Review Article

Accuracy of Spatial Data Used in Geographic Information Systems

Khagendra Thapa
Surveying Engineering Program, College of Technology, Ferris State University, Big Rapids, MI 49307
John Bossler
Center for Mapping, The Ohio State University, Columbus, OH 43220

ABSTRACT: Geographic Information Systems (GIS) are concerned with the collection, management, display, and analysis of spatial data. In order to utilize GIS, one needs to have appropriate hardware, software, and trained personnel. However, the cost of this portion of an automation project is small compared to that of data collection, which is very expensive. Moreover, the accuracy and quality of data required for different applications is not usually homogeneous. In this paper, a comprehensive outline of the different types of errors encountered in the process of data collection is presented. An overview of different errors encountered in the "primary and secondary" methods of data collection is explained. In addition, a brief summary of different standards and specifications used in the primary methods of data collection is provided. Finally, a comparison between the primary and the secondary methods of data collection is made.

INTRODUCTION

DATA COLLECTION is the most expensive part of a spatial information automation project. Blakeman (1987), Morse and Hovey (1990), and Thapa and Burtch (1990) report that data collection costs in Geographic Information Systems (GIS) are about 80 percent of the total costs of GIS. GIS usage has expanded tremendously in the last few years. It is estimated that thousands of GISs have been installed through out the world. There are at least 62 different GIS software products (Parker, 1989) available. The application areas of GIS are numerous: local, state, and federal governments; urban, regional, and national planning agencies; environmental planning, geology, forestry, and hazardous waste management; utilities such as gas, electricity, water supply, telephone, cable TV, etc. The list of users is nearly endless.

There are hundreds of vendors of GIS hardware and software. There are also those who are involved with consulting work associated with GIS usage. Typically, GIS consultants help the potential users of GIS to identify their needs. They also advise them about the capabilities of the hardware and software when selecting a GIS, the personnel required, etc.

Usually, developers, vendors, consultants, and users of GIS do not talk about the quality and accuracy of the data they are using in their GISs.

In this paper, we present a comprehensive outline of the different types of errors encountered in both primary and secondary methods of data collection. A comparison between the two methods is made. In addition, an outline of the importance of data quality and accuracy is provided.

QUALITY AND ACCURACY OF DATA IN A GIS

Data capture is one of the crucial steps in any automation project. It is not only the most expensive component but also all the decisions made as a result of using GISs are based on the data collected at the beginning of the project. Moreover, data usually outlive both hardware and software. With a view to makeing the data collection process associated with GIS usage more systematic, Thapa and Burtch (1990) introduced the concept of primary and secondary methods of data collection for use with GIS. Primary methods of data collection refer to methods of data collection in which data are collected directly from the field (ground surveying, photographs (aerial and terrestrial), and satellite imagery). Secondary methods of data collection refer to data collection in which data are collected from existing documents such as maps, charts, graphs, etc. The fundamental methods involved and the accuracy and quality associated with the data captured by primary and secondary methods are very different. Refer to Thapa and Burtch (1990) for more about these methods of data collection.

QUALITY AND ACCURACY OF DIGITAL DATA

GISs use digital data. Therefore, it is relevant to include a summary of the work done in developing digital cartographic data standards. According to the National Committee for Digital Cartographic Data Standards (NCDCDS, 1988), there are six fundamental components of digital cartographic data:

- lineage,
- positional accuracy,
- attribute accuracy,
- logical consistency,
- completeness, and
- temporal accuracy.

Lineage refers to a description of the source material from which the data were derived, and the methods of derivation, including all transformations involved in producing the final digital data. In addition, lineage must also include the specific control points used. The control points must be described with sufficient detail to allow recovery. Moreover, lineage must provide the transformation algorithm used along with the computational steps taken to avoid roundoff or to account for errors.

Positional accuracy tests must be made by comparing the spatial data to an independent source of higher accuracy. The test must be conducted using prescribed rules, e.g., those in the Spatial Accuracy Standards for Large-Scale Topographic Maps (American Society for Photogrammetry and Remote Sensing (ASPRS), 1987). Other accuracy tests include deductive estimates (NCDCDS, 1987), interval evidence, and comparison with the source. Attribute accuracy tests may be made either by deductive estimates, or based on independent samples from polygon overlay. Maintenance of logical consistency may be tested by using (NCDCDS,1988) the following methods:

- tests of valid values,

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- general tests for graphic data, and
- specific topological tests.

Completeness of the data quality report will include such information as selection criterion, definitions, relevant mapping rules, as well as geometric threshold such as minimum width, minimum area, etc.

Temporal accuracy refers to the currency of data. For example, international boundaries in 1991 may not be the same as in 1990, especially in Europe. Germany is united and Latvia, Estonia, and Lithuania have gained independence. Temporal accuracy is an important aspect of the accuracy of spatial data. The temporal aspect of the accuracy of spatial data seems to have been ignored by NCDCDS(1987) even though they do emphasize the inclusion of dates in various data collection and testing steps.

TYPES OF ERRORS IN DATA COLLECTION

An error is a difference between the true value and the observed value of a quantity caused by the imperfection of equipment, by environmental effects, or due to the imperfections in the senses of the observer. Errors are generally classified into three types: (1) gross errors and blunders, (2) systematic errors, and (3) random errors.

Gross errors are caused by carelessness or inattention of the observer in using equipment, reading scales or dials or in recording the observations. For example, the observer may bisect the wrong target in angle observations, or may record observations by transposing numbers, e.g., by writing 65.25 instead of 56.25. They could also be introduced by misidentification of a control point in an aerial photograph. Gross errors may also be caused by failure of equipment. Observations fraught with gross errors are useless. Therefore, every attempt must be made to eliminate gross errors. Normally, observation procedures are designed in such a way that one can detect gross errors during or immediately after the observations are taken. Some of the techniques used in detecting and eliminating gross errors include (Mikhail and Gracie, 1981) taking multiple readings on scales and checking for consistency using simple geometric and algebraic checks, repeating the whole measurement and checking for consistency, etc. In a statistical sense, gross errors are observations which cannot be considered to belong to the same sample as the rest of the observations. Therefore, the elimination of gross errors or blunders or mistakes is vitally important.

Systematic errors occur in accordance with some deterministic system which, if known, may be represented by some functional relationship. For example, observed slope distances if not reduced to the ellipsoid will introduce systematic errors. There is a functional relationship (Vanicek and Krakiwsky, 1982) between the observed distance, geoid ellipsoid separation, and the heights of the points between which the distance is observed.

In surveying, geodesy, and photogrammetry systematic errors occur because of environmental effects, instrumental imperfections, and human limitations. Some of the environmental effects are humidity, temperature, and pressure changes. These factors affect distance measurements, angle measurements, and GPS satellite observations, among others. Instrumental effects include lack of proper calibration and adjustment of the instrument as well as imperfections in the construction of the instrument, e.g., nonuniform graduations of the linear and circular scales. Systematic errors must be detected and observations must be corrected for systematic errors or they must be modeled by some mathematical model.

In a statistical sense, systematic errors introduce bias in the observations. Unlike gross errors, they cannot be detected or eliminated by repeated observations. Therefore, if systematic errors are present, the measurements may be precise but they will not be accurate.

Even after all the gross and systematic errors are removed, there will still remain some variations in the observations. These remaining variations in observations (which are small in magnitude) are called random errors. They cannot be represented by a functional relationship based on a deterministic model. Random errors occur due to the imperfections of the instrument and observer. An observer cannot observe a quantity perfectly. The observed quantity will be either too small or too large every time it is observed. If sufficient observations are taken, random errors possess the following characteristics:

- positive and negative errors occur with the same frequency,
- small errors occur more often than large errors, and
- large errors rarely occur.

Random errors are treated systematically by using a stochastic model.

ERRORS IN PRIMARY METHODS OF DATA COLLECTION

As stated in Thapa and Burtch (1990), the primary methods of data collection include the techniques of geodesy, photogrammetry, and surveying. All these techniques include random, systematic, and gross errors. However, the methods of observation as well as computation are designed in such a way that gross errors are eliminated, systematic errors are either corrected or are mathematically modeled, and random errors are treated systematically by stochastic models, for example, by using the method of least squares.

Errors introduced in the primary method of data collection include the following types:

- personal errors,
- instrumental errors, and
- enviromental errors.

Personal errors occur because no observer (surveyor or geodesist or photogrammetist) has perfect senses of sight and touch. This type of error includes reading errors, centering errors, as well as bisection errors. This also includes the personal equation which involves how a particular individual estimates the readings between graduations. Personal errors could be blunders, and systematic as well as random errors.

Instrumental errors include errors caused by imperfect instrument construction, or lack of adequate instrument adjustment or calibration prior to its use in data collection. Errors introduced by instrumental effects are mainly systematic in nature.

Environmental errors are primarily caused by variations in temperature, pressure, humidity, magnetic variations, obstruction of signals, winds, and illumination at the time of observation. Again, the errors introduced by environmental factors are mainly of a systematic nature and as such can be mathematically modeled and corrected.

ACCURACY STANDARDS

The primary methods of data collection are guided and controlled by the existence and use of accuracy standards. Accuracy standards for primary methods of surveying and mapping have been in existence for many years. In the United States, the first National Mapping Accuracy Standards (NMAS) were issued by the Bureau of the Budget on 10 June 1941 and were revised in 1943 and again in 1947 (ASCE, 1983).

According to NMAS horizontal accuracy "for maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scale of 1:20,000 or smaller, 1/50 inch" (ASCE, 1983). Further, NMAS states that these limits of accuracy shall only apply to well-defined points. Vertical accuracy standards of NMAS for maps

TABLE 1. DISTANCE ACCURRACY STANDARDS ADAPTED FROM FGCC (1984).

Classification	Minimum distance accuracy
First order	1:100,000
Second order class I	1:50,000
Second order class II	1:20,000
Third order class I	1:10,000
Third order class II	1:5,000

state that not more than 10 percent of the points tested shall be in error by more than one half of the contour interval.

NMAS was primarily developed to satisfy the needs of national mapping agencies such as the USGS, which produces maps at scales of 1:24,000 and smaller. With a view to provide accuracy standards for large scale mapping, ASPRS and ASCE developed large scale Engineering Map Accuracy Standards (EMAS) (Merchant, 1983). Unlike the NMAS, EMAS states that the number of points tested should be equal to 20 or more. In addition, EMAS also specifies that compliance testing be performed both for bias using t- distribution (t-test) within a 95 percent confidence interval one tailed test and a test for precision using chi-square distribution again within 95 percent confidence interval one tail test.

In order to assist local, state, and federal government agencies, private developers, and other individuals in preparing large scale map specifications, ASPRS and the American Congress on Surveying and Mapping (ACSM) have published large scale mapping guidelines (ASPRS and ACSM, 1987). These guidelines were originally developed by the USGS National Mapping Division.

ACSM and the American Land Title Association (ALTA) have developed Minimum Standard Detail Requirements for Land Title Surveys (ACSM and ALTA, 1988). ACSM/ALTA standards classify the accuracy requirements by land use. There are four land-use categories identified: urban, suburban, rural, and mountain and marshland. Corresponding to these land-use categories, there are four classes of surveys: A, B, C, and D. Minimum accuracy requirements for angle, distance, and closure for each class of survey are specified.

In order to "support the conduct of public business at all levels of government, for planning and carrying out national and local projects, the development and utilization of natural resources, national defense, land management, and monitoring crustal motions" (FGCC, 1984), the U.S. government maintains horizontal, vertical, and gravity networks. Each of these networks is divided into different orders and classes, depending on the accuracy requirements and specifications. The accuracy is expressed as a distance accuracy ratio. It is the ratio of the relative error in distance between a pair of control points to the horizontal distance between those points. The distance accuracy standards are given in Table 1. Notice that second-order and third-order accuracy standards are divided into classes I and II. For each of these orders and classes and for each of the three networks, FGCC (1984) has provided detailed minimum accuracy requirements which include considerations for network geometry, type of equipment needed, instrument calibration procedure to be used, detailed field procedures to be followed, and office procedures for adjustment and analysis of the results. For example, for first-order work one must observe 16 rounds of directions with a theodolite which has a least count of 0".2 and the standard deviation of the mean should not exceed 0".4.

FGCC (1989) has also published Geometric Geodetic Standards and Specifications for using GPS relative positioning techniques. There are six different "orders" of geometric relative positioning accuracy standards specified by the FGCC (1989). These are given in Table 2. The accuracies range from 0.3 cm + 0.01 ppm to 5 cm + 100 ppm. FGCC (1989) specifications and standards includes network design, geometry, connections, instrumentation, calibration, field procedure, and office procedures.

State professional societies and licensing boards have also developed and adopted their own cadastral surveying standards. Burtch and Thapa (1990) report that at least 26 out of 50 states have adopted some kind of surveying standard.

Earlier in this section, the method of least squares for handling random errors was mentioned. Bomford (1980) has given the objectives of adjusting observations using the method of least squares as (1) to obtain unique values for the unknowns which (2) will be of maximum probability and (3) find out the accuracy with which the unknown quantities are determined.

In surveying and geodesy more observations are taken than the minimum required to achieve the results. The extra mea-

TABLE 2. GEOMETRIC RELATIVE POSITIONING ACCURACY STANDARDS FOR THREE-DIMENSIONAL SURVEYS SPACE SYSTEM TECHNIQUES (FGCC, 1989).

		(95 percent confidence level) Minimum geometric accuracy standard		
		Base error	Line-length dependent error	
Survey categories	Order	e (cm)	p (ppm)	a (1:a)
Global-regional geodynamics; deformation measurements	AA	0.3	0.01	1:100,000,000
National Geodetic Reference System, "primary" networks; regional-local geodynamics; deformation measurements	A	0.5	0.1	1:10,000,000
National Geodetic Reference System, "secondary" networks; connections to the "primary" NGRS network; local geodynamics; deformation measurements; high-precision engineering surveys	B	0.8	1	1:1,000,000
National Geodetic Reference System (Terrestrial based); dependent control surveys to meet mapping, land information, property, and engineering requirements	(C)			
	1	1.0	10	1:100,000
	2-I	2.0	20	1:50,000
	2-II	3.0	50	1:20,000
	3	5.0	100	1:10,000

surements are used to provide a check for gross errors and to provide for some kind of assessment of precision using repeated observations. This is done by using some kind of adjustment of observations. The method of least squares is the common method used for this purpose. In simple terms, the method of least squares is a method of solving an overdetermined system of equations – one where there are more equations than unknowns. This method is formulated such that the sum-of-the-squares of the residuals (difference between observed values and estimated values) is a minimum. The adjusted observations are by no means the true values; however, a property (unbiasedness) of this method ensures that on average the adjusted observations are the true observations. Moreover, the least-squares adjustment may be carried out on any reference frame including a plane, ellipsoid, and in three dimensions.

The use of the method of least squares also enables us to compute the unknowns (e.g., coordinates) from the observed quantities such as angles, distances, and azimuths along with the accuracy estimates of the computed quantities. However, the unknown quantities (parameters) must be related to the observations by a mathematical model. This can also be used to adjust a combination of observations for a small network, for example, a network established for dam construction or a large network such as a national geodetic network involving thousands of observations and unknowns (Bossler, 1987).

The variances of the computed coordinates are obtained from the diagonal elements of the variance-covariance matrix. This matrix is obtained as a result of a least-squares adjustment (Mikhail, 1976; Vanicek and Krakiwsky, 1982; Uotila, 1986). The diagonal elements, and the off-diagonal elements of this matrix represent the variances and covariances of the unknowns, and they can be used to estimate the accuracy of data. By using these elements, one can plot absolute error ellipses of the station positions. There is a 39 percent probability (Blachut *et al.*, 1979; Dodson, 1990) that the least-squares estimate of the position of a point will lie within the error ellipse. To increase the probability to 95 percent or 99 percent the axes of the absolute error ellipses must be multiplied by 2.45 and 3.03, respectively. One problem with absolute error ellipses is that they are datum dependent and as such they increase in size as the distance from the fixed point(s) increases. This problem is overcome by plotting relative error ellipses which are also derived from the elements of the variance- covariance matrix (Blachut *et al.*, 1979).

ERRORS IN SECONDARY METHODS OF DATA COLLECTION

The secondary methods of data collection include all the errors contained in the primary methods. In addition, the secondary methods incur the following errors:

- Error in plotting control
- Compilation error
- Error introduced in drawing
- Error due to map generalization
- Error in map reproduction
- Error in color registration
- Deformation of the material
- Error introduced due to the use of wrong scale
- Uncertainty in the definition of a feature
- Error due to feature exaggeration
- Error in digitization or scanning

Error in Plotting Control

The first step involved in making a map is to plot the control points. The root-mean-square error (RMSE) involved in this process, e_1, varies between 0.17 and 0.32 mm for coordinatographs attached to photogrammetric plotters. The error introduced during a control survey using, for example, the Global Positioning System (GPS) can be ignored at plotting scale because one can achieve centimetre-level accuracy.

Compilation Error

Compilation of topographical maps entails bringing data from various sources to a common scale by photography. The error introduced in this process (Maling, 1989) is $e_2 = k\,e'$. The value of e_2 ranges between 0.30 mm and 0.32 mm where e' is the error in the detail survey, which ranges from 5 m to 7.5 m if the detail is collected by photogrammetric method for a map with a scale 1:25,000, and k is the amount of reduction in scale from that of the plotted detail to that of the compilation manuscript. It should also be noted that, in digital mapping, point features will have a different accuracy than line features. Normally, well defined point features can be compiled more accurately than line features. Moreover, even within line features the accuracy of compilation will vary depending on the defination and thickness of the features.

Error Introduced in Drawing

The drawing error, e_3, is usually introduced at fair drawing stage and is quoted (Maling, 1989) as ranging from 0.06 mm to 0.18 mm.

Error Due to Generalization

The generalization error is very difficult to quantify because the amount of error introduced depends on the type of feature and also on the character (or complexity) of the feature. This error could range from substantial for some features, e.g., coastlines to non-existent, e.g., for straight roads.

Error due to deliberate feature displacement occurs only when any two or more features to be portrayed on a map are so close that they cannot be plotted in their proper position without overlapping. Therefore, they are displaced at the time of plotting to make the map legible. For example, if there is a road on one side of a river and railway line on the other side, then the three features cannot be plotted without displacing some of them. The smaller the scale of a map the larger the displacement. Again, this error could be substantial depending on the map scale and the proximity of the features to be portrayed.

Error in Map Reproduction

The RMSE in map reproduction (Maling, 1989), e_5, varies between 0.1 mm and 0.2 mm.

Error in Color Registration

A color map is reproduced from a series of metal printing plates which are used to print on a paper one color at a time. The RMS error introduced in proper registration (Maling, 1989), e7, varies between 0.17 and 0.30 mm.

Error Introduced by the Deformation of the Material

Maps are normally printed on paper. The dimensions of paper change with changes in humidity and temperature. With an increase in humidity, the moisture content of paper may increase from 0 percent to 25 percent with a corresponding change in paper dimensions of as much as 1.6 percent at room temperature (Maling, 1989). The paper will not return to its original size even if the humidity is reduced because the rates of expansion and shrinkage are not the same. A 36-inch long paper map can change by as much as 0.576 inches due to a change in humidity.

Nearly all materials increase in dimension when heated and decrease when cooled. Paper is no exception to this rule. At the time of printing, the paper temperature is high. Therefore, it can be stretched up to 1.5 percent in length and 2.5 percent in width (Maling, 1989). After the paper dries and cools, it shrinks by 0.5 percent in length and 0.75 percent in width. The net change in the dimensions of the paper map after printing and cooling may be 1.25 percent in length and 2.5 percent in width (Maling, 1989).

Error Introduced by the Use of Uniform Scale

The scale quoted in a map is what is known as the principal scale which is true. For example, for the Lambert conformal projection the principal scale is true only along standard parallels. The scale is too small between the parallels and too large outside the parallels. Therefore, one should use the proper scale factor correction when digitizing a map or when measuring distances from maps.

When information from different maps is collected, then one has to make sure that they are using the same map projections and are of compatible scales. Revised "old" maps may have used different map projections in a new edition, but this may not have been stated in the peripheral information (Snyder, 1987).

Definition of Feature

Many natural features do not have a clear-cut boundary. For example, where does one exactly mark a coastline? Is it at Mean High Water (MHW), Mean Higher High Water (MHHW), or Mean Low Water (MLW)? Other features, such as the boundary between forested areas and non-forested areas, are also fuzzy. The width of a river is different at rainy and dry seasons, etc. Therefore, feature definition could introduce some uncertainty in the position of a feature. It must be recognized that not all features will exhibit this error.

Error Introduced Due to Feature Exaggeration

In order to increase the communicative value and legibility of a map, features are sometimes exaggerated because they cannot be portrayed at their proper dimensions. For example, a boundary line normally does not have a width yet when it is plotted on a map it occupies a substantial width. Some features are more exaggerated than others depending on the purpose of a map. For example, roads are exaggerated on a road map. Error due to feature exaggeration could be substantial depending on the scale and purpose of the map and the type of feature involved. Again, one must point out that not all features will have this kind of error.

Errors in Digitization

Digitization and scanning errors depend on the following factors:

- width of the feature,
- skill of the operator,
- complexity of the feature,
- resolution of the digitizer, and
- density of the features.

When digitizing a thick line, it is difficult to continually place the curser on the middle of the line. The operator is also likely to make more errors when digitizing in areas where the features are dense, for example, contour lines in mountainous areas. The operator is also likely to make errors when he/she is tired. Note that errors for point features will not be the same as for linear features. The digitization error is quoted (Petrie, 1990) as $e_{11} = 0.25$ mm. Line following techniques and scanners perhaps introduce fewer planimetric errors, but errors in feature tagging could be higher in the case of scanning.

Total Error

It is very difficult, if not impossible, to assess the total error introduced in the secondary methods of data collection because we do not know the functional relationship among the various errors introduced at different stages of the mapping processes, dimensional instability of the medium, and digitization. Assuming that a linear relationship exists between the total error and the individual errors, the total error may be computed by using the law of propagation of errors (Drummond, 1990, Uotila, 1986):

$$\text{Total error} = (e_1^2 + e_2^2 + e_3^2 + e_5^2 + e_6^2 + e_7^2 + e_{11}^2)^{1/2}$$

Worst case scenario

$$\text{Total (RMS) error} = (0.32^2 + 0.32^2 + 0.18^2 + 0.2^2 + 0.30^2 + 0.48^2 + 0.25^2)^{1/2} = 0.81 \text{ mm at map scale.}$$

Best case scenario

$$\text{Total (RMS) error} = (0.01^2 + 0.30^2 + 0.06^2 + 0.10^2 + 0.17^2 + 0.24^2 + 0.25^2)^{1/2} = 0.50 \text{ mm at map scale.}$$

The above computations show that the positions could be off by several metres if we use maps at scales of 1:24,000. This obviously is an unacceptable error for many applications.

NONQUANTITATIVE ERRORS

Factual errors, rather than positional errors, must also be considered. These errors could be of paramount importance. The following is a partial list of errors(which are nonpositional) found in spatial data (Thompson, 1987):

Error Due to Mislabeling

Errors caused by mislabeling could be embarrassing. For example, Thompson (1987) states "Your map designates our local pond as poison lake. Everybody around here knows that the original cajun settlers named it 'Lac des Poissons' because there were so many fish in it. Your map with the poison label is ruining my business."

Errors Due to Misclassification

Factual errors may also be introduced due to misclassification of roads, symbols, woodlands, etc. The use of proper names and spelling of names is equally important. Errors in names are especially prevalent in maps of foreign countries.

Errors Due to Feature Coding

Digitized features such as contour lines or rivers need to have their attribute information tagged. Errors are likely to occur during feature tagging. These are nonpositional errors.

Factual information is either right or wrong. Therefore, no accuracy specification or standard exists for this type of information.

A comparison of primary and secondary methods of data collection is given in Table 3.

IMPORTANCE OF DATA QUALITY AND ACCURACY IN A GIS

Prior to the introduction of computers in spatial data handling, spatial data were (and still are) displayed on maps which have inherent accuracy limitations, as stated earlier. Maps also state whether they satisfy National Mapping Accuracy requirements or not. The introduction of computers in spatial data handling has introduced a false sense of accuracy. Those who are not aware of the problems, limitations, and approximations involved in spatial data collection do not understand that one cannot use spatial data at scales larger than the scale of the original document from which the data were derived. Some claim "because I have digital data I can produce maps at any desired scale." This is not the case at scales larger than those that meet the specifications of the original spatial data set.

A GIS without the basis of accurate data is compared by Poiker, as quoted in Goodchild and Duduc (1987), to "a person with the body of an athlete in his prime time and the mind of a child." Obviously, the main functions of GIS such as map overlay, intersection, and analysis cannot be performed if the data are inaccurate. Rubber sheeting is not the proper procedure to get rid of the slivers and gaps introduced by the overlaying of incompatible spatial data because it can introduce potentially large errors which are unacceptable. If the spatial data are positionally accurate, slivers and gaps simply do not occur.

Data for use in GISs are obtained from several sources collected at different times. In addition, these data have variable scale, and possibly different map projections. Obviously, there are serious problems in comparing and relating spatial data unless the data are obtained from sources of high quality, that is, data collected according to well defined specifications and standards (Dahlberg, 1986).

The following is a classic example of how data used in a GIS are drawn from diverse sources which are of doubtful accuracy (Strong and Lenz, 1988):

> "The 1:24,000 and the 1:250,000 scale USGS topographic maps were used as base maps... . Political boundaries were digitized from the 1:24,000 scale maps while the 1:250,000 maps served primarily as a reference tool. Transportation data was obtained from one inch to a mile and half inch to a mile maps produced by the Alabama Highway Department. Wetlands data were obtained from the U.S. Fish and Wildlife service on 1:24,000 scale maps. Public water lines were obtained from a local engineering firm and from the Alabama State Planning Agency. Flood hazard maps came from the Federal Emergency Management Authority (FEMA) at scales from 1:12,000 and 1:24,000. Utilities data were obtained from several local utilities departments. Water quality information was obtained from an environmental impact report developed by the U.S. Army Corps of Engineers for the Tennessee-Tombigbee Waterway. The soil surveys for both counties provided the maps for soils layer. Digital data collected for the database included portions of two 1:250,000 digital elevation models and an early spring 1981 Landsat multispectral scanner scene."

From the above example, one can see the problems involved in integrating the data collected from scales ranging from engineering plans (1:500?) to small scale (1:250,000) topographic maps. These data were collected by at least ten different agencies. It would be interesting to know the age of the various data used along with their quality and accuracy.

A principal deficiency of spatial information systems is that they do not include information about the sources, quality, and accuracy of data. What type of spatial transformation has already been carried out with the data. All GIS software should be able to carry out an affine transformation which includes a six-parameter transformation between the two-dimensional coordinate systems used (Bossler, 1987). The six parameters include the effect of translation, rotation, and scale changes between the coordinate systems. Some GIS software, e.g., the Synercom system, already includes a six-parameter affine transformation known as ZORRO (Bossler, 1987). Goodchild and Gopal (1990) state:

> "No current GIS warns the user when a map digitized at 1:24,000 is overlaid with one digitized at 1:1,000,000 and the result is plotted at 1:24,000, and no current GIS carries the scale of the source of document as an attribute of the dataset. Few even adjust tolerances when scales change. Most vector systems perform operations such as line intersections, overlay or buffer zone generation at the full precision of the coordinates, without attention to their accuracy. As a result inaccuracy often comes as a surprise when the results of the GIS analysis are checked against ground truth, or when plans developed using GIS are implemented. An agency proposing a GIS-based plan loses credibility rapidly when its proposals are found to be inconsistent with known geographical truth" ... "We can now produce rubbish faster and with more elegance than ever before."

In addition to the error inherent in the input data, other errors are introduced during GIS manipulation functions (Walsh *et al.*, 1987). A GIS dealing with several different layers of data collected from manifold sources, scales, dates, and map projections will have its error propagated in a very complex way. It will be difficult to propagate these errors unless one can establish some empirical relationship among these different sources and layers of data.

Openshaw (1990) lists the following reasons why GIS developers and users have taken a very naive approach to GIS data accuracy and quality:

- Current use of spatial data is a continuation of the past even though we are using more precise tools than before. It was not a problem in the past. Why now?
- There is a lack of techniques for measuring uncertainty properties of spatial data and GIS outputs.
- The seriousness of the problem is unknown.
- Lack of consensus on the data quality and accuracy because user requirements vary widely.
- Lack of established rules for dealing with errors in GIS functions.
- Lack of standard methods for modeling error in GIS functions.

Emphasizing the need for accuracy and reliability of data in a GIS, Lanter and Veregin (1990) assert that a "GIS provides a means of deriving information without simultaneously providing a means to provide its reliability. The literature detailing GIS applications lacks concern for the presence of errors in spatial databases and their propagation through sequences of GIS functions ... input data quality is not often ascertained, functions are applied without regard for accuracy of the resulting products, and derived products are presented without an associate estimate of their reliability or an indication of the types of error

TABLE 3. A COMPARISON OF PRIMARY AND SECONDARY METHODS OF DATA COLLECTION.

Factors	Primary methods	Secondary Methods
Datum definition	taken into account	not taken into account
Map projection	taken into account	mostly ignored
Scale	wide range of scales	limited range of scales
Age of data	current	old
Accuracy	very high	low
Costs	high	low
Standards and specifications	very rigid standard and specifications	nonexistent
Density of observations	can be high depending on the requirements	low depends on type existing information
Nonquantitative accuracy or thematic accuracy	high	low
Generalization	Limited effect of generalization	very much affected by generalization
Displacement	not affected	affected
Exaggeration	not affected	affected

TABLE 4. POSSIBLE USES OF PRIMARY METHODS OF DATA COLLECTION (PETRIE, 1990).

Source of data	Equipment Used	Accuracy	Coverage	Typical Uses
Field survey	Total stations	very high	Areas less 20 acres	small engineering projects
Photogrammetric methods	Analog or analytical plotters	depends on scale high	large areas	national mapping, large eng. projects

TABLE 5. POSSIBLE USES OF SECONDARY METHODS OF DATA COLLECTION (PETRIE, 1990).

Source of data	Equipment Used	Accuracy	Coverage	Typical Uses
Existing plans & maps	Manual digitizer	low depends on scale, accuracy & age of maps	small areas	applied to areas in which accurate & current data not important.
Same as above	Line-following	Same as above	medium size areas	Same as above
Same as above	Raster scanning	Same as above	Large areas	Same as above

introduced by GIS processing." Tables 4 and 5 give the possible uses of primary and secondary methods of data collection.

CONCLUSIONS

- Rigorous standards and specifications exist for primary methods of data collection. However, no such standards and specifications exist for secondary methods of data collection.
- There is a real need for establishing some kind of standard and specification to be developed for spatial data used in GISs.
- Primary methods of data collection should be used in all those areas in which the spatial accuracy and age of data are critical.
- No rigorous method exists to evaluate the errors of secondary methods of data collection.
- Secondary methods of data collection contain numerous errors in addition to those found in the primary methods.

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