DESIGNING AN OPTIMAL AND SCIENTIFIC GIS PROJECT

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This paper will address the main ingredients of a scientific GIS such as: datum, map projections, geodetic controls, scale, information components, interchange of digital information, and accuracy standards.

Key words: Scientific GIS, Datum, Geodetic Control, Map Projections, Map Scale, Data Interchange

INTRODUCTION

Many terms have been and are used to express integrated and geographically (geodetically) referenced digital mapping systems. Examples include:

• Land Information System (LIS), • Geographic Information System (GIS), • Spatial Information System (SIS), • Land Related Information System (LRIS), • Multi-purpose Cadastre, • Land Record System, • Computer Aided Mapping Systems (CAMS), • Modern Cadastre, • Land Record and Resource Information System, • Land Data System, • Geographic Data Bank, • Land Data Bank, • Land Record Information System, • Community Geographic Database, • Automated Mapping System, • Automated Information Management System, • Geomatics, • Geoinformatics, • Geometronics, and • Spatial Information Mapping and Analysis (SIMA).

Of the many terms used, two terms, land information system (LIS), and geographic information system (GIS) have ultimately become very popular and acceptable to the surveying and mapping and allied communities. Both these terms are frequently taken as being synonymous. To some extent, this is correct, but the term GIS defines a broader area that includes statistical data and modelling. LIS is solely a land-based information system but GIS covers any information which is geodetically referenced and includes land information or other information. Therefore, an LIS is a part of a GIS. GIS can be defined as a computer-based system to capture, process or manipulate, store, edit, and display information (data) which is geodetically referenced. The function of a geographic information system is to process or transform raw data into information in a geodetically referenced form which will assist the decision maker in reaching an optimal decision (planning, design, and implementation).

The term GIS has also been used by some as a tool for information management without giving any consideration to the spatial identity of the information. To distinguish a GIS from computer-aided graphics we have used the term "Scientific GIS". A scientific GIS is defined as a spatial information system which uses the principles and meets the standards of the surveying and mapping sciences. Also, GIS is divided into three broad categories according to the objectives, capability of capturing information, and accuracy standards of the products:

- global
- regional
- local

Global or international GIS are generally small scale GIS whose objectives may be to study the figure of the earth (gravitational field), scientific research, navigational applications, environmental planning etc.

Regional GIS is a medium scale GIS, whose objectives may be to provide better information to planners, engineers, and earth scientists about the natural resources available (which are needed for all modern development works and ultimately to improve the quality of life) in a region, and to provide a regional approach for solving problems such as: flooding, accelerated erosion, environmental and ecological studies, population growth, etc.

Local GIS is a large scale GIS, whose objectives may be planning, design, execution, and maintenance of any limited area development project.

A generic GIS consists of the following fundamental components:

- Geographic or geodetic component
- Information component
- System component
- Accuracy standards.

GEODETIC COMPONENT

This component of GIS transforms information into a well defined reference system and checks the accuracy of the GIS products. The following factors comprise the geodetic component:

- datum/reference surfaces
- selection of mapping plane
- scale of base maps and map numbering system
- geodetic controls required to tie the map frame (or to define the mapping plane) to the mapping plane and the datum/reference surface.

Table 1: Proposed Datums

GIS	Region	Datum/Horizontal	Remarks
Global	Entire Earth	WGS 84	--------
Regional	Africa	African Datum	Rename and Adjust
,,	Asia	Asian Datum	Rename and Adjust
,,	Australia	Australian Datum	--------
,,	Europe	European Datum	Include the former USSR and Readjust
,,	North America	NAD 83	--------
,,	South America	South American Datum	Readjust
Local GIS	Entire Earth	Same as for Regional	--------

Datum/Reference Surface

The first thing to be considered in GIS planning is to choose a datum for referencing information into a location (longitude, latitude, X, Y) and elevation (from mean sea level, i.e., orthometric height or from the reference ellipsoid, i.e., ellipsoidal height). There are about fourteen main reference ellipsoids used around the world for surveying and mapping purposes. Selection of the appropriate reference ellipsoid for location and vertical datum for elevation affects the accuracy of GIS products. Many geodesists suggest a globally best fitting geocentric ellipsoid for the earth. Because of heterogeneous distributions of geodetic controls in different continents, one datum would not fit better regionally for all the continents. Therefore, seven different geocentric datums (six for six continents, and one for global coverage) have been suggested for global, regional, and local GIS (Table 1).

The vertical datum should be one geoid for the entire Earth, and all height computations should be based on that one vertical datum.

Selection of Mapping Plane (Map Projection)

The second step in planning a GIS is selection of a suitable mapping plane. Approximately 27 different types of map projections have been used around the world for surveying and mapping purposes. An appropriate combination of reference curved and plane surfaces can produce an optimal GIS. An unmatched mapping surface could cause severe errors in coordinates [Acharya, 1990].

Map Scales and Map Numbering

An optimal surveying and mapping system is an integrated GIS. The task of making an integrated GIS is almost impossible and cost ineffective if different agencies within a region or zone use different reference frames, and base maps. To obtain an integrated GIS, a well defined reference frame and map numbering system must be adopted within countries or states or zones by all agencies where GIS work is performed. For detailed explanation please refer to [Acharya, 1990].

Geodetic Control

A minimum of three control points are needed to uniquely define the mapping plane surface, i.e., to tie the map frame to the map projection plane and ultimately to the reference surface (datum). If mapping is to be done at a scale of 1:500, then control stations are needed for about every 200 meters [Acharya, 1990]. This means a very large number of control stations are needed for a large scale GIS. These stations are needed to present map features in correct relationship to each other, to the reference surface, and, ultimately, to the earth's surface. Two kinds of control stations are needed, horizontal and vertical. These controls maintain correct scale, position and orientation of the map. The horizontal as well as vertical control points become the framework on which map details are compiled. An accurate and optimal framework also permits map details to edge match perfectly from one sheet to the next and also to prepare mosaics or seamless maps. An example of minimum numbers of geodetic controls required for regional GIS is computed and given in Table 2.

From Table 2, one can see how huge numbers of geodetic control points are still needed to cover the continental area of the Earth. Without the use of GPS technology, another half century may be needed to accomplish this task. The number of geodetic controls required for the local type of GIS increases exponentially but local GIS may not cover the entire country or region. Usually local GIS are prepared for urban areas and areas of special interest. The number geodetic controls required depends upon the scale of base maps to be prepared.

INFORMATION COMPONENT

This is a major component of a GIS system. Information is collected using three techniques:

- ground survey method
- photogrammetric method (airborne)
- remote sensing (air and space borne)

Digital cartographic data is generated by digitizing conventional hard-copy maps, photogrammetric stereocompilation, softcopy photogrammetry (digital photogrammetry), satellite remote sensing, and different

Table 2: Geodetic Controls Required for Regional GIS

Continent	Areal Coverage square km	Density of control pts. per 25 square km	Total # of Controls needed	# of controls available* 2-D	New controls needed 3-D
Africa	22,612,063	1	904,482	7,800	896,682
Asia	17,601,806	1	704,072	596,000	108,072
Australia	7,715,294	1	308,611	44,300	264,311
Europe & Former USSR	25,179,431	1	1,007,177	2,385,000**	696,088 **
North America	21,535,902	1	861,436	490,000	371,436
South America	5,917,631	1	236,705	74,800	161,905
Total	100562127 Sq. km		4,022,483	3,597,900	2,498,494

* Source: World Cartography, UN Publication.
** Former USSR has only 200,000 control points available and needs an extra 696,088 controls. Europe has more controls than required.

types of thematic applications.

The information derived from data can be of three types:

- spatial : locational data
- attribute : non locational data
- temporal : informational changes (i.e. changes in data due to time changes).

Data collection or digitization can be done in either raster or vector mode. Most remote sensing data are acquired in raster mode and are stored in this format. It is less expensive to process and store data in compressed raster format unless data are specifically needed in vector format for a particular application.

The conversion of map data can be done using two main methods:

- manual digitization - the map is manually traced with a digitizing cursor. This approach is very time consuming and labor intensive but it works for almost all maps.

- electronic scanning - the map or drawing is scanned electronically and stored as a raster image with no intelligence. Images of scanned maps are then generally converted to a vector map and information from the data base is tied to them, as for example, soil type or land value. Scanning can be faster than manual digitization, but works best for clean, uncluttered maps which do not contain overwritten data.

  After scanning a document one of three main approaches to raster-vector conversion can be followed: heads-up digitizing, semi-automatic vectorization and automatic vectorization. In heads-up digitizing an operator scans in a map and brings it up on the screen. S-he then traces the lines off the screen by using a mouse to follow them. This works well for a multitude of map types and complexities. In semi-automatic mode, the computer attempts to follow lines automatically but stops and waits for operator intervention when it encounters a problem area. The operator then examines the problem, makes a decision and the computer continues. This works well for relatively clean maps without too much overwritten text and lines. In fully automatic vectorization the computer traces all the lines by itself, often in overnight batch mode. Editing is then done to clear up any remaining problem areas. This works only for very clean maps, such as contour maps, or large scale cadastral plans, but it is rarely applicable to most local government maps.

The problems of digital data collection in a GIS system are mainly:

- The quality of digital data for topographical mapping
- Interchange of digital information between different computer aided mapping system (CAMS).

<u>The Quality of Digital Data for Topographical Mapping</u>

Conventional topographical maps are produced within the accuracy required for a specific scale. Digital map data are collected for a specific scale, but, due to the fact that these data are expressed in ground coordinate values without any permanent accuracy statement attached to them, there is no way to recognize this fact from the digital map.

Interchange of Digital Information Between Different CAMS

Digital information interchange is one of the major problems of current GIS. Many private and commercial CAMS have been used for several years for collection and manipulation of the digital data, each one of them having their own base structure and their own capability to exchange data stored in different systems. This makes it very expensive and unpractical for the exchange of digital information among many potential users.

In 1982, the National Committee for Digital Cartographic Data Standards (NCDCDS) was organized under the leadership of the U. S. Geological Survey with the patronage of the American Congress on Surveying and Mapping. This committee published standards in the January, 1988, issue of the American Cartographer, covering three different subjects:

- spatial data structure
- cartographic features
- digital cartographic data quality

The basic unit, for these standards, is the feature, which can be graphic or non-graphic. For the graphic feature, the primitive elements are line, curve, symbol and graphic text. Some 2-D or 3-D features can be transferred through this format. Non-graphic features are attribute data which in general are text.

The Canadian Council on Surveying and Mapping has also developed standards for digital data exchange. Such standards provide a national format for the exchange of topographic data. The basic unit of this format is the feature which has graphic components and optional attributes and information about spatial relationships with other features. Primitive graphics are points, nodes, lines, and areas. Each feature has a CCSM feature classification code and a unique identification number.

In 1992 we expect the Spatial Data Transfer Standard (SDTS) to be adopted for the exchange of spatial data among U.S. Agencies.

SYSTEM COMPONENT

It is widely known that a GIS was developed due to the need to retrieve and manipulate spatial information more effectively with the help of computers. The main hardware factors that influence the performance and capacity of a computer system are word length, main memory size, processing speed, size of external storage, and data or exchange rate between external and main memory.

Traditionally computers were classified as [Lee, 1989]:

- large main frame super computers - ie. the Cray X-MP or Cray Y-MP
- main frame super computer - ie. the IBM 370
- super minicomputer - ie. the VAX 11/780, and MicroVax II
- mini super computer - ie. the NPL and the VAX 8978
- mini computers - ie. the PDP 11/70
- microcomputers - ie. the IBM PC, and other personal computers

Recent developments over the last few years have blurred traditional distinctions among computers. Annual mainframe performance/cost ratios grew by 16% whilst that of minicomputers grew by 34%. New CPU chips for desk-top work-stations have 64 bit word lengths (like mainframes) and are capable of addressing huge amounts of memory. Main memory size (RAM) continues to grow. Sixteen megabytes (MB) in microcomputers is not uncommon and many desk-top stations have over 64MB of memory. Processing speeds continue to grow (on average by 1.5 times/year). Several single processor CPUs have over 70 MIPS of processing power and 200 MIP work-stations have recently been announced. By 1993 we will see 1,000 MIPS of processing power, and 400 megaflops of floating point performance. By 1995 we will see the adoption of much faster parallel processing technology. All this means that polygon cleaning operations that took 8 hours two years ago will be done in ten minutes this year and within three minutes by 1995.

Storage capacities are also on the rise with 2.5GB 5.25" disks available. Transfer speeds from disk to main memory are also rapidly rising with 10MB/second capability. Even so, disk transfer speed continues to slow applications. Evolving systems such as disk striping and parallel disk arrays will help transfer speed keep pace with other related technologies.
Backup tape devices are also maturing. Digital D2 technology allows 165 GB/tape, with transfer rates of 16MB/sec. A 27 terabyte robotic jukebox is available that will store 100 million 300 page books in compressed format.

As an example a project to establish a 1 point/sq. meter digital terrain model (DTM) for the land portion of the earth covering 1.0×10^8 km^2 would contain 10^{14} points. It requires approximately 16 bits to document each elevation so the total database would be 1.6×10^{15} bits (equivalent to 1200 digital D2 tapes or two DD2 robotic jukeboxes). A further example of a sustainable development database for South America would contain 3-15 terabytes ($3\text{-}15 \times 10^{12}$) or one DD2 jukebox. Storage is thus vastly improved over what we could envision in 1990 and the technology is finally reaching a level where hemispheric and global GIS databases of sufficient detail for planning are finally feasible.

Database management systems are also improving in efficiency. Distributed databases with two phase commit are finally here, allowing data to be stored in multiple user locations yet accessed over networks. Fiber optic networks will be needed for large data volumes. Most GIS systems have their graphics database separate from their associated attributes. This is unfortunate (but understandable for performance reasons) since it is easy to get the data out of synchronization, and, with large databases it will be difficult to maintain database integrity. Hopefully, both graphics and attribute data can be integrated in one database on more GIS in the future.

A conceptual and fundamental GIS operation is shown in Figure 1. The primary objective of any GIS is to collect

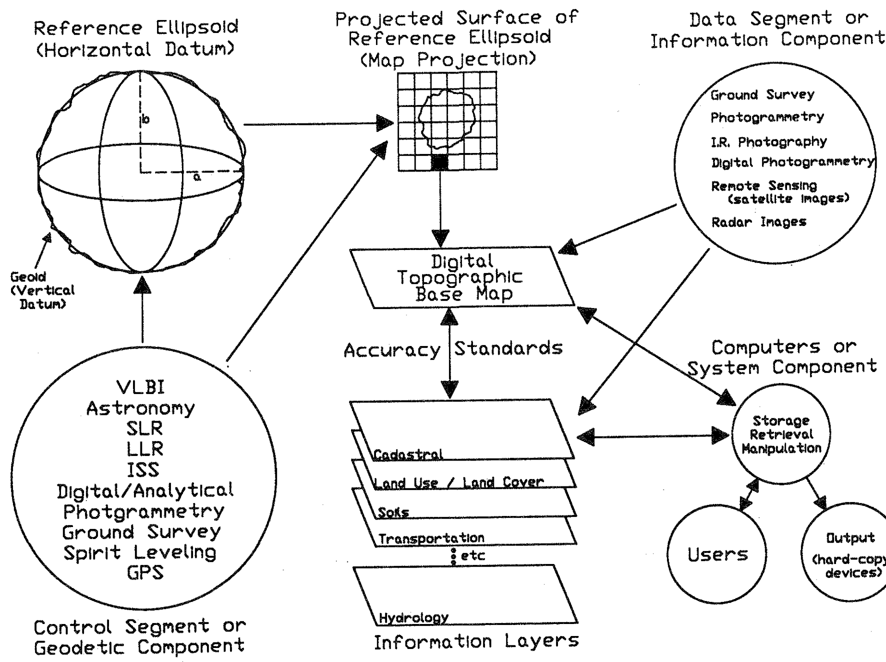

Figure 1: Conceptual GIS

information on part of the surface of the earth, store in a computer according to the location with respect to the earth's surface, and restore the information to analyze and manipulate for many applications such as natural resources planning, development work, etc.

Technical problems of GIS such as raster (grid) to vector (polygon) conversion and the interchange of digital information between different CAMS will influence the economic side of the GIS whereas the lack of sufficient training will impact GIS implementation and operations. Adequate GIS training requires the integration of many diverse disciplines taught in a variety of faculties and schools such as geodetic sciences (datums, map projections, and satellite positioning), management information systems (management issues, systems analysis and design, cost benefit analyses), survey sciences (conventional surveying, legal issues applied to land, photogrammetry, remote sensing, and geosciences) and computer science (database design, hardware, communications, security, software). Figure 1, a scientific and integrated GIS will only be possible if due consideration is given to the above mentioned components.

ACCURACY STANDARDS

A GIS accuracy standard is the degree to which perfection or reliability of measurement is attained in a surveying and mapping or GIS undertaking. Many organisations, especially those in developing countries, do not pay sufficient attention to its importance, and many systems presently in use are out of date due to rapid development of the technology. One must adopt field specifications and methods that will meet accuracy requirements and particular mapping standards. Accuracy standards are defined as the minimum accuracies that are necessary to meet specific objectives [FGCC, 1986, 1988].

The US National Map Accuracy Standard (NMAS) is very simple and easy to use because it is expressed in absolute terms and without any true scientific statistical concepts. NMAS does not provide consistency in the accuracy standards in conjunction with mapping from space, and computer aided mapping. A new approach for deciding statistical map accuracy standards should be designed and used for the scientific GIS. For details please refer to [Acharya and Bell, 1992].

OPTIMIZATION OF GIS

An optimal GIS has all the constituents of a scientific GIS, and is cost effective. The strategy of optimization discussed in this paper follows:

(i) Maximize the accuracy standards: The concept of optimization in the past was often to increase the precision, accuracy, and reliability, which are interrelated, without giving much emphasis on the other factors. In the past, given a specific cost, there were not many alternatives, because of the limited or expensive technology.

(ii) Minimize the cost: This should be done by analyzing a benefit/cost ratio. The analysis of the benefit/cost ratio is not always easy, since many of the economic benefits from the GIS output are intangible.

(iii) Maximize and integrate the product users: The output of a GIS is not complete itself but rather is an intermediate product. The cost of a GIS can be reduced by increasing users, departments and agencies and integrating the systems so that duplication is avoided, and costs and data can be shared.

All three strategies should be followed to optimize a GIS project. Cost effectiveness analysis is performed by analyzing a benefit/cost ratio. The benefit and cost analysis are performed separately by assigning benefit and cost evaluation factors and then combined to get the ratio. The burden of the cost of a GIS project can be substantially minimized if the system is shared by multi-users. Typical examples of multi-user GIS projects include the Planning Commission, City Planning Office, Geological Survey, Public Works Department, Natural Resources Department, Forest Services, Irrigation Department, Education Department, Police Department, Water Supply/Sewerage Department, Survey/Cadastral Department, Property Tax Commissioner's Office, Highway Department, Population Commission/Statistical Department, and utility companies.

A well designed optimal GIS project can serve many purposes for different users with nominal modification to the basic structure. For detailed study of optimization of GIS technique refer [Acharya, Talbert, 1992].

CONCLUDING REMARKS

In recent years, GIS technology has matured and offers powerful capabilities for all organizations which are dependent on maps and geographic data. A scientific and optimal GIS must meet many criterion besides economics to become an optimal and scientific GIS. These criteria include: principles of surveying and mapping science, availability of adequate geodetic controls, map accuracy standards, standards of format interchange, ease and economy to operate, and easy access for multiple users. The world is going through an information revolution sparked by developments in computer technology. The computer provides facilities to store, retrieve, compare, share, rearrange, transmit, repeatedly reuse information in real time that otherwise is impossible. Three factors, technology transfer, quality control, and optimal planning, will dictate the optimal yield of any GIS project. An exhaustive procedure of designing an optimal and scientific GIS has been discussed and recommended.

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REFERENCES

Acharya, Bishwa, and Bell, William. 1992. "Universal Accuracy Standards for GIS" (accepted paper) ASPRS/ACSM /RT '92 Global Change Convention, Washington D.C., August 2-14.

Acharya, Bishwa, and Talbert, Zel. 1992. "Choosing an Optimal Surveying Technique" ACSM/ASPRS Annual Convention, Albuquerque NM, March 1-5.

Acharya, Bishwa. 1990. "Optimizing Surveying and Mapping Systems" Ph. D. dissertation, Purdue University, West Lafayette, IN 47906

FGCC. 1986 and 1988. "Proposed Geometric Geodetic Survey Standards and Specifications for Geodetic Surveys Using GPS Relative Positioning Techniques" Versions Four and Five, National Geodetic Survey.

Lee, Y. C. & Zhang, G. Y. 1989. "Developments of Geographic Information System Technology" ASCE, Jour. of Surveying Engineering, Vol. 115, No. 3.