THE ERROR COMPONENT IN SPATIAL DATA

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Although most data gathering disciplines treat error as an embarrassing issue to be expunged, the error inherent in spatial data deserves closer attention and public understanding. This chapter presents a review of the components of error in spatial data, based on Sinton's scheme of roles in the measurement process and also on the categories in the US Proposed Standard for Digital Cartographic Data Quality.

BACKGROUND: ERROR AND DATA QUALITY DEFINITIONS

No map can be picked apart into completely independent pellets of information. There is something collective and comprehensive about the spatial representation. First, the map is spatially continuous and comiected. There is also a deeper reason. Individual facts become more useful information through an interaction with a structure of theory that provides a context to interpret the individual facts. In common usage, the main distinction between data and information arises from meaning, but meaning is context dependent. To be more concrete, the process of converting a particular fact into information must comprehend the fitness of that fact for some particular purpose. This line of argument provides an important introduction to the role of data quality in an information system.

Quality has various definitions in industrial engineering (Hayes and Romig 1977), but one accepted definition is `fitness for use' (Chrisman 1983). Recently, the US National Committee Digital Cartographic Data Standards Task Force (DCDSTF 1988) has adopted this definition formally for inclusion in a US national standard for exchange of spatial data. The standard requires a quality report that provides the basis for a user to make the final judgement - the conversion to information by interpretation for a particular use. This particular element of the US proposal has also been adopted, at least in spirit, by a British proposal (Haywood 1986), and the French (Salge and Sclafer 1989), among others.

Quality is a neutral term, fitting for a national standard, but the tough issues of quality are best evoked by the loaded word `error'. In common usage, error is a bad thing, and many professions related to spatial data share this attitude. For instance, geodesists, surveyors and photogrammetrists go to great lengths to reduce the error in their measurement products. For these disciplines the full attention focuses on the reduction of deviation between positional measurements and `ground truth'. Cartographers, perhaps because they often cannot remove all error, have two incompatible approaches, both designed to avoid the issue. One tendency is to generate authoritative maps, through their official status or some other form of paternalism. The traditional approach to standards places little emphasis on a user's determination of a particular need. The other tendency, more common in academic circles, adopts the communication paradigm and expects the cartographer to use all means to communicate the message (Robinson *et al.* 1984). The communication paradigm, like a paternalist agency, assumes that the map maker controls the process, particularly the judgement of fitness for use. In summary, the disciplines of mapping technology are bent on reducing error or minimizing its importance. While this may be a reasonable approach to foster the current divisions of labour, it does not lead to the full exploitation of spatial information.

Error is not a problem unique to spatial evidence. Other disciplines have created other solutions which are worth considering. Most physical, biological and social sciences integrate data collectors and data analysts into the same discipline, while mapping places them in distinct guilds. Perhaps as a result, error bars or some other estimates appear on the display of most physical measurements. Also, even the popular press presents a standard error of estimate for opinion poll results. Reporting error is not a sign of weakness in these other disciplines, because the error estimate provides crucial information which must be preserved for correct interpretation. The most developed scientific approach to error is the body of statistical procedures which have developed over the past century. However, many of the advanced techniques in statistics are not attuned to the problems inherent in geographical information.

For some attempts to understand the statistical basis of errors in spatial databases see White (1978), Goodchild and Dubuc (1987) and Goodchild and Gopal (1989).

Basic terms for error

Before delving deeper, it is useful to present some fundamental terms to discuss error. Under the general intent of describing data quality the goal is to describe fitness for some particular use. Many numerically oriented disciplines have developed a concept of error as a deviation (or distance) between a measurement and the `true' value. Different disciplines use different terms to refer to this concept, and some of these terms conflict. This chapter will follow the general practice of the mapping sciences (see DCDSTF 1988: 28) and use the term accuracy to refer to the closeness of an observation to a true value (or one accepted as true). This definition of accuracy implies an independent, objective external reality and sets the highest standard for the concept of accuracy. In some contexts, a measurement system may produce inaccurate results that preserve local relationships. Statistically, such a condition arises from `systematic' error (as opposed to random error). Systematic error involves a uniform shift of values, hence the term `bias' which is applied in some measurement sciences. Such systems are described by cartographers as having `relative accuracy', but this property is usually a sign that the process of data preparation (compilation) has not been completed. In the spirit of `fitness for use', relative accuracy may be perfectly viable for some applications, while unfit for others which depend on geodetic registration.

The concept of accuracy is essentially independent of the issue of resolution although both contribute to overall data quality. The resolution of a measurement system is the minimum distance which can be recorded. Clearly, resolution sets a lower bound on accuracy. It is considered good practice to make this minimum difference smaller than the accuracy of the whole system, but a user should not confuse the two. Both resolution and accuracy can be applied to the various components of spatial information, both attributes (Dueker 1979) and positions (Tobler 1988; see also Fisher 1991 in this volume).

This chapter argues that error is an integral part of spatial information processing. The goal is to cover the full range of error in geographical databases as a fundamental introduction to the nature of spatial data. The chapter first describes the conceptual role of error in the nature of spatial data with particular attention to the question `How many dimensions?' This is followed by a review of spatial error models in a variety of disciplines, structured by the categories proposed for the Quality Report mandated by the US National Committee for Digital Cartographic Data Standards. From this review, a comprehensive view of error should emerge.

DEALING WITH SPATIAL DATA: HOW MANY'DIMENSIONS?

It is relatively commonplace, particularly for those schooled in thematic cartography, to consider spatial data to consist of two major ingredients: position and attribute (see, e.g. Peucker 1972: 23). However, the concept of information in GIS cannot be restricted to recording attribute and position; more `dimensions' are required. Any measurement of these components has an inherent uncertainty. In general, error must not be treated as a potentially embarrassing inconvenience, because error provides a critical component in judging fitness for use. Understanding the error in spatial databases is necessary to ensure appropriate application of GIS and to ensure progress in theory and tool development.

Basic dimensions

It does not take a complex philosophical effort to observe that we inhabit a three-dimensional world. Distances of length, breadth and height serve to construct human artefacts and place them on the landscape. Thus, it is to be expected that a spatial database (a GIS) be embedded in the basic dimensions of the earth.

But are these physical dimensions the only ones? This question must be answered in order to understand the complete nature of spatial data. A scientific investigation must occur in the full dimensionality of the problem or critical issues become confused. Discovering the complete dimensionality of a geographical investigation is a crucial step, although it is not commonly approached in these terms. The design phase of an information system, often conducted as a `needs analysis', attempts to define all the information required. In many of the routine applications of this technology, the demands for information can be reasonably easily predicted. However, a major advantage of a GIS lies exactly in its ability to accommodate unanticipated needs. Fundamental dimensions may be distinct from the details seen in a typical needs study.

The design of GIS must understand the complete scope of the components of spatial information. The basic questions behind the `nature of spatial data' are: `What do we need to know and how should we structure that knowledge?'. An answer to these questions must address how we know what we know, because not all information is equally reliable or useful.

The initial answer to the full dimensionality of geographical information can be given using the long-standing conventions of cartography. The development of thematic cartography has fostered the recognition of space, attribute and time as the basic components of mapping. This list seems complete for describing the surface of the earth. However, the requirements for a geographical information system cannot be simply contained by a description of the surface of the earth. There is an important distinction between the real world and the symbolic representations that can be manipulated. To take Korzybski's (1948) dictum perhaps more literally than he did: `the map is not the territory'. In the early enthusiasm of GIS, users treated their data as a perfect model of the world too often. On slight reflection, it should be apparent that no representation captures a perfect replica of something as complex as the earth. These forcible deviations between a representation and actual circumstances constitute error.

Because error is inescapable, it should be recognized as a fundamental dimension of data. A scheme for representation should be extended to include the amount of deviation in each component (space, attribute and time). Only when error is included into the representation is it possible to answer some probing questions about the limitations of current knowledge.

Of course, one goal of any information specialist is to avoid needless error. By directly recognizing error, it may be possible to confine it to acceptable limits. Still, error cannot always be avoided cheaply or easily.

Beyond dimensions: the changing roles of position, attribute and error

In 1977, David Sinton (1978) presented a fundamental analysis of the information contained in a GIS. His three basic components (he used the terms location, theme and time) were widely accepted long before then in thematic cartography [Robinson (1960: 11-12) makes the distinction between `base data' and `subject matter']. Before thematic cartography emerged, map information was not viewed in as analytical terms. The development of thematic cartography led to the recognition that the geometrical framework of a map (the base layer) could be used to portray multiple `themes', essentially attributes of the objects represented in the base layer. In doing so, there is at least a tacit recognition of time as well.

The critical development in Sinton's paper was the recognition of three distinct roles that location, theme and time play in a particular information context. While the goal is to obtain a measurement, measurement of one component can only be made inside explicit constraints on the other components.

The roles Sinton described are termed fixed, controlled and measured. Most spatial information sources fix one of the three components; in the case of maps, it is time which is normally fixed. Of course it is possible to graph the amount of rainfall at a specific weather station over time, but this information is usually robbed of its temporal depth when placed into the spatial framework. Whichever it is, the fixed component does not exhibit any variation, by definition. In order to make a measurement, a second component is usually controlled, meaning that its variation is limited and predicted. A common form of spatial control is to summarize (total, average, etc.) a spatial distribution (attribute) for a collection zone or administrative region. These units provide the spatial control for the measurement of the thematic attribute. Once the fixed and controlled elements are established, it is possible to make a measurement.

Map sources nearly universally fix time, leaving space and attribute - the two components recognized by thematic cartographers. Time is a rich area for further research into the nature of spatial information (Langran and Chrisman 1988). However, to build a theory of error, it is important to scrutinize Sinton's distinction between controlled and measured.

Sinton's scheme was proposed largely to organize the difference between methods that control space compared with those that control attributes. Sinton's own work during that period had concentrated on grid cell databases which impose a lattice of cells as a control framework for a series of diverse maps. Each theme (attribute) was measured inside each cell. While Sinton's grid inventories were typically performed by armies of students, most remote sensing sources also fall into this general approach using nearly regular cells as control. These remote sensing sources include satellite platforms along with photogrammetric equipment used to create digital elevation matrices. Although some of these sources attempt to acquire only a categorical measurement (e.g. of land use), the inherent method permits a measurement on a continuous scale (as, e.g. reflectance or elevation). Not all forms of spatial control use a uniform tessellation of cells. Census tabulations and administrative data such as school attendance are usually summarized for irregular spatial units, often as a means to understand an unmeasurable continuous surface (such as population density). While these varieties of data are not usually handled together, the nature of spatial control creates some similarities discussed below.

The opposite case arises by using attributes as control in order to obtain spatial measurements. Sinton was particularly focused on types of maps such as vegetation, geology and soils. While these look like choropleth maps made with administrative zones, they are conceptually distinct, particularly when considering the error ramifications. No term has received universal approval for this form of map: Chrisman (1982a) suggested `categorical coverage', ESRI adopted the term `coverage' for a more general use in ARGINFO, Mark and Csillag (1989) used 'area-class map' (citing Bunge 1966: 14-23) and Muehrcke (1986) used `mosaic surface'. All these terms communicate the difference much better than Burrough's (1986a) use of the `choropleth map' to cover both cases.

Beyond the categorical coverage, many other circumstances require attributes as control to obtain positional measurement. Much of the traditional cartography on topographic maps and nautical charts portrays discrete `features'. Recognition of a feature's existence is the control, then the spatial footprint is recorded. To some extent, a `feature' database is fairly similar to a coverage database without the concern for exhaustive, comprehensive and exclusive classification. Whereas a coverage forces all places to have one and only one category present, a particular feature may have a number of distinct characteristics, while much of the study area is simply a void. Still, these two are unified to the extent that the attribute classification provides control to the geometric measurement. Without cataloguing all of the differences, it should be apparent that these diverse cases deserve consideration in understanding the nature of spatial data and its inherent error.

A TAXONOMY OF ERROR IN GIS DATA

Understanding error in GIS must take account of Sinton's framework, although an alternative approach is suggested by Veregin (1989). This section will take up the testable components specified in the US Proposed Standard, connecting them to Sinton's framework. After this review, the different views of disciplines will be placed in some sort of perspective.

Positional accuracy

The best established issue of accuracy in the mapping sciences has been lumped into the testable component of `positional accuracy' by the US Proposed Standard (DCDSTF 1988: 132-3). The geometrical accuracy of maps has been a topic of concern long before computerization. The earlier US National Map Accuracy Standard (Bureau of the Budget 1947) considered the accuracy of 'well-defined points' as the sole measure of a map. The well-defined point means that there is no attribute ambiguity; it can act as control for the positional measurement. Because it is a point, there is no dimensional ambiguity either. The focus on the most identifiable cartographic features persists in the revised procedures for testing large-scale line maps adopted recently by the American Society for Photogrammetry and Remote Sensing (ASPRS) (1989). The disciplines of geodesy, surveying and photogrammetry define map accuracy as absolute positional accuracy. There was an attempt in the earlier drafts of the ASPRS standard to separate the components of bias (mean deviation) in a test, leaving the relative accuracy as an identifiable quantity (standard deviation from the mean). However, there was well-placed opposition, and the standard reverted to a single measure of absolute accuracy (root-mean-square deviation from zero). The fact that certain government agencies wish to have a simple standard does not mean that the problem is simple. A test for positional accuracy will generate a set of displacements between the observed and `true' values. These numbers should be reported so that a user can extract the particular measure for the particular use. In a GIS setting, bias can often be eliminated through some form of best fit. In fact, many geometrical measures like polygon area are immune to such systematic (`relative') errors (Chrisman and Yandell 1988), although the fundamental tool of polygon overlay relies upon_ absolute positioning between layers.

In testing a GIS layer, the source of `truth' may be relatively easy to determine. There are often external sources of higher accuracy for a few features in a database (such as monuments used as control for topographic maps which are also located in street intersections). Still, it may be necessary to obtain the higher accuracy data directly, causing a potential recursion. The ASPRS standard specifies that a check survey to determine true locations must have a positional accuracy of one-third the amount expected for the product to be tested. Any such survey must ultimately tie back to the geodetic reference network. Indeed, the geodetic reference network cannot be checked in this manner, since it is constructed from relative measurements to create the absolute framework for everything else. The arcane nature of geodesy will become more relevant to the average GIS user as Global Positioning System (GPS) surveys become more prevalent.

Although the positional accuracy of maps is well accepted, few actual tests are published (one test of USGS DLG data appeared in Vonderohe and Chrisman 1985). The National Map Accuracy Standard is written like the text of a nuclear weapons treaty because it places each producer in charge of the decision of whether to test or not. Users of positional information, even if it claims to comply with the National Map Accuracy Standard, should be aware that the particular product was probably not tested. Most US agencies infer that the particular sheet would have passed the test based on compliance with certain specified procedures and equipment. This inference should be calibrated with a testing programme, but even that may be less frequent than most users imagine. As the new standards come into force, and the technology for direct field measurement (e.g. with GPS technology) becomes available, perhaps the prevalence of testing will change.

Many of the data in a GIS do not fit the restrictive definition of well-defined points. There are two approaches to resolve this. The standard approach assumes that all features on a map can be characterized by the error in the position of the well-defined points. This is an unwritten assumption behind many efforts in cartography. However, this assumption can only be used as a lower threshold. The uncertainty in positioning an `ill-defined' object must be added on to the error in the well-defined points. But where would the lack of definition come from? The fact that an object does not have a sharp location to test may come from certain geometrical constraints. For example, the standards expect to test right-angle road intersections, so that the linear feature can be confined to a specific point. This geometrical characteristic goes beyond Sinton's framework. However, many of the features in a GIS do not fit purely geometrical constraints. The object may not really have the sharp attribute definition required to rely on the attribute for control. A number of research workers (e.g. Burrough 1989) have recognized that fuzzy sets often are a better description of certain layers. In this case, it would be impossible to test for positional accuracy without converting the fuzzy classification into a sharp system of control. These cases are better handled by including the attribute alongside the position in the test, a concept developed below.

Attribute accuracy

Testing attribute accuracy falls into two broad groups, depending on the level of measurement of the attribute. Position has a built-in metric, that is, the conversion between coordinates and distance makes sense. The measurement of error is quite direct with such a metric. Some attributes use continuous scales whose values can be treated in much the same manner as position. The clearest example is the surface of relief or elevation, encoded in digital terrain models of various descriptions. In fact, the ASPRS standard includes specific treatment of the positional accuracy of contours, treated as a three-dimensional position. The horizontal allowance for the contour under the map accuracy standard is widened by the horizontal equivalent of half the contour interval vertically. This works because elevation is measured in the same metric as horizontal position. In practice, the photogrammetric treatment is accepting that horizontal accuracy and vertical accuracy cannot be separated in the contour presentation.

More generally, a surface can be tested by measuring the deviation between the `true' height and the observed height reported by classical descriptive statistics as with positions. When a surface is expected to be essentially continuous, an impressive array of mathematical tools is available to analyse the spatial variation. A field of geostatistics has arisen around an approach to interpolation called `Kriging' which creates models of spatial dependence and lag (Burgess and Webster 1980; Burrough 1983, 1986a, 1991 in this volume). These models of spatial variation offer important tools to the GIS user, but they are restricted to the particular form of spatial data where the attribute is continuous and measured at locations controlled by specific sampling sites (e.g. wells) or controlled to a regular grid. Kriging has developed in the natural sciences, often to treat interpolation between sparse sampling sites. There is a related mathematics developed from the spatial adaptation of time series analysis in the social sciences under the general title 'spatial autocorrelation'. Sometimes spatial autocorrelation deals with continuous measures of distance between points. However, in geography it is more often targeted to removing the effects of spatial collection zones on spatially aggregated attributes (Cliff and Ord 1981; Goodchild 1988). There are significant differences between the area basis of this `modifiable areal unit problem' (Arbia 1989) and the point basis of Kriging, but both use a form of spatial control, with attributes measured. For this combination, there are many analytical procedures which have been developed, but these procedures are not as widely used as they should be (Burrough 1986b).

The other group of attributes are categories, usually nominal classes as used in land use, soils and vegetation inventories. Polygon coverages of such maps have formed a critical core of early GIS operations because they could benefit from simple analytical tools such as polygon overlay (Goodchild 1978). Some commentators on GIS follow the pattern in most sciences and consider categorical data to be of lower standing. These authors are often correct in their criticism of the blind adoption of sharp set theory for much more complex environments (e.g. Burrough 1989). However, the role of control in spatial data cannot be taken by a continuous measure. In the pure form, categorical coverages are constructed by setting the attribute as control and measuring the location of the boundaries between classes. In practice, of course, there is significant error in identifying the categories on such maps. Certain disciplines, particularly remote sensing interpretation, place central importance on testing the accuracy of classification. With categorical attributes, there is no such thing as a close value or a metric of deviations. A class is either right or wrong (some wrong answers might be ordered by degree of dissimilarity, but that nuance will be ignored here). So, there is no easy summary of performance to compare with the summary statistics of deviations reported in the ASPRS positional test. A test involves determining the classification from two sources, and ideally one should be a source of higher accuracy. The results of a test will create a square misclassification matrix, cross-tabulating the observed category with the true result. In reading this matrix, it is possible to proceed by rows or columns. A row consists of all the observations which should have been classified in a particular category. A column consists of all the observations which were so classified. The diagonal of the matrix will fit both, and captures the agreement of the two sources. Errors along rows are errors of omission with respect to that category. Errors along columns are errors of commission. In medicine these are called false negatives and false positives respectively.

It is common to summarize this matrix by the percentage correct, the total of the diagonal. This measure, unfortunately, is not a reliable index of success across projects with differing frequencies in the various categories (Rosenfield and Melley 1980; Chrisman 1982b). A number of alternative measures of success have been suggested, notably Cohen's Kappa, a measure which deflates the percentage correct by the amount which could be expected to fall into the diagonal under an independent rule of joint probability. Still the raw matrix offers the most complete information to assess fitness for use.

The misclassification matrix is typically obtained through a process of point sampling (Berry and Baker 1968; Fitzpatrick-Lins 1981). A set of points is selected from some spatial sampling scheme, and the classification obtained from each source. Despite its widespread use, there are some difficulties associated with such a point-based approach. The classifications on a coverage map are not always a pure fit to the sharp set theory required to make it work. Often a classification system has some implicit (or explicit) scale involved. If a point happens to fall in a convenience store (in US context; in UK a newsagent) parking lot, does that mean that a residential land use code is invalid? The residential category involves a bit less homogeneity than the mathematical purity would suggest. A few neighbourhood commercial enterprises are a part of residential character, such businesses would not locate in purely commercial surroundings anyway. Hence, the point sampling method cannot really test simply one point, it involves an area and it can become confused when it is near an edge. In some tests, the points are deliberately positioned away from edges, but that may introduce a whole new set of difficulties. One alternative, not much practised yet, is to produce the misclassification matrix by overlaying a complete second coverage (e.g. see Ventura, Sullivan and Chrisman 1986). The second coverage can be chosen deliberately to use a similar scale and resolution in its categories or a more refined set of categories and more detailed scale (see for example Beard 1987). In either case, the result of the overlay will give a raw measure of area in the misclassification matrix. Furthermore, the nature of the overlaid objects will give some clues to the origin of the error. Chrisman (1989) has presented a taxonomy of the results obtained. He creates a basic distinction between error caused by misclassifying whole objects (identification error) and error in positioning boundaries (discrimination error). The former is a purely attribute error, but the latter includes some of the `fuzzy' effects discussed by many authors. These two tendencies create specific forms in the overlay test. Identification errors will have lines mainly from one source, while discrimination errors will tend to have lines in roughly equal amounts from the two sources. In addition, this taxonomy is modified by the effects of scale. Smaller and larger objects may clearly arise from different sources. Considering all the possible ramifications of error, it seems unlikely that a single number can compress all the information available from such a test.

In Sinton's framework, a test for attribute accuracy fits the opposite cases compared to positional accuracy. The classical test of a well defined point (attribute controlled, position measured) depends critically on identification of the proper points to test. If the wrong point is tested, error estimation procedures based on Gaussian error will misbehave dramatically. There is significant literature in the fields of geodesy (e.g. Crossilla 1986) and photogrammetry (e.g. Kubik, Lyons and Merchant, 1988, and Shyue 1989) on detecting such `blunders'. Outlier handling procedures are not designed as tests of attribute accuracy; their mathematics make them more like the tests of logical consistency discussed below. However, the fundamental cause for such blunders may be in the identification of the point to test.

B. Logical consistency

The traditional approach to map accuracy never makes explicit mention of a category of testing which has become quite important in the computer age. Actually, a large amount of the manual practice of cartography involved testing the logical consistency of the product with the highly sophisticated visual processor of the human cartographer. The human eye-mind combination can detect slight gaps in linework and other patterns, but it is difficult to discipline employees to spend all day scrutinizing a complex map. In some agencies, it was common to test the consistency of a coverage of polygons by colouring them in with coloured pencils. This process would point out missing lines by finding that colours (keyed by the soil labels) would not have an intervening boundary. The process would also detect any polygon without a label to start the colouring. It might take the employee all day to check a polygon network which could be checked in a minute or less using a computer algorithm for topological testing (Chrisman 1986, 1987).

The use of the topological model in modern GIS provides one example of logical consistency checking. The redundant nature of the topological encoding can detect a number of flaws in the data structure (White 1984; Chrisman 1987), such as missing boundaries or unlabelled polygons. Use of logical consistency checks can avoid errors which would be interpreted as routine errors in position or attribute.

The topological model is not the only means to check logical consistency. Whenever there is some external mathematical or logical relationship which must be maintained, a consistency test should be administered. Some database management systems implement valid ranges on attribute fields, but the spatial nature of a GIS, with the ability to relate layers, offers a much richer set of consistency checks. A simple computation of point-in-polygon could avoid placing buoys on dry land or rivers outside their floodplain. Although these seem ridiculous, a GIS database will contain such errors until the full analytical power of the tool is turned back against its own database. Once an error is detected by a logical consistency check, it may be resolved through a panoply of procedures, approximating the manual process of compilation which resolves conflicting sources.

Completeness

The last component of testing in the US Proposed Standard is completeness. In some circumstances, usually in creating a base layer of named objects such as parcels, census tracts or whatever, there is an externally known list of objects which should appear in the database. A coverage of parcel polygons could be tested polygon by polygon as a verification of attribute accuracy. A simpler, less complete check could be performed by checking whether the database included all the parcels in the master list. All differences could be immediately flagged as errors. Such a test falls somewhere near a logical consistency check and an attribute accuracy test. For convenience, it can be termed completeness.

Another aspect of completeness deals with the mapping rules associated with many cartographic presentations. Some categorical coverages will set a threshold of minimum areas or widths to include on the map. Often these are prescribed in the manual, but never explicitly tested. This aspect of the quality report deals with the scale effects discussed in the context of the polygon overlay testing procedure.

ERROR: A DISCIPLINARY MOSAIC

Investigations of geographical information have been an amalgamation pasted together from a variety of different disciplines. The list of different forms of error presented above naturally connects to the divergent problems of specific disciplines. Each discipline constitutes a group faced with a particular circumstance - a particular set of tools and purposes. Any combined view depends on understanding the diversity and mobilizing the different perspectives to a redefined purpose. Disciplinary difergences are relatively common, but particularly notable in the treatment of spatial error.

Error reduction is a primary goal in the earth measurement disciplines of surveying, photogrammetry and geodesy. These disciplines have developed procedures to obtain reliable positional measurements through the use of repeated measurement and a specialized version of least-squares estimation (Mikhail 1976). Much of the mathematics for surveying adjustments has been developed inside the discipline without substantial borrowing from other disciplines, because it is tailored to the specific form of error expected from each type of equipment. By contrast, social scientists (including geographers) tended to develop quantitative methods by borrowing statistical tools from others. The approach to error is thus imported as well. Standard statistical procedures deal most directly with errors from sampling, although there has been substantial development of spatial autocorrelation. Cartographers have developed two distinct tracks, an analytical school and a communication school. The first fits in with quantitative geography, while the second treats the psychophysical process of map reading and the divergence between the message intended and received. Out of these utterly incompatible disciplines, the field of GIS must try to forge a unified understanding of the errors that occur and how they must be treated.

LIVING WITH ERROR

Once a model of error is developed, what good does it do? In the traditional view, say of a surveyor, a measure of error helps to eradicate error. Under such a regime, a data producer (map maker) attempts to keep all maps accurate to a specified tolerance. Many agencies embarking on an automation campaign do so inside the guidelines of their disciplinary perspective. It is only natural to carry along the attitudes towards error.

As GIS develops, databases will become more and more pivotal to a diverse range of users, and the ability to determine a blanket tolerance will become less certain. Measures of data quality will provide a key to suitability for a specific task (fitness for use). With this transition, any disciplinary narrowness will not survive.

The field of GIS should also put significant effort into the development of methods to report and visualize the error in databases. A reporting scheme would permit statements, such as those permissible using standard statistical tests, except that they would adjust for the particularly spatial form of the error. A few such tools, mentioned above, exist, but most do not. Even fewer are implemented in production GIS.

REFERENCES

American Society for Photogrammetry and Remote Sensing (1989) Interim accuracy standards for large scale line maps. *Photogrammetric Engineering and Remote Sensing* 55: 1038-40

Arbia G (1989) Statistical effect of spatial data transformations: a proposed general framework. In: Goodchild M F, Gopal S (eds.) *Accuracy of Spatial Databases.* Taylor & Francis, London, pp. 249-60

Beard M K (1987) How to survive on a single detailed database. *Proceedings of AUTOCART08.* ASPRS/ AGSM, Falls Church, pp. 211-20

Berry B J L, Baker A M (1968) Geographic sampling. In: Berry B J L, Marble D F (eds.) *Spatial Analysis.* Prentice Hall, Englewood Cliffs New Jersey, pp. 91-100

Bunge W (1966) *Theoretical Geography.* Gleerup, Lund Sweden

Bureau of the Budget (1947) *National Map Accuracy Standards. US* Government Printing Office, Washington DC

Burgess T M, Webster R (1980) Optimal interpolation and isarithmic mapping of soil properties. I. The semivariogram and punctual Kriging. *Journal of Soil Science 31:* 315-31

Burrough P A (1983) Multiscale sources of spatial variation in soil. I. The application of fractal concepts to nested levels. *Journal of Soil Science 34:* 577-97

Burrough P A (1986a) *Principles of Geographical Information Systems for Land Resources Assessment.* Clarendon Press, Oxford

Burrough P A (1986h) Five reasons why geographical information systems are not being used efficiently for land resources assessment. In: Blakemore M J (ed.) *Proceedings of AUTOCARTO London, Vol.* 2. Royal Institution of Chartered Surveyors, London, pp. 139-48

Burrough P A (1989) Fuzzy mathematical models for soil survey and land evaluation. *Journal of Soil Science 40:* 477-92

Burrough P A (1991) Soil information systems. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 153-69, Vol 2

Chrisman N R (1982a) A theory of cartographic error and its measurement in digital databases. *Proceedings of AUTOCART05.* ASPRS, Falls Church, pp. 159-68

Chrisman N R (1982b) Beyond accuracy assessment: correction of misclassification. *Proceedings International Society of Photogrammetry and Remote Sensing Commission IV,* 24-IV, pp. 123-32

Chrisman N R (1983) The role of quality information in the long-term functioning of a GIS. *Proceedings of AUTOCART06, Vol.* 2. ASPRS, Falls Church, pp. 303-21

Chrisman N R (1986) Quality report for Dane County soil survey digital files. In: Moellering H (ed.) *Report 7, National Committee for Digital Cartographic Data Standards, pp.* 78-88

Chrisman N R (1987) Efficient digitizing through the combination of appropriate hardware and software for error detection and correction. *International Journal of Geographical Information Systems 1:* 265-77

Chrisman N R (1989) Modeling error in overlaid categorical maps. In: Goodchild M F, Gopal S (eds.) *Accuracy of Spatial Databases.* Taylor & Francis, London, pp. 21-34

Chrisman N R, Yandell B (1988) Effects of point error on area calculations. *Surveying and Mapping 48:* 241-6

Cliff A D, Ord J K (1981) *Spatial Processes: models and applications.* Pion, London

Crossilla F (1986) Improving the outlier separability in geodetic networks according to the generalized orthomax criterion. *Manuscripta Geodaetica 11:* 38-47

DCDSTF (1988) The proposed standard for digital cartographic data. *The American Cartographer 15:* 9-140

Dueker K J (1979) Land resource information systems: spatial and attribute resolution issues. *Proceedings of AUTOCART04 Vol. 2.* ASPRS, Falls Church, pp. 328-36

Fisher P F (1991) Spatial data sources and data problems. In: Maguire D J, Goodchild M F, Rhind D W (eds.) *Geographical Information Systems: principles and applications.* Longman, London, pp. 175-89, Vol 1

Fitzpatrick-Lins K (1981) Comparison of sampling procedures and data analysis for a land use and land cover map. *Photogrammetric Engineering and Remote Sensing* 47: 343-51

Goodchild M F (1978) Statistical aspects of the polygon overlay problem. In: Dutton G (ed.) *Harvard Papers on Geographic Information Systems, Vol 6.* Addison-Wesley, Reading Massachusetts

Goodchild M F (1988) *Spatial Autocorrelation.* CATMOG (Concepts and Techniques in Modern Geography), Vol. 47. GeoBooks, Norwich

Goodchild M F, Dubuc O (1987) A model of error for choropleth maps with applications to geographic information systems. *Proceedings of AUTOCARTO8.* ASPRS/ACSM, Falls Church, pp. 165-74

Goodchild M F, Gopal S (eds.) (1989) *Accuracy of Spatial Databases.* Taylor & Francis, London

Hayes G E, Romig H G (1977) *Modern Quality Control.* Bruce, Encino California

Haywood P E (ed.) (1986) *Final Draft Papers of the Working Party to Produce National Standards for the Transfer of Digital Map Data.* Ordnance Survey, Southampton

Korzybski A (1948) *Science and Sanity: an introduction to non-Aristotelean systems and general semantics,* 3rd edn. The International Non-Aristotelean Library Publishing Co., Lakeville CT

Kubik K, Lyons K, Merchant D (1988) Photogrammetric work without blunders. *Photogrammetric Engineering and Remote Sensing* 54: 51-4

Langran G, Chrisman N R (1988) A framework for temporal geographic information. *Cartographica 25 (3):* 1-14

Mark D M, Csillag F (1989) The nature of boundaries in 'area-class maps'. *Cartographica 26 (1):* 65-78

Mikhail E H (1976) *Observations and Least Squares. IEP,* New York

Muehrcke P C (1986) *Map Use,* 2nd edn. JP Publications, Madison Wisconsin

Peucker T K (1972) *Computer Cartography,* Resource Paper 17. Association of American Geographers, Washington DC

Robinson A H (1960) *Elements of Cartography,* 2nd edn. Wiley, New York

Robinson A H, Sale R D, Morrison J L, Muehrcke P C (1984) *Elements of Cartography,* 5th edn. Wiley, New York

Rosenfield G, Melley M (1980) Applications of statistics to thematic mapping. *Photogrammetric Engineering and Remote Sensing 46:* 1287-94

Salge F, Sclafer M N (1989) A geographic data model based on HBDS concepts: the IGN cartographic database model. *Proceedings of AUTOCARTO9.* ACSM/ASPRS, Falls Church, pp. 110-17

Shyue S W (1989) *High Breakdown Point Robust Estimation for Outlier Detection in Photogrammetry.* Unpublished PhD dissertation, University of Washington

Sinton D (1978) The inherent structure of information as a constraint to analysis: mapped thematic data as a case study. In: Dutton G (ed.) *Harvard Papers on Geographic Information Systems, Vol.* 6. Addison-Wesley, Reading MA

Tobler W (1988) Resolution, resampling and all that. In: Mounsey H (ed.) *Building Databases for Global Science.* Taylor & Francis, London, pp. 129-37

Ventura S, Sullivan J G, Chrisman N R (1986) Vectorization of Landsat TM land cover classification data. *Proceedings URISA 1:* 129-40

Veregin H (1989) A taxonomy of error in spatial databases. *Technical Paper 89-12.* National Center for Geographic Information and Analysis University of California, Santa Barbara California

Vonderohe A P, Chrisman N R (1985) Tests to establish the quality of digital cartographic data: some examples from the Dane County Land Records Project. *Proceedings of* AUTOCARTOT ASPRS, Falls Church, pp. 552-9

White M (1978) A geometric model for error detection and correction. *Proceedings of AUTOCART03.* ASPRS, Falls Church, pp. 439-56

White M (1984) Technical requirements and standards for a multipurpose geographic data system. *The American Cartographer 11:* 15-26