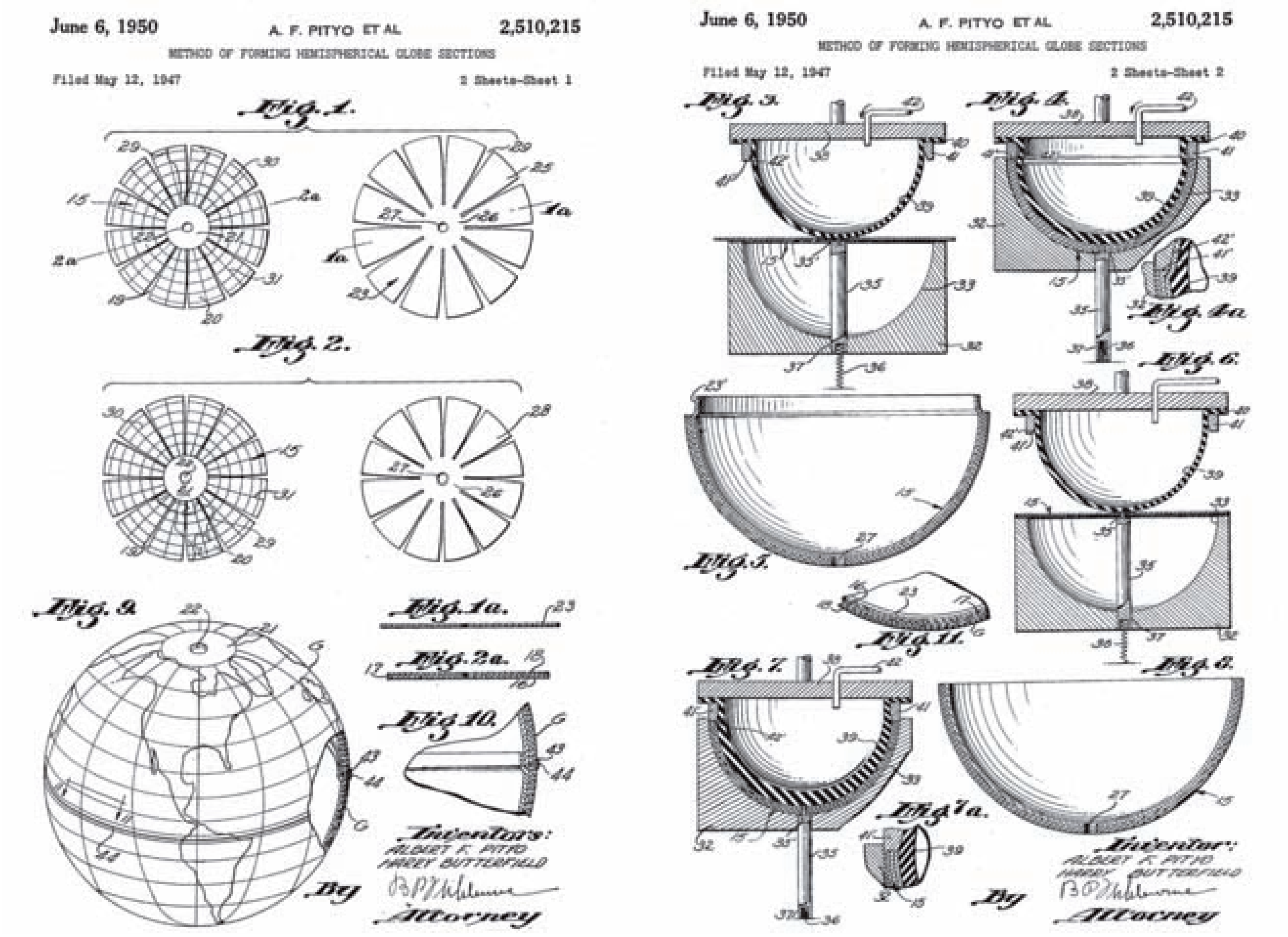

FIG. 346. ARTWORK SUBMITTED FOR THE METHOD OF FORMING HEMISPHERICAL GLOBE SECTIONS PATENT. U.S. Patent 2,510,215, filed 12 May 1947 by Albert F. Pityo and Harry Butterfield, and awarded 6 June 1950. These illustrations describe the globe sections for the northern and southern hemispheres as well as a perspective view and "enlarged fragmentary vertical section" of the assembled globe, produced by a compression apparatus also described in the application.

Except for occasional reviews and product announcements as well as scholarly essays on the presentation of large, specially designed globes to world leaders like U.S. President Franklin D. Roosevelt, British Prime Minister Winston Churchill, and Soviet Premier Joseph Stalin, the cartographic and geospatial literature says little about the design and production of globes in the twentieth century. By contrast, patent records offer useful insights into manufacturing practices and the creativity of inventors (fig. 346).

JAN MOKRE

SEE ALSO: Marketing of Maps, Mass

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Views of Earth from Space. Outer space is generally defined as space more than 100 kilometers (62.1 miles) away from the earth's surface. Obtaining images of earth from space in the twentieth century was a monumental conceptual and technological achievement. These images provided unprecedented regional perspectives of land use/land cover and biophysical processes, and the related data resulted in new cartographic products, including detailed image maps of the earth and animations for processes as varied as tracking hurricanes, monitoring urban expansion, and measuring seasonal changes in biomass. In addition, geographic information about remote places on the planet became available.

The first aerial photograph was taken by Gaspard-Félix Tournachon (known as Nadar) in 1858 from a tethered balloon only a few hundred meters above Petit Bicêtre, France (Colwell 1997, 6). In 1935, photographs obtained from the Explorer II balloon at an unprecedented altitude of 22 kilometers (13.7 miles) documented the curvature of the earth. On 24 October 1946 the first photograph of the earth from space was acquired by a 35 millimeter motion picture camera onboard an unmanned captured German V-2 rocket that attained an altitude of 104 kilometers (64.6 miles) but did not achieve orbit (fig. 347) (Reichhardt 2006). Between 1945 and 1950 cameras flown on numerous V-2s captured useful regional cartographic information. In 1950 the engineer who developed the camera flown onboard the V-2 rockets predicted in *National Geographic* that these types of images would become commonplace in mapping the earth's surface (Holliday 1950, 512).

The Soviet Union's successful launch of the Sputnik 1 satellite in October 1957 spurred an intensified effort by the United States. The first photograph of earth acquired by a U.S. satellite was collected by Explorer VI on 14 August 1959. The first crude television image of earth from an orbital platform was obtained by the TIROS 1 (Television Infrared Observation Satellite) on 1 April 1960. In 1960 the U.S. Central Intelligence Agency's Corona spy satellite was placed in orbit for one day, and the following day its film canister was ejected and snatched out of the air by a specially equipped aircraft (see fig. 822). The camera carried on that flight was retroactively called the KH-1 (Keyhole) and was capable of producing images with a spatial resolution of approximately 25–40 feet. In one day it yielded more images of the Soviet Union than the entire U-2 suborbital aircraft program (McDonald 1995; Richelson 1999).

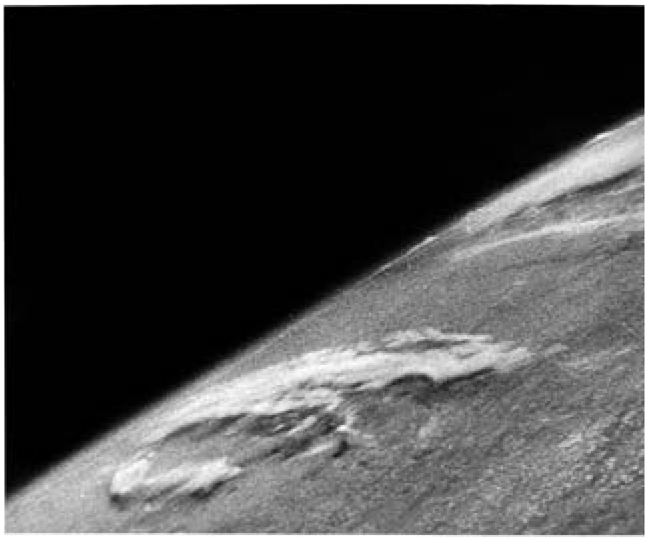

FIG. 347. THE FIRST PHOTOGRAPH OF EARTH FROM OUTER SPACE, 24 OCTOBER 1946.
Image courtesy of the Johns Hopkins University Applied Physics Laboratory.

In addition to orbital platforms, humankind launched numerous satellites that traveled great distances from earth. Cameras pointed back at the earth captured unprecedented views. These hemispherical images of the earth are of significant value. Prior to their creation, most people were very earth-centric, in that they believed that the earth was relatively large, resilient, and, of course, very important. After viewing images of the earth from space, some realized that the earth is a relatively small, fragile ecosystem that revolves around the sun in the immense blackness of space. For example, thirteen days after Voyager 1 was launched toward Jupiter on 5 September 1977, an onboard camera pointed back toward the earth to obtain the first-ever picture of the earth and its moon together (fig. 348). Similarly, the first image of earthrise over the lunar horizon was recorded by astronauts onboard the National Aeronautics and Space Administration's (NASA) Lunar Orbiter 1 in 1966. The most iconic earthrise image was obtained in 1968 by NASA's Apollo 8 (fig. 349). One of the most famous images of the twentieth century was the view of the fully illuminated earth taken by the Apollo 17 astronauts in 1972 (fig. 350). Since the mid-1970s the National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellites (GOES) have routinely provided hourly full-disk images of the earth, and since 1981 NASA's space shuttle astronauts have acquired thousands of photographs of earth from space.

Beginning in 1972, governments and private industry have launched numerous platforms into orbit to monitor the earth (Jensen 2007). The most notable earth resource mapping satellites and their initial launch dates include: NASA's Skylab (1973); NASA's Earth Resources Technology Satellite (ERTS), retroactively named Landsat (1972); the European Space Agency satellites (1975); the French SPOT (Système Probatoire d'Observation de la Terre) image satellites (1986); the Indian Remote Sensing satellites (1988); Canadian Radarsat (1995), with all-weather, day/night remote sensing capability; NASA's Earth Observing System (1999); and commercial satellites by EOSAT (Earth Observation Satellite),

FIG. 348. EARTH AND ITS MOON FROM THE VOYAGER 1 SATELLITE, 18 SEPTEMBER 1977. The moon is artificially brightened by a factor of three.
Image courtesy of Great Images in NASA, Washington, D.C.

FIG. 349. EARTHRISE OVER THE MOON OBTAINED BY APOLLO 8 ASTRONAUTS, 24 DECEMBER 1968. Earth is about five degrees off of the lunar horizon.
Image courtesy of Great Images in NASA, Washington, D.C.

Space Imaging which became GeoEye (IKONOS satellite in 1999), ImageSat International (EROS A in 2000), and DigitalGlobe (QuickBird in 2001). GeoEye, Inc., merged with DigitalGlobe, Inc., in 2013.

JOHN R. JENSEN

SEE ALSO: Map: Images as Maps; National Aeronautics and Space Administration (U.S.)

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FIG. 350. FULL-DISK PHOTOGRAPH OF THE EARTH FROM SPACE TAKEN BY APOLLO 17 ASTRONAUTS SHORTLY AFTER LAUNCH, 7 DECEMBER 1972.
Image courtesy of Great Images in NASA, Washington, D.C.

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U.S. National Air and Space Museum, Space History Division. 2008. "Top NASA Photos of All Time." *Air & Space Smithsonian* 23, no. 4:30–39.

Goode, J(ohn) Paul. J. Paul Goode, perhaps the first twentieth-century American thematic cartographer, was born in Stewartville, Minnesota, on 21 November 1862 and educated at the University of Minnesota, where he received his BS in 1889. Goode received a PhD in economic geography from the University of Pennsylvania in 1901, and spent most of his career in the Department of Geography at the University of Chicago, where he developed courses in thematic cartography and mapping. A charter member of the Association of American Geographers (AAG), he served as coeditor of the *Journal of Geography* from 1901 to 1904, helped organize the Geographic Society of Chicago, and was appointed by U.S. President William Howard Taft to help lead a tour of the United States for a distinguished group of Japanese financiers (Haas and Ward 1933).

Goode was an innovative geothematic cartographer who developed some of the very first courses in American academic cartography, notably "A Course in Graphics" and "Cartography," which stressed basic principles of statistical and thematic cartography (McMaster and McMaster 2002, 307–8). Interesting examples of Goode's cartography may be found in his small book, *The Geographic Background of Chicago* (1926), which includes United States population centroid maps, economic maps depicting economic resources such as coal and trade, and comparative maps showing areal relationships among Europe and the United States.

Of all his accomplishments, Goode is best known for the homolosine projection (Goode's homolosine equal-area projection) and his widely used atlas, first published in 1923 as *Goode's School Atlas* (Goode 1923). His primary goal in creating the projection, first presented in 1923 at the AAG's annual meeting (Goode 1925), was to create an equal-area transformation that minimized shape distortion by blending sinusoidal and homolographic projections at 40°44′11.8″. The sinusoidal projection was used for the entire earth up to the latitude at which east-west scale is identical on both projections, and the lobes were completed using the homolographic (Mollweide) projection. Goode felt his hybrid projection had several positive attributes, including: (1) it presents the earth's entire surface; (2) it is strictly an equal-area projection; (3) it preserves shape exceptionally well in low latitudes, where it renders Africa and South America about as perfectly as possible with a single map projection; and (4) parallels of latitude are shown as straight lines trending with the equator, thereby facilitating studies in comparative latitudes (Goode 1925, 121–22).

Although students focusing on cartography were rare during this period, Goode produced two PhDs at Chicago, Henry M. Leppard and Edward Bowman Espenshade, who continued his work on base map development as well as many generations of the *Goode's School Atlas*, later *Goode's World Atlas*, published by Rand McNally. Leppard, who succeeded Goode at Chicago, stayed until after World War II, when he went to the University of Washington (where he worked with John Clinton Sherman) and later to UCLA. Espenshade spent his entire career at Northwestern University, where he continued to edit *Goode's World Atlas*. Goode died in Chicago on 5 August 1932.

ROBERT B. MCMASTER

SEE ALSO: Academic Paradigms in Cartography: Canada and the United States; Atlas: School Atlas; Projections: Interrupted and Polyhedral Projections; Rand McNally & Company (U.S.)

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Gravimetric Survey. See Geodesy: Gravimetric Surveys

Grid Coordinates. See Coordinate Systems; Projections: Projections Used for Military Grids

GUGK (Russia). See Glavnoye upravleniye geodezii i kartografii (Chief Administration of Geodesy and Cartography)

Gulf War (1991). The first Gulf War, also known as the Persian Gulf War and which the Allied forces named Operation Desert Storm, took place from 16 January to 6 April 1991, after a long period of military buildup in the region (termed Operation Desert Shield). The war was a response to Iraqi president Saddam Hussein's invasion of neighboring Kuwait on 2 August 1990, following a dispute over oil fields. The United Nations (UN) Security Council began sanctions after the invasion, and U.S. President George H. W. Bush began assembling a coalition of eventually thirty nations to retake Kuwait. Bush ordered U.S. troops to Saudi Arabia at the Saudis' request, and by the war's outbreak 230,000 American troops had arrived. Another 200,000 soldiers eventually were mobilized, making the total allied coalition one of the largest assembled armies ever. A UN Security Council ultimatum of 8 November 1990 called on Hussein to leave Kuwait by 15 January 1991. On 16 January, Bush won congressional approval for war, rejecting a Soviet-Iraqi peace plan, and issued his own deadline for removal by 23 February at noon. The air campaign began on 17 January involving aircraft stationed in Europe, Turkey, and several Gulf nations as well as on aircraft carriers and flying over a thousand sorties a day, destroying much of Iraq's infrastructure. Five hours after the first dawn attacks, Saddam Hussein broadcast on Baghdad state radio that "the great duel, the mother of all battles has begun," and started firing Scud missiles at Israel. The air war was followed by a ground assault starting 24 February (figs. 351 and 352). In a lightning-fast campaign designed by General Norman Schwarzkopf, U.S. and coalition forces with massively superior strength broke through Iraq's desert defenses and defeated the Iraqi Army in only four days (100 hours) of combat (fig. 353). Allied forces entered Kuwait City on 26 February. In retreating from Kuwait, the Iraqi army set fire to over 500 of that country's oil wells, but suffered massive casualties, especially along the so-called "highway of death." Largely because of publicity over the carnage there, Bush declared a unilateral cease-fire. On 3 March, Iraq agreed to abide by all of the UN resolutions and starting on 4 March, Allied prisoners of war were released. The official cease-fire was on 6 April, by which time 532,000 U.S. forces had served in Operation Desert Storm. Despite reports that over 100,000 Iraqi deaths had occurred, military experts now agree that Iraq suffered between 20,000 and 35,000 casualties. Coalition losses were 240 killed (148 of them American) and 776 wounded (458 of them American). The coalition lost only four tanks; Iraq lost over a thousand.

From a cartographic standpoint, the Gulf War was remarkable as a technological turning point. With so little reporting from Saudi Arabia due to the embedded reporting and censorship, newspapers, news magazines,

FIG. 351. COLIN POWELL GIVING A MAP-INTENSIVE WHITE HOUSE BRIEFING DURING THE GULF WAR. Powell, the chairman of the Joint Chiefs of Staff, is shown with administration officials on 24 February 1991.

Image courtesy of the George Bush Presidential Library and Museum, College Station.

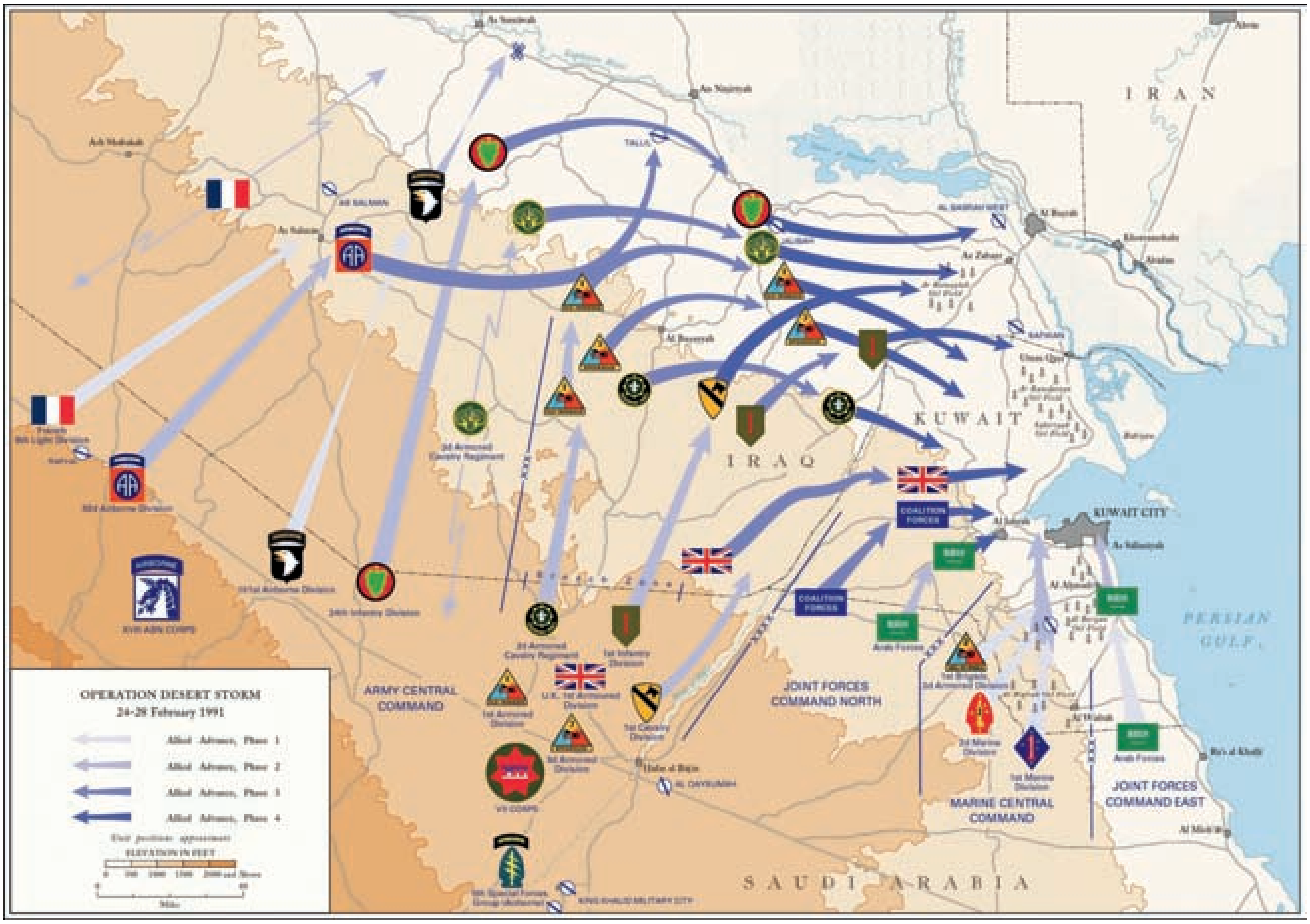

FIG. 352. U.S. MILITARY OFFICIAL OFFENSIVE MAP OF THE LIBERATION OF KUWAIT. The map depicts the so-called "Hail Mary" or "left-hook" attack.

Image courtesy of the U.S. Army Center of Military History, Washington, D.C.

and television used maps extensively to point out locations and locate ships, air bases, and ground troops, especially before 24 February. Maps used during the air war included regional and national maps, with air bases added as well as suspected locations of Iraqi defenses and divisions, such as the Republican Guard. Media coverage during the war made extensive use of maps. Newspapers and news magazines published war special editions, including glossy pull-out maps. The inclusion of maps in television news coverage, best symbolized by television journalist Peter Jennings digitally "walking" across a large 3-D map of the gulf region, anticipated the pervasiveness of GoogleEarth.

The Gulf War was probably the zenith of paper map use in wartime, while simultaneously all-digital geographic information systems (GIS) and satellite-positioning technologies were also used pervasively for the first time. For example, as part of the U.S. effort to produce paper maps, the Defense Mapping Agency's St. Louis and Brookmont, Maryland, plants went into twenty-four-hour operation. Two hundred person-years of overtime were used to generate 12,000 new map products (only 600 all-digital) involving over 100 million sheet maps, "the greatest number of maps produced for a single purpose in history" (Clarke 1992, 84). These were airlifted to Saudi Arabia and assigned a higher priority than medical supplies. New mapping produced for the war included 1:50,000 coverage (and other scales) for Kuwait, Saudi Arabia, Iraq, and part of Syria—a total of 760 line maps, 26 city maps, 125 Joint Operations Graphics, 380 terrain maps, 125 satellite and other image maps, and 76 hydrographic charts.

Digital map products were, however, rapidly becoming the norm. The transition was forced by the integration of imagery and by data from the Global Positioning System (GPS), which revealed the need for greater flexibility in choosing projections and datums and a need for data fusion and integration. During the war,

FIG. 353. A DEFENSE MAPPING AGENCY JOINT OPERATIONS GRAPHICS (JOG) SAVED FROM AN AIRCRAFT COCKPIT DURING THE AIR WAR. Size of original: 46.5 × 41.8 cm. Private Collection. Image courtesy of Adam Campbell, Gumball Productions, San Diego.

the Selective Availability (SA) option on the GPS was turned off, and numerous operational problems with the satellite constellation were solved, partly by expediting the launch of several GPS satellites. Imagery added to the mapping process included intelligence sources from overhead satellites, and the JointSTARS imaging radar system that could image in poor weather and at night (Clarke 1992, 85–86).

The impact of the Gulf War on cartography as a whole produced a recognition of the power of advanced high-technology systems and the realization that mapping intelligence (now termed GEOINT—geospatial intelligence) contributed directly to the success of the Allied war efforts. This continued to be true during the war's aftermath, when priorities shifted to the relief effort, enforcement of continuing sanctions, and remediation of environmental contamination caused by depleted uranium, oil fires on land, and deliberate oil leaks at sea.

KEITH C. CLARKE

SEE ALSO: Cruise Missile; Journalistic Cartography; Military Mapping of Geographic Areas: Middle East; Warfare and Cartography

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